Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Information Technology and Electrical Engineering
Department of Electric Power Engineering

Jens Høen Hval

Development and testing of a Home Energy Management System control structure for a Norwegian household prosumer during high-demand conditions

Master's thesis in Energy and Environmental Engineering
Supervisor: Eilif Hugo Hansen
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Preface

The submission of this master's thesis concludes my five years as a student at the Norwegian University of Science and Technology, and the work presented is the product of my final semester. I am grateful for the opportunity to work on and learn about the interesting and important topic of facilitating efficient use of energy and power in buildings, a topic that for me personally was relatively unexplored until mid-January.

I want to thank my supervisor, Eilif Hugo Hansen, and co-supervisor, Kjell Sand, for willingly sharing their perspectives and providing excellent guidance when needed. I would also like to thank Hanne Sæle and Nicolai Feilberg for providing information and data I was unable to find myself.

My biggest appreciation towards my family and my biggest fan for helping with proofreading, and providing motivation and food at stressful times. Thank you. And at last, congratulations to my fellow students. Dazzling jewels, having magnificent minds, thank you for enlightening these five years!

Abstract

As the peak power consumption is expected to gradually increase during the next decade, electricity grid operators must invest in order to guarantee the grid's ability to handle the increasing power peaks. These investments are costly, and it is therefore expected that the grid tariff imposed on electricity consumers will increase. To facilitate this, the Norwegian Water Resources and Energy Directorate (NVE) proposed in 2017 to change the grid tariff structure, going from an energy-based tariff to a capacity-based tariff. By this tariff, electricity consumers will subscribe to an amount of power capacity, and if exceeding this capacity, this over-consumption will be extra costly for the consumers. If this tariff is being put into place, Norwegian households might want to invest in Home Energy Management Systems that can control the household demand as not to exceed the limit given by the subscribed capacity. This is also facilitated by the installation of smart energy meters in Norway, which provide data on electricity use as frequent as every 2.5 seconds.

The work in this thesis involves the development of a Home Energy Management System control structure, or algorithm, that can perform load controlling actions to avoid over-consumption. The time of year when over-consumption is most likely to happen is during winter, when the demand for heating is largest. By utilizing the demand flexibility offered by electric space heating loads, the household's demand can be reduced for a period of time when the non-deferrable load is large. The control structure is dependent on controllable/flexible loads, that all are prioritized by the user. By the priority selection, the user can determine which space heating loads should have the highest priority, and which should have the lowest. If the household demand exceeds the demand limit, the Home Energy Management System will try to turn off the space heating loads, starting with the lowest prioritized loads, until the demand no longer exceeds the limit. The load control development also emphasizes to minimize the loss of comfort associated with the decrease in room temperature. The load control will, by pre-determined comfort conditions, always ensure that the temperature is over a specified minimum temperature, which is determined by the user. The control structure is also able to utilize any distributed generation assets combined with battery energy storage to use this energy to maximize the comfort for specific rooms that are pre-defined by the user.

A simple Simulink model of an apartment is developed, giving the ability to simulate how the indoor temperature changes with respect to the status of the space heating loads in the apartment. Combining this with a typical load profile for a Norwegian household, an electric vehicle load and associated photovoltaic panels and battery energy system storage, the simulations are carried out for a cold winter day in Norway. The simulation results indicate that the control of space heating loads alone is not sufficient for shifting demand on an hour-to-hour basis. The control of space heating loads can reduce the demand for shorter periods, and if the measurements of power are averaged over shorter intervals than 1 hour, like 15 minutes or 1 minute, the economic savings by the developed load control can magnify significantly. In addition to this, utilizing larger flexible loads can also reduce the 1-hour-measurement-based capacity-based grid tariff cost. This is demonstrated by scheduling the electric vehicle charging, and the results show that the grid tariff cost may be reduced by over 30 %, while preserving a sufficiently comfortable temperature indoors.

Sammendrag

Med den forventede økningen i elektrisk topplast det neste tiåret, må norske nettselskap investere for å sikre at nettet har nok kapasitet til å håndtere denne økningen. Investeringene koster mye, og det er derfor ventet at nettleia som norske strømforbrukere må betale også vil øke. For å muliggjøre dette foreslo Norges vassdrag- og energidirektorat (NVE) i 2017 å endre nettleia fra dagens energibaserte tariff til en mer effektbasert tariff. Hovedforslaget gjaldt en nett-tariff hvor kunder skal abonnere på en bestemt mengde effektkapasitet, og der all effektforbruk som overgår denne kapasiteten, kalt over-forbruk, vil bli belastet med en høyere pris. Hvis denne tariffen tas i bruk vil norske husholdninger muligens ønske å investere i energistyringssystemer som kan kontrollere husholdningens lastbruk, slik at forbruket ikke overskrider den abonnerte effektgrensen. Utrullingen av de nye AMS-målerne, som kan gi data om energi- og effektforbruket hvert 2.5 sekund, muliggjør også implementeringen av slike styringssystemer.

Arbeidet i denne oppgaven omhandler utviklingen av et slikt styringssystem, nærmere bestemt en algoritme for automatisk effektkontroll som skal kunne holde forbruket i en husstand under effektgrensen gitt av den omtalte nettleia. Over-forbruk vil mest sannsynlig være et problem om vinteren, når behovet for oppvarming er størst. Ved å utnytte forbruksfleksibiliteten som finnes i romoppvarmingslaster, kan husholdningens forbruk reduseres i perioder der forbruket av ikke-fleksible laster er høyt. Lastkontrollalgoritmen belager seg på kontrollerbare fleksible laster, som alle er rangert i prioritet. Brukeren skal bestemme hvilke romoppvarmingslaster som har høyest og lavest prioritet. Hvis husholdningens effektforbruk overgår effektgrensen, vil styringssystemet forsøke å skru av romoppvarmingslastene. Den vil først forsøke lastene med lavest prioritet, og deretter de med høyere prioritet, helt til forbruket ikke lenger overskrider grensen. Lastkontrollalgoritmen vil også vektlegge å minimere reduksjon av komfort i forbindelse med temperaturfall i huset. Lastkontrollen vil, ved hjelp av forhåndsdefinerte komfortbetingelser bestemt av brukeren, sørge for at romtemperaturen er over en bestemt minimumstemperatur. Styringssystemet skal også kunne nytte seg av lokal energiproduksjon og -lagring, ved å bruke den produserte energien til å maksimere komforten i utvalgte rom.

En enkel Simulink-modell av en leilighet er utviklet for å kunne simulere hvordan romtemperaturen endrer seg med hensyn på statusen (på/av) til romoppvarmingslastene i leiligheten. Ved å kombinere dette med en typisk lastprofil for en norsk husholdning, en elbil og lokal energiproduksjon og -lagring, så er simuleringer gjennomført for en kald vinterdag i Norge. Resultatene indikerer at styringen av romoppvarmingslaster alene ikke er tilstrekkelig for å forflytte forbruk fra en time til en annen. Derimot kan lastkontrollen redusere forbruket i kortere perioder, og hvis effektmålingene er snittet over kortere perioder enn én time, som f.eks. over et kvarter eller minutt, kan de økonomiske besparelsene ved å bruke lastkontrollen økes betydelig. I tillegg til dette, kan styring av store fleksible laster redusere den effektbaserte nettleia også for avregningsintervaller på én time. Dette er demonstrert ved å planlegge ladingen av en elbil, og resultatene viser at nettleia kan reduseres med over 30 %, samtidig som det opprettholdes en tilstrekkelig behagelig innendørstemperatur.

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Abbreviations

AMS	=	Smart metering system
BESS	=	Battery energy storage system
CB tariff	=	Capacity-based tariff
DSO	=	Distribution system operator
EV	=	Electric vehicle
EWH	=	Electric water heater
HAN	=	Home area network
HEMS	=	Home energy managment system
MPP tariff	=	Measured peak power tariff
NVE	=	Norwegian Water Resource and Energy Directorate
PV	=	Photovoltaic
ToU	=	Time-of-use
V2G	=	Vehicle-to-grid

Chapter 1

Introduction

The peak power consumption in Norway is expected to increase[1]. In 2018, it was expected that Norwegian electric grid operators would have to make huge grid investments to handle this peak increase. As a result of this investment, The Norwegian Water Resource and Energy Directorate proposed in 2017 a structural change of the grid tariff, with the goal of forming a grid tariff that shows the real cost of consuming power. The proposed main idea was the capacity-based tariff, in which electricity consumers will pay for a given amount of grid capacity [W], and that power consumption over this limit is charged at an extra, more expensive, rate. Under this tariff regime, electric power consumers will be incentivized to minimize the consumption exceeding the specified demand limit, commonly referred to as "over-consumption".

During winter months, when the temperature decreases, the demand for space heating increases. In Norwegian households, and for Norway in general, most of the space heating appliances are powered by electricity. Because of this, the power consumption in Norwegian households reaches its peak during the winter, and this is thus when the problem of over-consumption is most relevant. In addition to space heating loads, the electric vehicle (EV) penetration in Norway is significant and increasing. The charging requires a vast amount of power, making the problem of EV charging highly relevant when aiming to minimize the over-consumption for Norwegian households.

Space heating electric loads demand a lot of power, but they also provide a source of demand flexibility as they can be turned off for a limited period of time, without affecting the user comfort significantly. Because of this, space heating loads can be turned off to reduce the demand for electricity for a period of time. This also goes for the electric water heater, which can be turned off for a longer time without applying major comfort losses on the user.

In light of all this, the interest for Home Energy Management Systems (HEMS) is increasing. These systems can, in different ways, control the electric loads in a household with the purpose of providing the user some kind of benefit, in most cases an economic benefit. This involves e.g. Smart House technologies, smart charging of EVs and efficient utilization of possible renewable energy resources produced on-site. In Norway, the penetration of smart energy meters is increasing, and they provide multiple possibilities of energy management. The smart meters facilitate the implementation of HEMS in Norwegian homes, but as to date, this is a relatively fresh commercial arena where a lot is expected to happen in the coming years.

The work presented in this thesis will cover these mentioned topics. A HEMS for Norwegian homes is explored, with the goal of developing and testing a control structure for load management. This load management structure is developed with the general goal of reducing the over-consumption in the household. The problem of reducing the demand for electricity at specific times while minimizing the experienced comfort loss for the user will be approached and attacked, as well as the trade-off between economic saving and loss of comfort. The control structure will also involve both efficient utilization of distributed energy production and energy storage. The former in the form of rooftop photovoltaic (PV) panels, and the latter as a battery energy storage system (BESS). The control and utilization of these should contribute to the same aforementioned goals, thus economic savings while preserving the comfort level for the user.

To test the control structure, a model of a Norwegian household with typical household loads and load profile is developed in Simulink. The model is designed to replicate the typical Norwegian household's electricity demand during a winter day, and be able to simulate simple dynamics between space heating loads in a room and the room temperature. In addition to this, the model includes rooftop PV panels with an associated battery for energy storage. The control structure developed is tested on the modelled household with PV, BESS and an EV. The simulations are presented, and the results are discussed to investigate the performance and impact of the tested load control.

The thesis is organized as follows:

- Chapter 2 presents the motivation, key facts and the conceptual framework around the approached problem.

- Chapter 3 elaborates on the methods for reducing the demand for grid-supplied power in households.
- Chapter 4 presents the typical household electric loads that can be utilized when reducing or shifting the demand for grid-supplied power, the physical principles regarding this, as well as typical household load profiles and overall electricity consumption.
- Chapter 5 introduces the development of the load control structure used in the load management.
- Chapter 6 presents the modelled household with its load profile, loads and physical structure.
- Chapter 7 elaborates on the different points and results of interest that must be investigated to properly assess the performance of the developed control structure.
- Chapter 8 considers the simulation scenarios and the associated results.
- Chapter 9 gives the discussion and investigation of the results.
- Chapter 10 draws the final conclusion of the work and results presented in this thesis.
- Appendix A presents the simulation results.

Chapter 2

Electric power and energy use in Norway

2.1 Electrical power and energy

By G. M. Masters, energy can be thought of as the ability to do work, while power is the rate of which energy is generated or used[2]. Power can therefore be seen as the energy that is generated/used per unit time, and energy as the power generated/used over a period of time. Energy is given in joules [J], and thus power is given in joules per second [J/s], also called watt [W]. Mathematically, energy is obtained when multiplying power by time. Likewise, power is obtained when dividing energy by time. Electrical power is the power bound in moving streams of electrons or charges, and electrical energy is the ability to do work by these streams of electrons. However, in the electrical industry the preferred energy unit is watt-hours [Wh]. One watt-hour is the amount of energy that is generated/used when an electric generator/load of one watt runs for one hour. The relationship between joules and watt-hours, both measures of energy, is thus given as:

$$1 \text{ Wh} = 1 \text{ W} \cdot 1 \text{ hour} = 1 \text{ W} \cdot 3600 \text{ seconds} = 3600 \text{ J}$$

In this thesis, electric loads are often mentioned. Devices, things and objects that are using (consuming) electric power are called loads. A 50 W light bulb is therefore characterized as a 50 W load.

2.2 The electrical grid

In Norway there are millions of households, enterprises and industry companies, that all depend on the supply of electricity. The electricity is produced at various locations, at both big and small power stations, and is distributed to all electricity customers through the electricity grid. The grid is owned by different grid companies/operators, and consists of three layers with different voltage levels - the transmission grid, the regional distribution grid and the local distribution grid[3]. Statnett owns most of the transmission grid, while the rest is mainly owned by local distribution system operators (DSOs). The grid companies are responsible for grid maintenance and investment, and are financed by income from the grid tariff that all electricity customers must pay. Because of the fact that the Norwegian electrical grid is a natural monopoly, grid companies operations are regulated by the Norwegian Water Resource and Energy Directorate (NVE)[4].

2.3 Energy and power consumption in Norway

The total electricity consumption in Norway was in 2012 130 TWh, and is estimated to increase to 143.2 TWh, giving a 10 % increase, by 2030[5]. This increase is mainly due to increased population and electrification[6]. For Norwegian households, the total electricity consumption was 36.3 TWh in 2012, so this consumption plays a significant role. The electric energy consumption varies throughout the year, as can be seen from Figure 2.1 taken from NVE's website [1]. The electricity consumption during the winter months is more than during the summer, due to the increased need for heating resulting from cold outdoor temperatures. Due to this the total energy consumption is highest for the months of December to March.

In addition to seasonal variations in electricity use, the hourly load is also changing during the day. This can be seen from Figure 2.2, also taken from NVE's website [1]. The figure shows electricity usage from hour to hour on a cold winter day in Norway, for both weekdays and week-ends. The main contributors to the electricity consumption are buildings (households and service enterprises/companies) and industry [5]. At night, when people, and society in general, are sleeping/not active, the electricity demand is low. For weekdays, the load increases rapidly around 7h in the morning, and reaches a peak around 9h. This is the period when people get up and start their daily morning routine. Industry starts up around 7h-8h and has a constant high electricity consumption, which starts to decreases around 16h [7]. At this point, people get home from work, and the household electricity consumption naturally increases. From 16h and towards 22h, the typical household electricity consumption is high and is reaching its peak around 18h-20h,

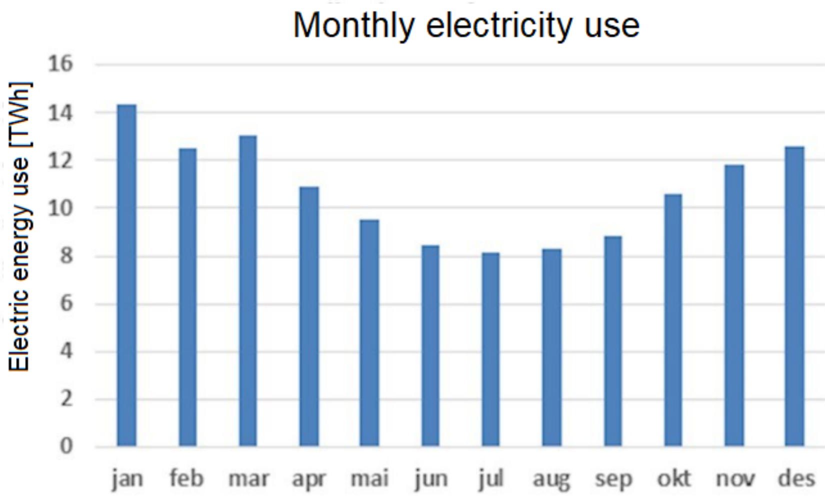

Figure 2.1: Typical monthly electricity use in Norway [1].

as is shown in Figure 2.3. The figure shows the hourly load profiles each month for a typical household in Norway. From Figure 2.2 and Figure 2.3, it can be seen that the two separate grid peak loads, respectively around 9h and at 18h, are somewhat coherent with the two peaks for the household load profile as well. These times are commonly referred to as the grid's "peak hours".

Both the peak power consumption(the maximum grid load measured) and the total electric energy consumption for Norway has increased since the 1990's. In 2016, the total electric energy consumption had increased by approximately 24 % since 1990, while the peak power consumption had increased about 33 % [1]. This can be seen from Figure 2.4. NVE states that this trend will continue, and that the peak load can continue to increase more than the electric energy consumption. The main reason for this is the increase of high power appliances, e.g. EV charging and instant water heaters. Because the grid must be dimensioned to handle the peak load, the increase in peak load forces grid companies to make investments in the grid. NVE expected in 2018 that grid companies would have to invest approximately 135 billion NOK in the period from 2018-2027. 27 % of this expected investment, that is 36.45 billion NOK, is caused by the expected increase in peak load[8]. Due to the investments, it was predicted that the grid tariff that all customers have to pay would increase by 30 % from 2015 to 2025 [9]. A survey measuring the power consumption for 500 customers of Ringeriks-Kraft Nett for one year, showed that the average amount of hours that the load was 90 - 100 % of the maximum measured

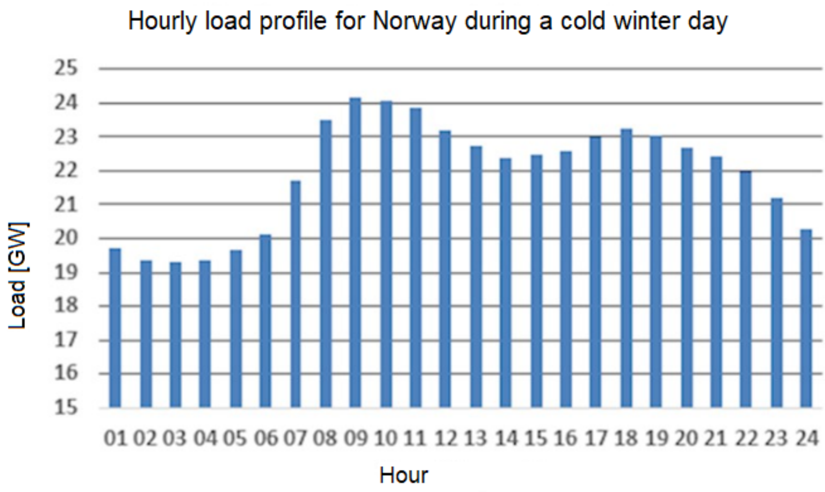

Figure 2.2: Typical hourly electricity use in Norway [1]

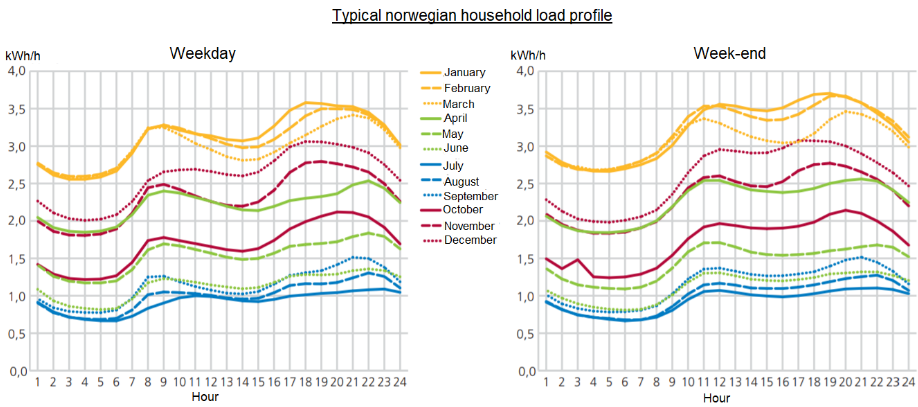

Figure 2.3: Typical Norwegian household load profile for every month, taken from SSB [7]

load was 33 hours[9]. That means that the 10 % highest load happened during 0.38 % of the time. By that, it is evident the peak load for the households can be significantly reduced if demand is trimmed or shifted for a relatively small amount of hours during the year. With this in mind, NVE proposed ideas for restructuring of the grid tariff, with the goal of incentivizing peak load reduction for all electricity customers. This will be elaborated more in section 2.5.

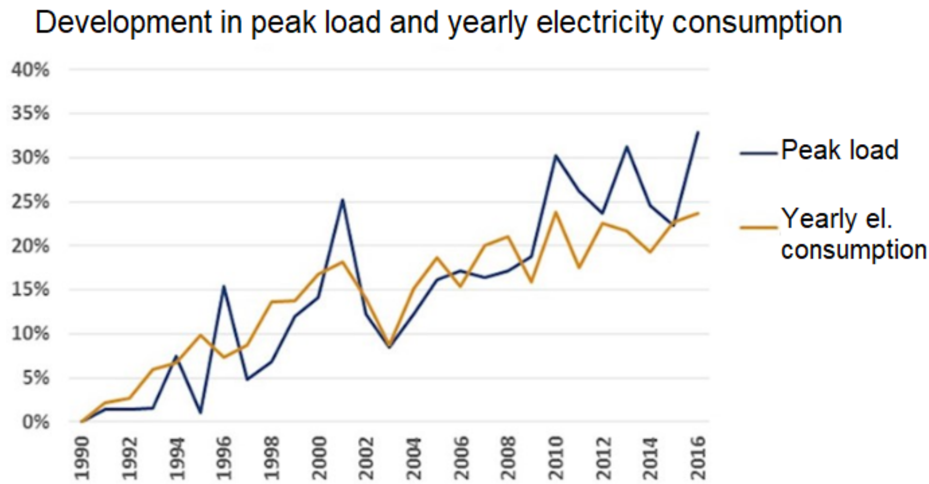

Figure 2.4: Development of peak load and electric energy consumption in Norway from 1990 to 2016 [1].

2.4 Smart meters

Smart meters, or the AMS (Smart Metering System), is replacing the traditional energy meter in all Norwegian households, by demand from NVE[10]. The smart meter automatically reads the hourly electricity consumption for the household, and sends this to the DSO. This time period can also be decreased to every quarter-hour (15 min.). The AMS also gives households the ability to observe their own consumption and, by installing third party services, other opportunities for energy management[10]. Even though the smart meter only sends hourly consumption to the DSO, households may acquire more detailed and frequent data on their electricity use by use of the HAN (Home Area Network) port[11]. From this, the active power import[W](from the grid), can be acquired every 2.5 seconds and every 10 seconds, while the active power export[W] (from PV installations etc.) can only be acquired every 10 seconds. Thus, the AMS can facilitate the process of customers feeding in power to the grid when the customer has installed power production means, like PV panels. Phase currents [A] and voltages[V], reactive power [VAr] can also be acquired every 10 seconds. Every 1 hour, data on active energy import and export [Wh] as well as reactive energy [VArh] can be acquired. All the data made available through the HAN-port can also be made available for the DSO, but only with admission and approval from the household.

NVE stated that all DSOs were responsible of installing the AMS at every Norwegian household, and as of 1st of January 2019, 92.8 % of all consumers had installed or was in the process of installing the new AMS[12].

2.5 Electricity billing scheme

In 2017, NVE published a hearing in which they proposed new ideas on how the grid tariff could be restructured[9]. The main goal was to form a grid tariff that would act as an incentive for less power consumption during peak hours for all grid electricity consumers. NVE proposed one main idea, and two additional alternatives, for this tariff, respectively: A capacity-based tariff, a time-of-use tariff and a tariff based on the maximum power consumption. Companies, enterprises, academics and interest organizations were not hesitant to give their feedback on these ideas. In this section the current billing scheme will be presented, as well as the new grid tariff proposals from NVE, and some of the feedback they received.

2.5.1 Current scheme

Today, most Norwegian households pay a monthly electricity bill consisting of two main parts: one grid tariff and one supply tariff. The supply tariff is paid to the electricity supplier for the household, while the grid tariff is paid to the local grid company, who owns and operates the electrical grid. The grid tariff consists of two terms[13]. The first term is the energy fee, which is present to cover the cost of using the grid. This cost mainly represents the transmission losses in the grid, and is given as [NOK/kWh]. The second term is the fixed fee, and is given as [NOK/year]. This is present to cover the fixed costs and investment cost for the grid companies.

2.5.2 Capacity-based tariff

The capacity-based tariff involves, as the current structure, an energy term. In addition to this, the customer must subscribe to an amount of capacity(kWh/h), in which the hourly power consumption that exceeds this capacity will be charged with an over-consumption fee (NOK/$\frac{kWh}{h}$). Then, the fixed fee of the capacity-based tariff includes both a fixed term and a term based on the amount of subscribed capacity. As an example, if a customer has subscribed to a 5 kWh/h capacity, and during one month never consumes, on the hourly average, more than 5 kWh/h, the customer will only pay the fixed fee, the capacity-subscription fee and the energy fee. On the other hand, if the customer during one hour of that month extracts, on an hourly average, 6 kWh/h, the customer will in addition have to pay for the 1 kWh/h over-consumption, given by the over-consumption fee. Table 2.1 shows NVE's proposed price levels for the different terms.

Capacity-based tariff proposal

Fixed fee		Energy fee	Over-consumption fee
Fixed term	Subscribed capacity term		
1060 NOK/year	689 NOK/$\frac{kWh}{h}$/year	0.05 NOK/kWh	1 NOK /$\frac{kWh}{h}$

Table 2.1: The proposed price levels of the capacity-based tariff.

This tariff proposal received different feedback from the energy sector. Most of them agreed that all customers should be incentivized to reduce their load during peak hours. But still, not everyone agreed upon that the capacity-based tariff was well suited. Multiple companies and organizations pointed out that the tariff will incentivize to reduce/shift the customer's peak load during all times, also at times when the total grid load is low[14, 15]. Statnett, who was generally positive to the capacity-based tariff, also stated that the price signals of such a tariff would be better if the time resolution of each power measurement was smaller than one hour[16]. With more frequent power measurements the ability to "punish" the use of high-power loads acting during short periods will increase.

2.5.3 Time-of-use tariff

The time-of-use (ToU) tariff consist of two terms, one fixed term and one energy term. The energy term is time-dependent, meaning the price of energy will vary depending on the season and the hour of the day. The price will be more expensive during winter time than during summer time, and will be even more expensive if it is winter daytime.The idea is that each distribution system operator can increase the price at the times when the distribution grid load is high. By this, all customers will be incentivized to reduce their load at these times regardless if their own consumption is high or low. NVE's proposal of the given price levels is shown in Table 2.2.

The ToU tariff also recived mixed feeback, and multiple DSOs and interest organizations expressed that the ToU tariff was the better alternative compared to the capacity-based tariff[14, 15, 17–19]. This was apparently because it is easier for household customers to understand this tariff, and also it will give price signals to reduce the load only when

Time-of-use tariff proposal

Fixed fee	Energy fee		
	Summer	Winter	Winter daytime (06h-20h)
1749 NOK/year	0.122 NOK/kWh	0.152 NOK/kWh	0.38 NOK/kWh

Table 2.2: The proposed price levels of the time-of-use tariff.

it is necessary. Yet, another DSO, Trønderenergi Nett, stated that the ToU was not comprehensible for small customers[20].

2.5.4 Measured power peak tariff

The measured power peak tariff is used today for big customers like industrial companies, commercial buildings etc.[13], but in the hearing NVE also porposed this tariff for smaller customers, namely normal households. The tariff consists of a fixed term, an energy term and a power term. The power term is given in NOK/$\frac{kWh}{h}$, and is calculated with respect to the maximum hourly load for the customer during each month or day. NVE also proposed that the frequency of peak power measured could be higher, so that the customer e.g. paid for their peak power load daily. NVE stated that the measured power tariff was percieved as hard to understand and uncontrollable by a test group of consumers. Regardless, some DSO's had already tested this tariff for their customers and recieved positive results. This was also shown by the feedback from some DSOs, who preferred the measured power tariff over the capacity-based tariff[14, 17, 19]. The price proposal from NVE will not be given here, as it will not involve in the evaluation of the algorithm as will be explained later in the thesis.

The price proposal for the measured power grid tariff is shown in Table 2.3, and the peak power consumption is measured daily and penalized.

Measured power peak tariff

Fixed fee	Energy fee	Peak power fee
1749 NOK/year	0.05 NOK/kWh	1.86 NOK/ $\frac{kWh}{h}$/day

Table 2.3: The proposed price level for the measured power peak tariff.

Chapter 3

Reducing the grid-supplied power demand in households

If the capacity-based grid tariff is chosen as the new grid tariff structure, households will be penalized by over-consumption over the decided demand limit. To reduce the possible over-consumption, there are several strategies that can be utilized to reduce and shift the demand for shorter or longer time periods. These strategies are often used to reduce the peak load demand, and can also be called peak reduction strategies. In this chapter some of these strategies will be discussed.

3.1 Demand reduction by use of demand side flexibility

Flexibility in the energy system has traditionally only been a concern for electricity producers, as production assets must be able to follow instant changes in demand. During the last 15-20 years, as peak demand has continued to increase, and installation of distributed generation and AMS has increased, the topic of demand side flexibility has arised[21]. Demand side flexibility is primarily the ability of electricity consumers, like households, to either shift or reduce demand at certain times. The goal with this is to reduce the fluctuations in the load demand, and by that improve utilization of the grid capacity. When the load is shifted, called "load shifting", the demand is reduced at peak hours, while the demand is increased either before or after peak hours. An example of load shifting is by charging an electric vehicle at night (while the grid load is low) instead of in the evening or morning (when grid load is high). When the demand is reduced, but not moved to another time, it is called "load shedding". Load shedding during peak hours is also called "peak clipping". Load shifting and peak clipping is illustrated in Figure 3.1. For households, load shifting is the most relevant, while load shedding is of more relevance for big industry/big electricity consumers[22]. The types of household loads that can offer demand flexibility will be discussed in chapter 4.

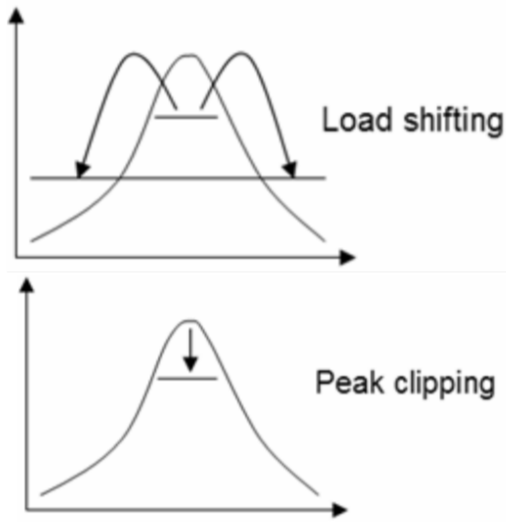

Figure 3.1: Load shifting and peak clipping illustrated on a load profile, gathered from [21]. Load on y-axis and time on x-axis.

Demand side flexibility therefore considers the household demand that potentially at some times can either be displaced or turned on or off, but in the current situation is not, due to a lack of incentives. Price signalling is one measure that can cause demand response, activating the demand side flexibility. This is the type of incentive NVE is trying to create with the new grid tariff structure explained in section 2.5. By making large power demand peaks in general more expensive, or by making electricity consumption more expensive at times when the grid load is high, households have an economic reason to change their consumption behaviour. This incentive must be big enough to actually make households want to change behaviour, especially if it involves a loss of comfort for the household. In addition to this, households must be very well informed about the price signal, and proper monitoring of the household consumption must be present. Households have traditionally showed little response to price signals because of this, but with the installation of the AMS, this could change[22].

3.2 Demand reduction by use of PV production

The amount of grid-connected PV panel installations is increasing in Norway. In 2012 the total installed PV capacity was 9952 kWp [23], and had increased to approximately 68 MWp by 2018. Wp is the watt-peak, and is further explained in the next paragraph. Annual installed PV capacity in Norway increased by 59 % from 2016 to 2017, and yet increased 52 % from 2017 to 2018, based on reports from Multiconsult and Asplan Viak [24, 25]. The PV installation increase is present for both households and enterprises, and is expected to increase further. For households, the installation cost of PV systems have decreased 30 % from 2014 to 2017, respectively from 20 NOK/Wp to 14 NOK/Wp. This can be seen from Figure 3.2. 30-40 % of the PV system cost is associated with the PV panels, while the rest is represented by installation cost and other components like the inverter and control system [26].

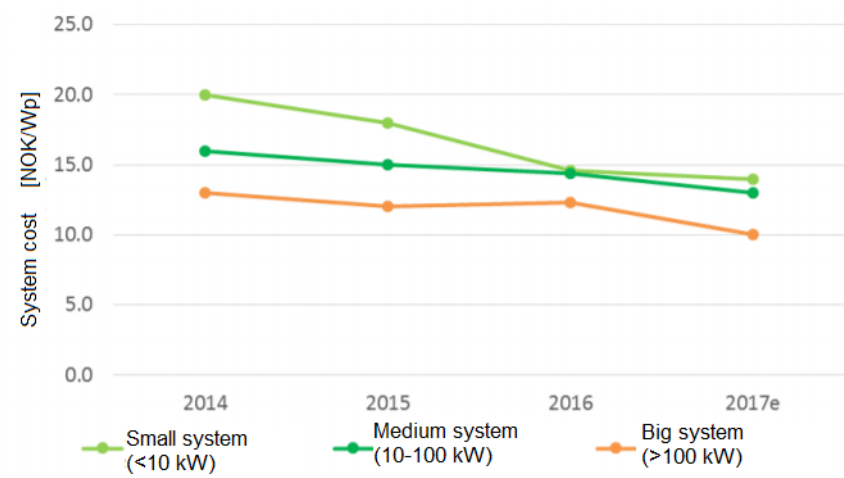

Figure 3.2: Development of PV system cost in Norway, with expected cost for 2017. Gathered from [24].

The common way to denote installed capacity of PV systems is by watt-peak [Wp] instead of the normal watt. This is because the output generation from a PV system is highly dependent on the solar conditions, which can vary a lot. 1 Wp of installed capacity means that under standard conditions the system generates 1 W. The standard condition is defined as an solar irradiance at 1000 $\frac{W}{m^2}$, panel temperature of 25 °C and Air Mass equal 1.5 (1.5 AM).[24]. Yearly solar irradiance in Norway on a horizontal surface spands from approximately 1000 $\frac{kWh}{m^2}$ in the south to approximately 700 $\frac{kWh}{m^2}$ in the north. Respectively, that corresponds to 1000 and 700 hours of standard condition solar irradiance each year.

Even though the potential to generate electricity from solar irradiance exist in Norway, the potential of reducing peak grid load is modest. This is because the PV production is highest during summer, while the load is highest during winter. This is illustrated in Figure 3.3, where a typical household load profile in Central Norway is graphed along the PV production of a 3.06 kWp PV system at the same location. During winter, when load is high and the peak load demand for the household occurs, the PV production is comparably small. Therefore the PV system production characteristics is not ideal for households in Norway, regarding reducing the peak load demand.

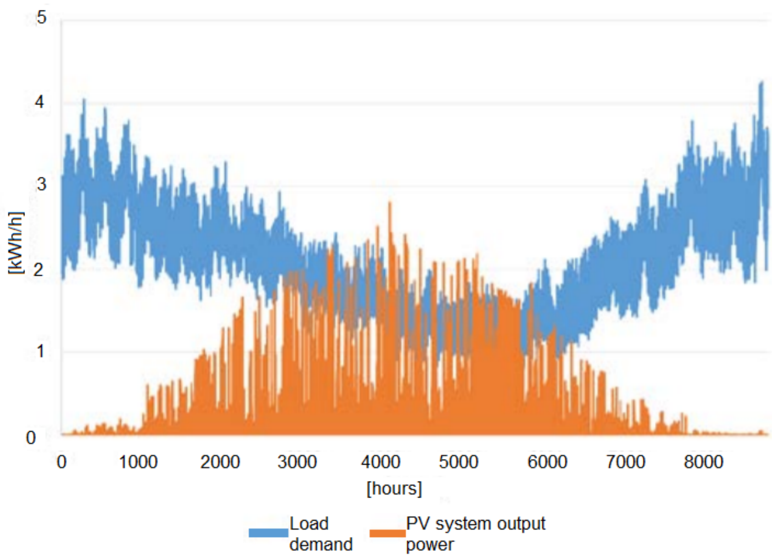

Figure 3.3: Typical household load demand and PV production from a PV system during a full year, starting at 0h on the 1st of January, both located in Central Norway. Gathered from [27].

Alongside the seasonal negative correlation between PV production and household load, the daily production curve for PV systems must also be investigated. PV system production naturally follows the position of the sun on the sky. Production starts at sunrise and increases gradually until the sun is at its highest (typically mid-day) and production decrease as the sun moves towards sunset. This is not ideal, as the two daily peak loads(i.e. when the demand for energy is highest) happens at morning and evening, while the grid load is smaller during mid-day. The time when the PV production is at its maximum is also dependent on the orientation of the PV panels. This is illustrated in Figure 3.4, with an arbitrary household load profile in blue, and the production curves for identical PV systems in red, green and yellow, that are oriented in different directions. Figure 3.4 shows how the peak of PV production does not coincide with either of the two daily consumption peaks, and also that the production profile of the PV system can be changed with the orientation of the panels. Thus, the daily PV production peak can be time shifted to some extent. For peak load reduction purposes(without energy storage options), it could therefore be important to design the PV system so that the PV production profile fits the load consumption profile.

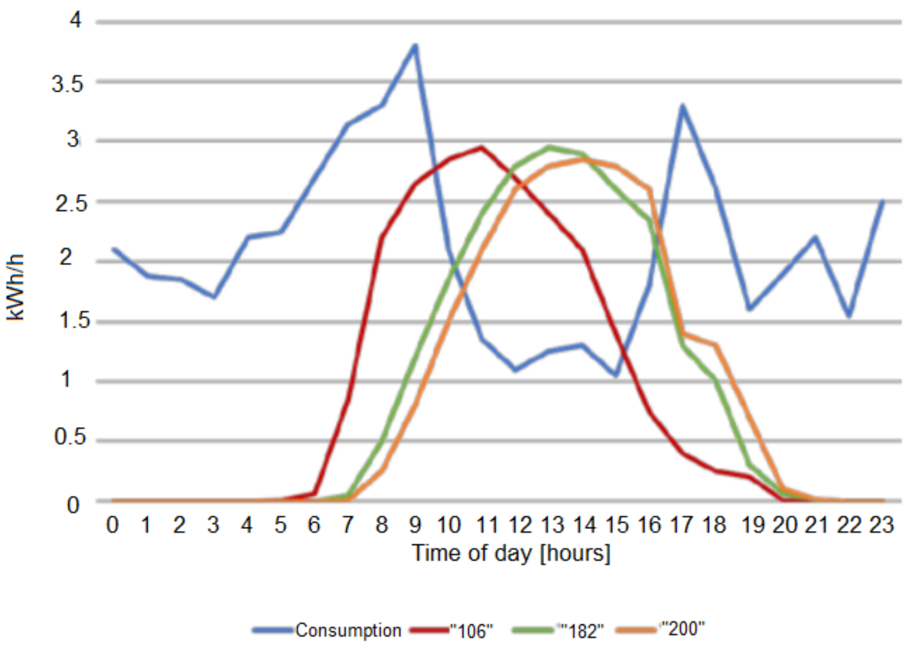

Figure 3.4: Arbitrary household load curve in blue, and PV production with equal panels with different orientation in red(106°), green(182°) and yellow(200°). Gathered from [28].

Regardless of optimizing the oriented direction of the PV panels, studies show that future households with PV systems without energy storage will not be able to reduce the peak load in the grid[28]. This is, as mentioned, because of the negative seasonal correlation between PV production and peak load, as Figure 3.3 shows.

Households with grid-connected PV systems under 100 kW, called "surplus" customers or prosumers, are today paid by their power supplier for the energy that they produce and supply top the grid[29]. Bremdal and Sæle[27] evaluated how the restructuring from an energy based grid tariff to a measured power grid tariff(subsection 2.5.4) would affect prosumers with PV installations. They concluded that a power grid tariff would reduce economical benefits for the prosumers, while encouraging self-consumption instead of supplying power to the grid, especially during peak hours. Self-consumption for households with PV systems refers to the principle of using the PV produced energy to serve the household's demand instead of supplying the grid. This can be achieved by optimizing the PV panel direction or by using battery energy storage systems.

3.3 Demand reduction by battery energy storage systems

Battery energy storage systems (BESS) in the grid gives the opportunity of daily load leveling. It can also be referred to as the "battery" further on in this thesis. The principle of load leveling is illustrated in Figure 3.5. The battery can be charged up during low-load periods, and discharged during high-load periods to decrease the demand for grid-supplied electricity.

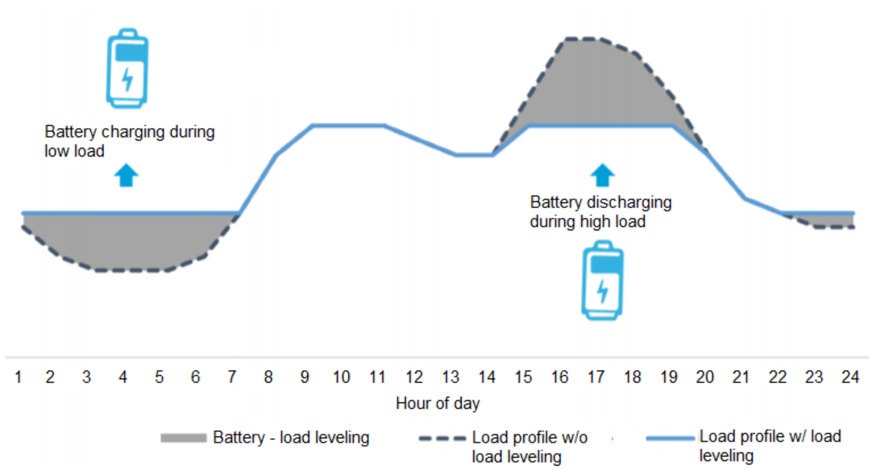

Figure 3.5: Illustration of load leveling by a battery energy storage system. Gathered from [30].

The BESS can be associated with distributed generation systems, like household PV systems, to give the possibility of storing the energy produced on-site. For households in Norway that have installed PV systems, a BESS can increase the extent of self-consumption during summer time, and also contribute to load leveling during winter[23]. During summer time, when the PV production might exceed load demand for the household and the grid load is low, the excess energy can be stored on the battery and used later to supply the household demand. During winter, when the PV production is low and the grid load is high, the BESS can store the produced energy and use this for peak shaving purposes. As mentioned earlier, this can be beneficial if dealing with a capacity-based tariff. The on-site battery will then, when used, supply parts of the household demand, and thus reducing the households demand for grid electricity without reducing the demand itself.

Degefa et al.[31] found that for households with an installed PV system (3.06 kWp) and BESS (6.4 kWh/3.3 kW), the yearly peak power supplied from the grid got reduced by 8.74 %. The BESS utilization was optimized with respect to daily forecasting of both PV production and load, and the BESS could use both electricity from the PV installation and the grid to charge. The study also showed that the average daily peak demand got reduced by 17 %. The BESS combined with PV can therefore play a significant part in reducing peak demand for households in Norway.

NVE states that it is expected that the amount of battery capacity in Norway will increase towards 2030, mainly due to the increasing amount of electric vehicles and PV installations. The accumulated storage capacity in the Norwegian electric vehicle (EV) fleet can increase from 2.5 GWh in 2016 to 100 GWh by 2030[32]. With development in the vehicle-to-grid (V2G) technology this storage can be utilized for load leveling for EV owners[33]. NVE also predicts an increase in batteries in combination with PV systems in buildings in Norway, but not as evident as the increase of EV-based storage. By the assumption that every 1 kWp with building installed PV will bring 1 kWh with installed battery capacity, it is predicted that by 2030 the battery capacity associated with PV systems in buildings will increase to between 1500 MWh and 14 000 MWh[32]. The predicted increase is thereby highly uncertain.

Judging by today's situation, battery storage does not provide economic benefits if used for load leveling purposes. This is because the BESS is expensive and that today's price of energy between high-load and low-load periods is not big enough.[32]. With the restructuring of the grid tariff, and possibly a change in energy prices offered from power suppliers, load leveling actions might be incentivized enough to make BESS investments profitable.

3.4 Home energy management systems

As demand side flexibility and combined PV and BESS have the ability to reduce the peak load in households, the utilization of these resources require active monitoring and control of the household's load and production, and possible reduction of comfort and convenience. If the utilization of demand side flexibility is demanding for the household, i.e. it is time-demanding or intellectually difficult, this can prevent the utilization of the flexibility[34]. In other words, if home owners actively have to monitor their household load, and actively respond(i.e. turn of loads) when their load is reaching a certain threshold (as could be the case when having a capacity based tariff), this can be experienced as a too big barrier for them and thus prevent utilization of the flexibility. On the other hand, if the home owners experience that they are being economically rewarded in such extent that the time-use is and comfort-loss is worth it, this barrier might be overcome[21].

One way of releasing the potential of demand side flexibility is by the use of autonomous systems that can monitor and control the energy use in the household, including the battery usage if the household have installed a PV system and BESS. Such system is called a Home Energy Management System, and its main goal is to control electricity usage with regards to a specified purpose. This purpose could be to maximize economic savings, reduce peak load, increases self-consumption and so on. For households with HEMS, the end-goal is often economically driven: reduce cost or maximize savings[35]. This is done by installing a system which can control household loads and BESS usage, by utilizing information such as instantaneous load, electricity/grid tariffs, outdoor and indoor temperatures and such. In Norway, the installation of smart meters, providing useful information on energy usage, is an enabler of HEMS[36]. After installation and by proper programming of such a system, households do not have to actively do anything to manage their energy use, and also the experienced loss of comfort and convenience should be minimized. That means that the system must have clear boundaries in regards to which household loads that can be turned off/turned on, and in which extent they can be turned off over time.

HEMS are often based on historical data such as statistical consumption, PV production etc., and/or based on real-time calculation algorithms[35]. HEMS might optimize the energy use over the day with regards to electricity prices, PV production and load constraints, but some load control algorithms are only focusing on real-time information for decision-making without optimizing. Non-optimization algorithms are more simple and require less information than optimization algorithms. Some examples of different HEMS algorithms will be discussed in chapter 5.

Chapter 4

Flexibile household loads

As discussed, demand side flexibility is a resource that is coherent with households loads, in which some of these loads can be turned on/off to reduce the demand load at certain times. Some types of flexible loads are loads that are used for heating purposes, and other types are loads that can be planned in terms of use, like EV charging, washing machines etc. For Norwegian households, approximately 64 % of the total annual electricity consumption is used for room heating, 15 % is used for water heating and the last 21 % is used for other electric appliances like lighting, oven, washing machine, kitchen appliances, television, personal computers etc. [37, 38]. As the electricity consumption for heating purposes is so high, this gives some flexibility in terms of thermal storage. This will be further discussed. As mentioned in section 2.3, the load peaks for a typical household appears around 9h in the morning and 18h in the evening, and to minimize these peaks it is important to know how electricity is used in Norwegian households, and on which loads. This knowledge will be helpful in determining the household loads that can be controlled to perform load shifting or peak clipping. In this chapter, household loads will be discussed as well as some physical principles about thermal storage.

4.1 Thermal storage

Thermal storage in households are often associated with the thermal storage of sensible heat. This means that heat is stored as internal energy within a substance by increasing its temperature without changing the substance's chemical composition or phase[39]. All substances can store sensible heat, and their storage ability is specified by their specific heat capacity. The specific heat capacity for a substance, c, is defined as the amount of energy that 1 kg of the substance absorbs (or emits) when the temperature of the substance is increased (or decreased) by 1 °C[40]. Specific heat capacity is therefore given as $[\frac{J}{kg \cdot K}]$, and the heat capacity of an object is obtained by multiplying its specific heat capacity by the object's mass. The volumetric heat capacity $C = c \cdot \rho$ can also be used, where ρ is the density of the object/substance. By using the specific heat capacity for e.g. air, the amount of energy it takes to raise the temperature of air by 1 °C can be found, which will prove very useful when dealing with household indoor temperatures. Wood, water, air and concrete are all materials which can be present in a building, and these materials have different specific heat capacities. The heat capacity of these substances is given in Table 4.1.

Material	ρ $[\frac{kg}{m^3}]$	c $[\frac{J}{kg \cdot K}]$	C $[\frac{J}{m^3 \cdot K}]$
Air	1.23	1008	1239.84
Wood	500	1600	800000
Concrete	2300	1000	2300000
Water	1000	4190	4190000
PVC	1390	900	1251000

Table 4.1: Thermal constant attributed for some substances[40].

As can be seen from Table 4.1, 1 m^3 of water at 20 °C holds more energy than 1 m^3 of air at the same temperature. That also means that when 1 m^3 of water is cooled down 1 °C, more heat is released to the surroundings than when 1 m^3 of air is cooled down 1 °C. The amount of sensible heat that is absorbed in a substance during a change in temperature is given by Equation 4.1

$$Q = \rho \cdot c \cdot V \cdot \Delta T \tag{4.1}$$

where Q is the stored heat[J], c and ρ is defined as previously explained, V $[m^3]$ is the volume of the substance and ΔT is the temperature change in the substance [41].

The exchange of sensible heat will occur at all times when there is a temperature difference between two substances, e.g. the indoor air and the surfaces of the household building. When there is heated wood, concrete or water present in a room space, this will cause the space temperature to decrease slower than if the space is only filled with air. This is because wood, concrete and water, as explained, has better heat storage capabilities than air.

This ability of materials to store heat could be very important for peak reduction in Norwegian household buildings. As stated, 64 % of the annual electric household consumption is used for space heating. Thermal storage allows e.g. indoor electric heaters to be turned off for a period of time and still maintaining a comfortable indoor temperature. The same goes for electric water heaters. Electric water heaters in residential buildings can be turned off for a period of time without causing major comfort losses for the household. Shutting off electric space and water heaters during times with peak load is therefore a load-shifting measure for peak reduction.

Regarding thermodynamic properties in a building, the thermal conductivity λ is also important. The thermal conductivity of a substance gives the ability of heat transfer through the substance, and is given in $[\frac{W}{m \cdot K}]$. For materials with high thermal conductivity, heat transfer through the material happens faster than for materials with smaller thermal conductivity. For residential buildings, it is favorable that the exterior walls have a low thermal conductivity, thus good insulation, to prevent heat transfer, heat loss, through the walls. For a building wall, with thermal conductivity λ and thickness d, separating inside air (temperature T_2) and outside air (temperature T_1), the heat transfer though the wall per wall area, ϕ $[\frac{W}{m^2}]$, also called the heat flux, is given as in Equation 4.2[40]. See Figure 4.1 for illustration.

$$\phi = \frac{\lambda}{d} \cdot (T_2 - T_1) \tag{4.2}$$

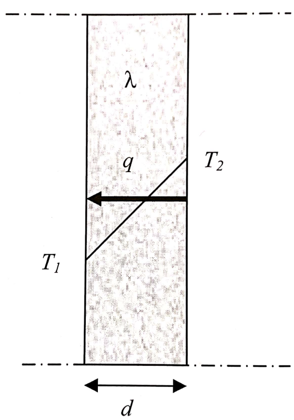

Figure 4.1: Illustration of heat conduction through a wall, from [40]. "q" is the heat flux.

Often the thermal resistance or thermal transmittance of a wall is used instead for the thermal conductivity[40]. The thermal resistance r and transmittance u of a unit wall area, with thickness d and conductivity λ is given as

$$r = \frac{\lambda}{d}\left[\frac{m^2 \cdot K}{W}\right] \qquad u = \frac{1}{r}\left[\frac{W}{m^2 \cdot K}\right] \tag{4.3}$$

The insulation specifications for building walls and windows in Norway are often given in terms of u, also called the U-value.

4.2 Typical households loads

A survey done by the company Sikom, where approximately 300 participated, shows what types of loads the participants had at home or at their cottage[42]. The results are illustrated in Figure 4.2. It shows that most households have space heating in terms of electric radiators and floor heating. Most households also have the electric water heater (EWH) for water heating, and dishwasher and washing machines/dryer for washing. Appliances for cooking, the stove and induction top are also widely used. The EV penetration for this group of participants was about 20 %.

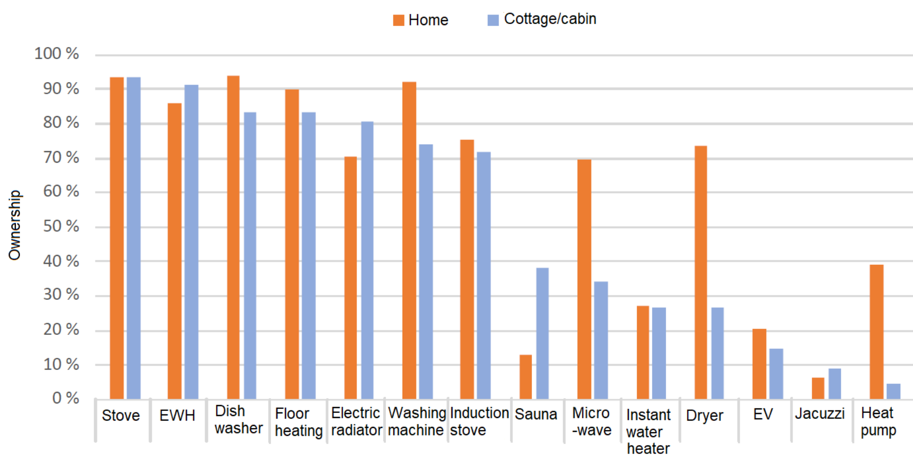

Figure 4.2: Survey results done by Sikom about household load ownership. Gathered from [42].

The loads that were surveyed in Figure 4.2 are mainly loads that in some way can serve as flexible loads. Most relevant for this thesis is the appliances used for heating purposes as these loads are very suitable for HEMS control. In addition to this, EVs as loads will be investigated.

4.2.1 Thermostat controlled loads

A simple thermostat is a switch that goes on/off based on temperature readings from a sensor in the thermostat. The thermostat's main function is to keep the temperature of a certain material/object/space at a desired set point. Electric heaters are often controlled by a thermostat. It is switched on when the temperature reaches a lower set point, and is turned off again when the temperature reaches a maximum set point. The set points are often set as some interval/tolerance around the desired temperature, which makes the temperature fluctuate between the higher and lower set point temperatures. When the temperature is within the specified interval, the thermostat is unchanged. If the desired temperature is T_d, measured temperature is T_m and the temperature tolerance is ΔT, the switch status S for the thermostat controlled load will be as shown in Table 4.2.

S	T_m
1	$\mathrm{T}_m < T_d - \Delta T$
0	$\mathrm{T}_m > T_d + \Delta T$
unchanged	$\mathrm{T}_d - \Delta T < T_m < T_d + \Delta T$

Table 4.2: Relation between thermostat temperature and status.

Electric radiators, electric floor heating and electric water heaters all are thermostat controlled, and these loads, their usage patterns and flexibility will be mapped in the coming sections.

Electric water heaters

The electric water heater (EWH) should serve the household with hot water at all times. The EWH consists of one (or more) insulated tanks equipped with a heater. The EWH heats up the water in the tank to a specified temperature, and is controlled by a thermostat. The typical load profile for a water heater depends on the households hot water consumption. In theory, the water heater will be on for longer periods when hot water is used, because of the incoming cold water must be heated. When the water has reached a certain temperature, the thermostat turns off the heater, and will only be turned on again for shorter periods to maintain the desired water temperature. The desired water temperature is typically between 60-90 °C, and the water temperature should not be in the range 20-45 °C because of possible growth of the Legionella bacteria[40].

EWH operates at several kW when they are on, which for most households is a big instantaneous load. By turning off or avoiding turning on the EWH when the load is high is therefore an effective measure for load reduction in households. As mentioned, water has high heat storage capabilities, and the water heater can therefore be turned off for periods without causing major comfort losses for the household.

Electric radiators

The electric radiator is commonly used in Norwegian households, and is controlled either by thermostat or by adjusting the load. It heats up the surrounding air by convection and radiation(electromagnetic waves) from the exterior surface. Because air has relatively small thermal storage capabilities, the surrounding temperature will drop quickly when the radiator is turned off. This means that it is able to shift the load for a shorter period than the EWH. Regardless, air offer some thermal storage, which means radiators can offer flexibility in terms of reducing short termed peaks without significant losses in comfort for the household.

A rule of thumb is, according to the supplier Elkjøp[43], that electric radiators used for space heating of a certain area should have at least 70 $\frac{W}{m^2}$. Regardless, the amount of power needed for heating is dependent on a lot of factors, especially the insulation of the room/building.

Electric floor heating

By Figure 4.2, floor heating is widely used in households, in both homes and cottages. They are controlled by thermostats, either sensing air temperature or floor temperature. Electric floor heating can be utilized by two different approaches.

The first one is by heating cables in the floor. These are electrical conductors supplying heat by their ohmic losses when conducting current. Heating cables are often embedded in floors made of concrete, tiles or PVC, and are often used on bathrooms. The installed load in bathroom heating cables is at maximum 150-200 $\frac{W}{m^2}$, depending on the material[40, 44]. For non-bathroom floors, the highest allowed power is 80 $\frac{W}{m^2}$. For bathrooms, the desired temperature is often high, so the thermostat set point is higher than for other rooms, while it should not be over 26 °C for living rooms[40]. Because heating cables heats up either concrete, tiles or PVC, materials with relatively high thermal storage capabilities, heating cables can be turned off for a longer time than electrical radiators, and by that provide more flexibility in terms of load shifting. This also means that they will be on for a longer time intervals than the radiators as well, because the heating process takes more time.

The second approach is by heating foils in the floor. These are electrical elements of foil between two layers of plastic, that are easily installed in between layers in the floor. Heating foils are most often used to heat up wooden floors. Wood possess better heat storage capabilities than air, and less than concrete. Thus, heating foils can be disconnected for household load demand reduction for a longer time than electrical radiators, but not as long as floor heating cables.

4.2.2 Electrical vehicle

The Norwegian government want 100 % of new cars sold in Norway after 2025 to be zero-emission vehicles, which based on todays situation mostly will be EVs. That means, by NVE's prediction, that there will be 1.5 million EVs in Norway by 2030[45]. This means that EV charging will be a concern that is growing the coming years. Today, EV chargers demands power in the range of 2 kW - 50 kW, and the accumulated EV charging could create capacity problems for the Norwegian grid. For households, the EV charging can cause higher peak demand if the charging is not well planned, and with a new grid tariff structure this could be costly.

Based on a survey mentioned in NVE's report, most of the EV charging happens during evening and night. The survey mapped at what hours EV were charging and not fully charged, and the results can be seen in Figure 4.3. From 17h and on later, when people get home from work, EV charging increases, and 19-21 % of the survey participants charge their EV at hours 19h - 02h. The peak in number of charging vehicles happens at night, with around 23 % of EV owners charge at 03h. This shows that many EV owners plan their EV charging at night, but there are still a relatively big share of EVs charging at the evening during peak hours. For future scenarios, NVE states that approximately 75 % of the EV charging energy is consumed at household level, while 15 % is consumed at work-placed chargers and 10 % at fast chargers (22 kW). Based on this it is safe to assume that EV charging is a load that should be included when dealing with household peak load reduction.

By assuming that the average yearly driven distance per car from 2018, 12140 $\frac{km}{year}$[46],

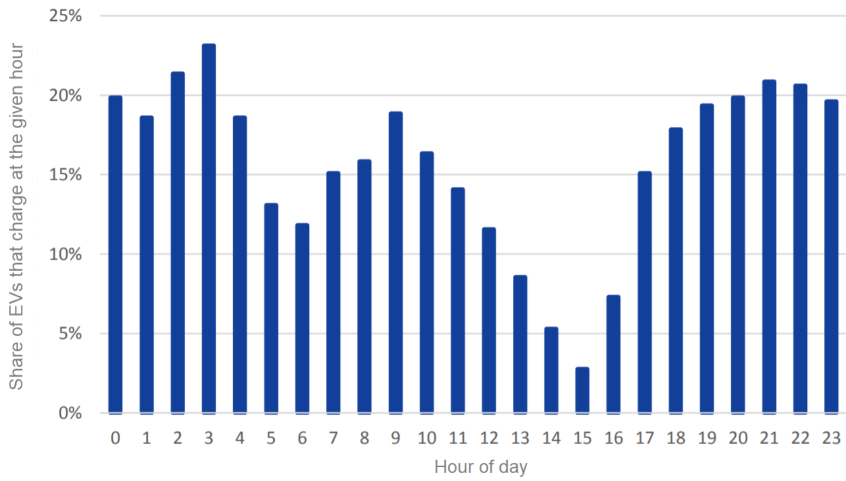

Figure 4.3: Results from survey(397 participants) mapping EV charging hours. Gathered from [45].

is distributed evenly throughout the year, the average daily driven distance per car is approximately 33 km. Assuming EV consumption on 0.25 kWh/km on cold days, this yields a daily energy consumption of 8.25 kWh[45]. With the majority of EVs charging at household premise, where it mostly exist fuses at 10-16 A (230 V), this gives a charging load of 2.3 - 3.7 kW [45]. This yields that during 2-3 hours of the day, households with an EV will increase its load demand by approximately 2-4 kW.

4.3 Non-deferrable loads

The loads that are not advantageous or possible to shift in time, is in this paper called not-flexible or non-deferrable loads. These are loads that are used unpredictably or/and that will cause to much inconvenience or discomfort if deferred. This goes for television, radio, personal computers, WiFi, lighting etc. As previously stated, these loads typically make up 21 % of the annual household electricity consumption. This number also includes waching machines/dryers and dish washers. These are loads that in general can be deferred, but in this paper the load demand for these will be covered as non-deferrable. Ultimately, the load control algorithm presented in chapter 5 will not be able to predict what times are most optimal for the use of these loads. Some examples of typical non-deferrable electrical appliances and their load power are presented in Table 4.3.

Appliance	Load [W]
Vacuum cleaner	1000
Hairdryer	750
Toaster	1000
Waffle iron	800
Television	100
Fridge	160
Freezer	175
Kitchen fan	75
Stove	2200
Coffee maker	1500
Stereo	25
Electric clock	2

Table 4.3: Some non-deferrable electric appliances and their load power. Gathered from [42].

4.4 Household load profile

The household's load profile for non-defferable loads can vary from household to household, depending on their everyday life routines. Samples taken over 3 months for 100 households at Huseby in Trondheim gives indications on how this load profile can be. For these samples, weekday electricity consumption was measured for all 100 households over the span of 3 winter months. From the application LoadPal[1], the electricity consumption for space heating was derived from the total consumption. This was done by combining consumption data and outdoor temperature data and from these the temperature-sensitive part of the consumption was estimated. The not-temperature-sensitive consumption is thereby everything else, both non-deferrable loads and water heating. No extra information about the households was accessed, other than that they were all situated in apartment blocks. The average load profile during high-load months is shown in Figure 4.4.

As can be seen from the plot, the heating load is small compared to the total consumption. As 65% of the annual household electricity consumption is associated with space heating, it is expected that this share is even bigger during winter months. For the residents at Huseby, space heating demand was approximately 40 % of the total demand. This is because the apartments are situated in apartment blocks, where a lot of

[1] LoadPal was not directly accessed, but data was provided by its developer, Nicolai Feilberg

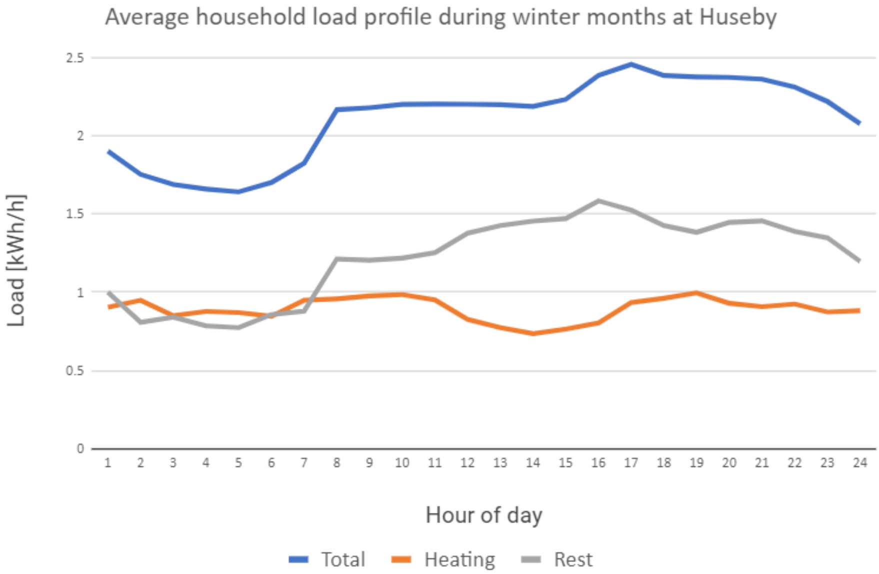

Figure 4.4: Average measured load profile for households living in apartment blocks at Huseby.

the exterior apartment surface is bordered to other apartments and not the outdoor air. This reduces the overall demand for space heating. The plot also shows that the demand for heating is relatively constant throughout the day, ranging between 0.75 to 1 kWh/h. The demand that is not associated with space heating stays relatively constant through the night, mostly because of the EWH and lighting, and rises from 7h-8h, when people typically get up for work. During people's morning routine, hot water is often consumed (showers mostly), which leaves the EWH consumption to stay high during 8h-10h[37]. What might be considered abnormal about the not-heating curve in Figure 4.4, is the continued increase towards 16h. This might be due to people for different reasons staying at home during the daytime.

Figure 4.5 shows the average Norwegian household load profile for January in 2006, the month with highest demand during 2006. The plot shows the usual "morning-peak" at 8-9h, and followed by a gradual decrease in consumption until approximately 14h, where it starts to increase again until it reaches its highest peak around 18-19h. At this point most people get home from work, which increases the non-heating load consumption like making dinner, showering, lighting, etc. The consumption stays high during the evening, until it decreases again at night. In 2006, the EV penetration in Norway was still relatively small(1667 vehicles)[47], so EV charging was not a big contributor to this load profile.

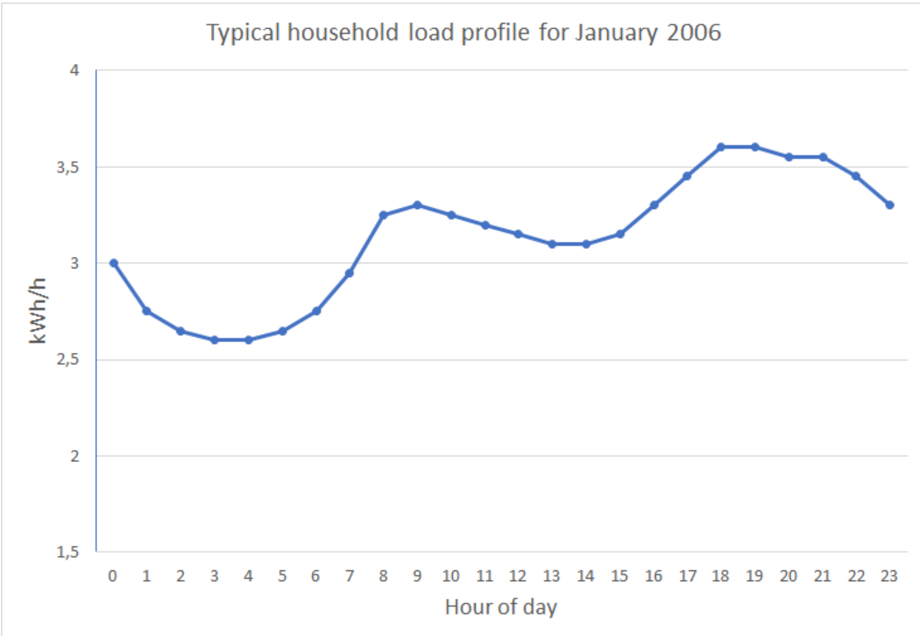

Figure 4.5: Average load profile for Norwegian households in 2006. Data estimated from Figure 2.3, gathered from [7].

Both load profiles in Figure 4.4 and Figure 4.5 show a reduction in load demand during the night, and a big increase in the load during morning (7h-9h). While the load at Huseby continues to rise, Figure 4.5 shows a decreasing load during mid-day. They both show the evening-peak at different times as well. This shows that the daily load profile for a household can deviate from the average load profile given by SSB, which can be caused by many factors like differences in building type, type of user profession, geographical placement and climate etc. Still, Figure 4.5 show the major trends in household electricity consumption, which will be useful when designing the simulation system in chapter 6.

4.5 Household electricity consumption during max-load month

In 2016, Norwegian households had on average approximately 16000 kWh consumption of electricity. In 2006, it was approximately the same [48]. This energy is not used evenly throughout the year, as shown in Figure 2.3. Based on this figure, the daily household electricity consumption was approximately 74 kWh for January, which was the month with highest demand. This sums up to approximately 2300 kWh for the entire month. This yields that the January consumption was approximately 14.4 % of the total annual consumption.

In a report published by SINTEF [49] on household electricity consumption, electricity consumption measurements are presented. The consumption from 17th of May 2010 and one year forwards was measured for 16 households at Fosen in Trøndelag, with an average total electricity consumption of approximately 24000 kWh/year. Measurements show that the month with highest consumption was January, with a consumption of almost 12 % of the annual consumption. This value is somewhat similar to what was found from the SSB load profile. The monthly consumption measurements are presented in Figure 4.6.

Assumptions on daily energy consumption during winter

Based on the values presented in section 4.5, it is assumed that for a typical Norwegian household, consuming 16000 kWh of electricity a year, the monthly electricity consumption during a high-load month (January) is approximately 12-15 % of the annual consumption. From this, the daily electricity consumption should range in between 62 - 77 kWh during a day in a high-load month. These numbers will be used when developing the simulation model for a typical household in chapter 6.

When the yearly electricity consumption for heating is 64 % of the total electricity consumption, it can be assumed that during the winter months the heating consumption is somewhat higher than 64 %. For the development of the model presented in chapter 6, it is assumed that approximately 80 % of the daily consumption is for space heating purposes, and the last 20 % is used on water heating and non-deferrable loads. This will also be used in the development of the simulation model.

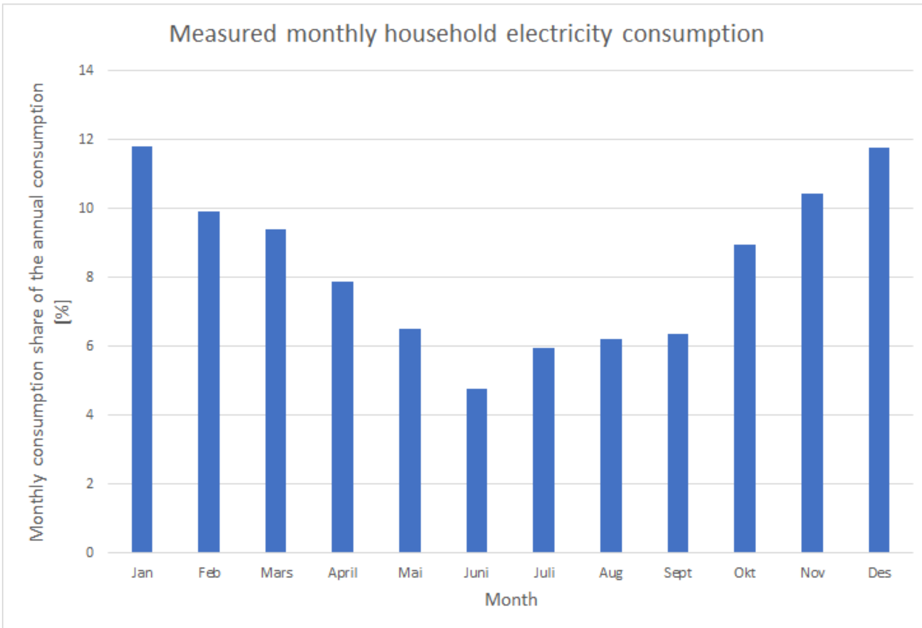

Figure 4.6: Monthly household electricity consumption as percentage of annual electricity consumption. Based on measurements gathered from [49].

Chapter 5

Development of HEMS control structure

Home energy management systems (HEMS) is a topic that has been widely researched upon decades, and achieved a lot of progress over the last years[50]. Controlling household loads with respect to some specific purpose can be approached different ways, highly dependent on the control purpose. HEMS can be designed for the sole purpose of minimizing cost for the users, but also aspects like minimizing energy use or peak demand can be prioritized. In addition, the user-experienced comfort loss resulting from the load control is minimized. Taking this into account, HEMS design can be approached different ways. In this thesis the focus will be on designing a HEMS control structure, specifically a load control algorithm, that can utilize the flexibility in thermostat-controlled loads (e.g. space heating loads and the EWH) to reduce the household load demand at times when the load demand surpasses a specified capacity limit/demand limit. This is done to reduce the cost of the capacity-based grid tariff. In addition to this, the algorithm should also include control and utilization of a PV panel and BESS, also with the goal of reducing demand when the load is higher than the specified capacity limit. The implementation of such control algorithm in Norwegian households is also discussed, as it should be possible to implement in typical households. Furthermore, this could also be implemented in the Smart House at NTNU in Trondheim, but this will mainly be out of scope for this thesis.

A brief literature review considering HEMS algorithm structures will be presented in this chapter, followed by the development of HEMS control structure for load control. The algorithm presented in this thesis will be based on the algorithm developed in Skulstad's master thesis[42], and therefore this algorithm will be used and thoroughly elaborated.

5.1 Literature review

Optimized load scheduling

HEMS algorithms have by many been designed to exploit dynamic electricity prices and thereby control household loads to minimize the electricity payment. Mohsenian-Rad et al. [51] proposed an automatic scheduling algorithm that optimized electric appliance use by the purpose of reducing energy cost and minimize the waiting-time of deferred loads in a real-time varying electricity price environment. A price predictor as well as linear programming was utilized to create the optimized schedule, and it resulted in convincing reductions on both payments and peak load. This was also achieved by Zhao et al.[52] with an optimization approach. Du et al.[53] also presented an optimized scheduling of thermostat-controlled loads to reduce electricity payment and maximize user comfort. Price forecasts, consumption forecasts and user comfort constraints were put together at day-ahead basis, optimized with respect to prices and comfort, and later adjusted with respect to real-time deviations from the forecasts. In the article by Hubert et al. [54], the load scheduling is optimized for residential electricity consumers with integrated energy storage, with respect to dynamic prices, thermodynamic constraints and user comfort. The results shows economic saving for the consumer/prosumer as well as load peak reduction. As there is no doubt that optimized scheduling can provide efficient home energy management system, it requires extensive amount of available data for predictions (price, load) and processing power for fast real-time optimization. This barrier might make implementation of such HEMS in a typical household difficult, and therefore load control algorithms using optimization techniques to perform load scheduling will not be used in the development of the algorithm for Norwegian households.

Involving load priorities and BESS for cost reduction

Utilizing preset load priorities for different loads is another way of designing load control algorithms. By mapping the household's flexible loads, and then letting the user define the most valuable loads towards the least valuable loads, this can be used as a decision-making tool for load control. Boynuegri et al.[55] presented an algorithm for reducing the household electricity bill, by performing load control by utilizing load priorities together with BESS control. The BESS is only charged from on-site renewable generation resources, like PV panels. The algorithm shifts the household loads based on the battery state of charge (SOC) and the cost of electricity. Low-prioritized loads can be shifted to other times if the battery SOC is low or/and the electricity price is high. The testing of the algorithm presented in this article shows that the electricity bill is reduced by 28 %. Still, the algorithm does not secure certain comfort levels, and can cause loads to be turned off for a long time if the price of electricity remains high.

Some general control strategies for utilization of PV and BESS

In [35] there are presented several common control structures for the utilization of PV and BESS. Optimized load planning is one approach that is often used when controlling the charging and the discharging of the BESS. For these control structures, on-site PV production is predicted as well as the household load demand, often one day ahead, and with respect to the electricity prices the optimal schedule in term of economic benefit is found. These types of control structures also require detailed information about the system, e.g. information on weather conditions and electricity prices. Other control structures could be based on real-time measurements of the PV production, the grid electricity cost, the state of charge in the battery and load priorities. Based on these parameters and the possibility of load control, the real-time optimal electricity supply (grid or PV and BESS) can be found to reduce the electricity payments.

Event-based load control with prioritized loads

Pipattanasomporn et al. [56] presented a HEMS algorithm for load control in response to a demand response signal. In this article load priorities are also utilized to perform load control to guarantee and force the household demand under a certain limit when the demand response signal is activated. The demand response signal is presented as a curtailment on the demand for a certain duration. E.g. the DSO can activate a demand response signal during peak hours, in the form of requesting/forcing households to reduce their demand to a certain limit. The algorithm utilize control of space cooling loads, EWH, clothes dryer and the EV to reduce the household demand. These loads must be given a priority by the home owner, in which the home owner decides what loads are most and least valuable. If there is a limit on the load, the HEMS will run through the loads, from least valuable to most valuable, and turn off the loads until the total grid-supplied load is under the demand limit. All loads have certain specified operational conditions/comfort level settings, e.g. user preferences for temperature for the space cooling loads and water temperature for the EWH. If the comfort condition for a load is violated, the load will request to be turned on. E.g. if the space temperature in a certain room is too high, the air conditioner load will be requested to turn on. The HEMS will then check if the requested load is allowed to turn on. If the household demand is under the demand limit, the load is allowed to turn on. If the household load is not low enough, the HEMS will run through the loads that are "on", starting with the lowest priority load, and turn it off if it has a lower priority than the load that is requested on. After a load has been turned off, the HEMS will again check if the updated total grid-supplied load is under the limit. If it is under the limit, it will allow the load to turn on. If not, the HEMS will continue to try to turn of the load with second-to-least priority and so on. The flowcharts for the algorithm used are shown in Figure 5.1 and Figure 5.2. The total system algorithm consist of an outer loop and an inner loop. The outer loop, shown in Figure 5.1, checks the condition of all the appliances and sends a request to turn on the appliance if the condition is violated. This load request is sent to the inner loop, the actual load control algorithm shown in Figure 5.2, and the status (on/off) of all appliances are decided by the inner loop.

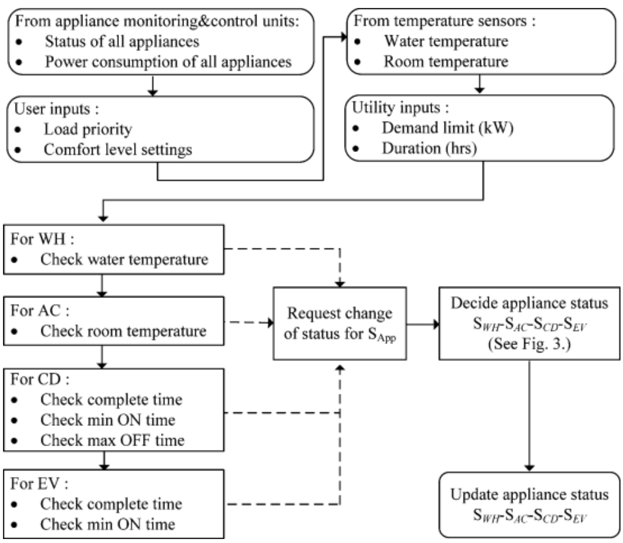

Figure 5.1: Flowchart for the algorithm used in [56]. WH: Water heater. AC: Air conditioner. CD: Clothes Dryer. EV: Electric vehicle. Where it says "See Fig. 3" see Figure 5.2 instead.

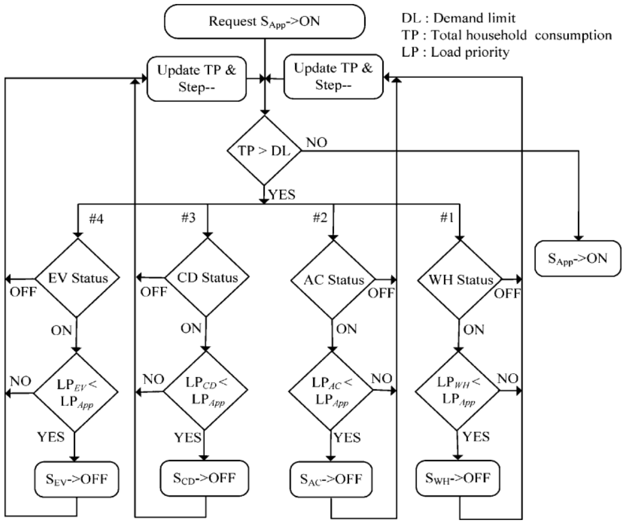

Figure 5.2: Second flowchart for the algorithm used in [56].

5.2 HEMS main functionality

The developed algorithm should be designed to utilize the presence of flexible household loads, with the overall goal of reducing the capacity-based grid tariff without compromising the level of comfort and convenience that is required by the user. Because Norwegian households use electric heaters for space heating, these space heaters can be utilized as a flexible resource. The algorithm should therefore be able to facilitate the use of thermal storage in order to keep the total grid-supplied household load under a certain limit, as to not be penalized by over-consumption by the grid tariff. This involves controlling the on/off status (S) of the loads. In addition to this, the algorithm should also reduce the loss of comfort resulting by the load control. The relevant measure of comfort will therefore be the indoor temperatures. PV and BESS should be utilized to serve the same functionality as the load control, meaning it should either reduce over-consumption over the load capacity limit or preserve the comfort for the users, or both if possible. The algorithm should also maintain automatic control, without unnecessary involvement from the users. Another desirable feature of the algorithm, which was pointed out by Skulstad[42], is easy implementation in Norwegian households. This means that the algorithm should require minimal extensive information that is not already provided for households.

The control structures presented by Boynuegri et al. [55] and Pipattanasomporn et al.[56]

are both based on real-time monitoring and control of the system by programmed reactions when certain events occur. These events could be that the household load violates the limit, or that the conditions for the appliances are violated. When these events happen, the system recognizes the event and reacts accordingly. This type of control structure, which is not dependent on optimization software, is easier to implement to a controller [42], thus reducing the implementation barrier. In addition to this, the control structure in [56] can, with several modifications, be used as a starting point for the development of the HEMS algorithm. The main modifications would be to

- make the demand response signal (the demand limit/curtailment) active at all times. This will allow the HEMS to continuously maintain the household load under the limit given by the capacity-based grid tariff.

- not allow loads to turn on if it causes the total grid-supplied load to violate the limit. The HEMS algorithm must check if the total grid-supplied load will violate the limit if the requested load is turned on, before it is actually turned on. This will reduce the number of times the same load is turned on and off rapidly.

- change the loads as to fit Norwegian households. The cooling load will be replaced by heating loads. Heating loads like floor heating cables also provides more thermal storage capacity than air conditioners, which may increase the performance of the HEMS algorithm.

- add functionality so that the HEMS algorithm can turn on loads even if it involves breaching the load limit. The algorithm in [56] does not allow loads to turn on if the load limit will be breached. If loads are turned off for a long time this can reduce the comfort of the users drastically, and may also be dangerous. If space heating loads at winter time is not allowed to turn on, this can cause significant space temperature decrease. To prevent this, there must be specified certain conditions that will force the load to turn on, even if this causes the household load to violate the limit. These comfort conditions will be called *critical comfort conditions*. This type of functionality will preserve the user comfort level at a certain minimum.

- add functionality that facilitates efficient use of the energy that is produced by the PV plant and stored on the BESS. The idea of combining load priority levels into the utilization of BESS, presented in [35], could be useful for implementing battery energy utilization into the HEMS algorithm.

5.3 Controllable loads and their comfort conditions

The loads that can be implemented in this algorithm for home energy management will be typical deferrable Norwegian loads, as presented earlier. This involves electrical thermostat-controlled space heating loads, e.g. electrical radiators and electrical floor heating loads, the EWH and EV. For the space heating load and the EWH, the comfort level conditions and critical comfort level conditions must be established. These are normally determined by the user. The EV will not have operational conditions, as the charging is decided to be scheduled at night. This will be discussed in subsection 5.3.3 and section 5.6. For all loads, they will in practice be connected by relays that are controlled by the HEMS. For the thermostat-controlled loads, both the relay and the thermostat must be "on"-switched for the load to be on. When either the relay or thermostat is off, the load will be turned off, regardless if the other component is on. This is important to know when designing the control system.

5.3.1 Space heating loads

For the space heating loads, the user must define the ideal room temperature(reference temperature) T_{ref} for each room where there is a controllable space heating load. In general this is the same temperature as the thermostat in that room is set to. The temperature difference between the reference room temperature T_{ref} and the measured room temperature T_m in which the space heating loads in the room should be requested to turn on is defined as $\Delta T_{comfort}$. This should be set equally or higher than the ΔT on the load thermostat, described in subsection 4.2.1. Thereby, when T_m is less than $T_{ref} - \Delta T_{comfort}$, the algorithm will request to turn on the space heating loads in that room. The thermostat will also be turned on at this point, allowing the load to turn on. When T_m is more than $T_{ref} + \Delta T_{comfort}$ the thermostat will turn the load off.
As stated, the user must also determine the maximum allowed temperature difference, $\Delta T_{critical}$, between T_{ref} and T_m. When the temperature deviation $T_{ref} - T_m$ in a room equals $\Delta T_{critical}$, the space heating loads in that room are turned on, regardless if the household load violates the demand limit. This defines the critical comfort condition for the space heating loads. When the critical comfort condition is violated, the loads in that zone can not stay or be turned off, i.e. they must be turned on. This way, the energy management system will ensure that the room temperature never will go below a certain limit, given that the space heating loads are capable of heating the room. The implementation of the $\Delta T_{critical}$ also means that as long as the temperature deviation $T_{ref} - T_m$ is less than $\Delta T_{critical}$, the space heating loads in that room are allowed to turn

Notation	Description
T_{ref}	The reference temperature for the room
T_m	The measured room temperature
$\Delta T_{comfort}$	The minimum temperature difference between T_{ref} and T_m which will cause the loads in that room to be requested on
$\Delta T_{critical}$	The maximum allowable difference between T_{ref} and T_m . If the deviation is more than this the heating loads in the room will be forced to turn on

Table 5.1: Description for variables used in deciding operational conditions for the space heating loads.

T_m in room n	Status for space heating loads in room n
$T_m \geq T_{ref} + \Delta T_{comfort}$	Thermostat will turn off heating load
T_{ref} - $\Delta T_{comfort} < T_m < T_{ref} + \Delta T_{comfort}$	Load can be turned off by algorithm if total grid-supp load violates limit
T_{ref} - $\Delta T_{critical} < T_m < T_{ref}$ - $\Delta T_{comfort}$	Thermostat will be turned on. Algorithm will not allow load to turn on if total grid-supplied load violat
$T_m \leq T_{ref}$ - $\Delta T_{critical}$	Thermostat is still on. Algorithm will force load to turn on even if grid-supplied load violates limit

Table 5.2: Description of operational conditions for the space heating loads.

off. Some short explanations of the space heating load operational conditions are also showed in Table 5.1 and Table 5.2.

5.3.2 Electric water heater

As the electric water heater is a huge asset for flexibility in terms of huge thermal storage capacity, it is evident that such load should be involved in a HEMS for load control. Ideally, the conditions for the EWH would be similar to that of space heating loads. If the water temperature is measured, the user can define the $T_{comfort}, \Delta T_{comfort}$ and $\Delta T_{critical}$ for the water temperature, and thus allowing the HEMS to control the EWH the same way as for space heating loads. But, most EWH does not offer this option. Traditional EWH seldom offers the possibility to measure the exact water temperature, and therefore the control of a traditional EWH can not be performed the same way as the control for space heating loads. On the other hand, EWHs with accessible in-tank temperature measurements does exist, and by the arising interest of HEMS it is likely that the utilization of such EWHs increase in the future.

In [42], it was established operational conditions in which the traditional EWH can be controlled. First, the HEMS will save the time at which the EWH is fully heated. This is done by monitoring the total household load, and when this load suddenly is reduced the same amount as the nominal power of the EWH, the HEMS will understand this as the time at which the EWH is at maximum temperature. In the algorithm, the time (in hours) it takes to heat the water tank by 65 °C, $t_{heatingtime}$, and the maximum time allowed until the EWH should fully heat up again, $t_{maxoff-time}$, should be given. Based on this, three time intervals are defined. They are shown in Figure 5.3. Normally, EWH should preferably be heated up at least once every day. Because of this, time interval 1 is the time from the EWH was last fully heated, until the the time is 24h-$t_{heatingtime}$. During this time interval, the EWH will be requested to turn on. The load control algorithm will not be able to turn on the EWH if the water temperature is not low enough to turn on the thermostat, which might be a likely scenario during this time interval. During the second interval, interval 2, the EWH priority is set to max priority, and will still be requested to turn on. Interval 2 is the time from 24h - $t_{heatingtime}$ until $t_{maxoff-time}$. This means that it will only be turned off if the household load is violating the demand limit and all other loads have been tried to be turned off. During interval 3, when the time from the EWH was last fully heated has reached $t_{maxoff-time}$, the algorithm will turn on the EWH, regardless if the household load is violating the limit. Interval 3 defines that the critical comfort condition is violated.

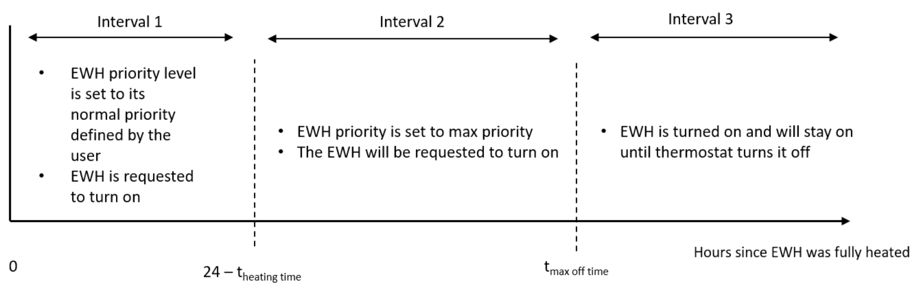

Figure 5.3: Time intervals for defining operational conditions for the EWH.

Even though these conditions could work for the EWH, it is still not the optimal way of control. The whole control structure is depending on the fact that the HEMS can monitor at what time the EWH is fully heated. This might be difficult if there are household load appliances that have the same nominal power as the EWH. It is easier to control the EWH if the water temperature could be monitored, a functionality that only is offered by new "smarter" EWHs.

5.3.3 EV

As the electric vehicle is a load that can both be scheduled and has a large nominal power, it is important that the EV charging is incorporated to the HEMS. In the article of Pipattanasomporn et al. [56], the user must set the wanted hour of the day in which the EV should be used, and the minimum battery state of charge (SOC) required at this time. This would require the HEMS to monitor the SOC of the EV battery. Even though some cars can offer this function of smart charging, it should not be necessary for it to be included into the HEMS. The algorithm in [56] does not present any mechanism to charge the EV if the EV is not allowed to turn on because of the demand limit. Based on this, it is decided that the most convenient way to implement EVs into the HEMS is by using scheduled charging. This will be elaborated on in section 5.6.

5.3.4 PV and BESS

The PV and battery are not household loads like the space heating loads, the EWH and the EV, but still the utilization of these will serve the same function as turning off a load: The demand for grid power will be reduced. Therefore there must be certain operational conditions for the utilization of PV and battery. The control will depend on the state of charge in the battery. If the battery is being utilized, the instantaneous PV production will also be utilized because the battery can not charge and discharge at the same time. The HEMS will never decide to use the instantaneous PV power as supply without also using the battery, unless the battery SOC is either empty (minimum required SOC) or full (maximum allowable SOC). The battery will only be allowed to supply power when the SOC is over the minimum required SOC, SOC_{min}. Also, it will only be allowed to charge as long as the SOC is under the maximum allowable SOC, SOC_{max}. These SOC requirement must be decided by the user, and can be set higher/lower than 0/100 % if the user do not want the battery to fully discharge/charge, as this could decrease the performance of the battery.

Unlike the controllable loads, the BESS operation is not decided by some comfort conditions, and will therefore always be able to supply power as long as the SOC is over the minimum required SOC.

5.4 Load priorities and utilization of PV production and BESS

The user must select what priority each space heating load has, in order to maintain the highest comfort level possible. For instance, if the household consist of two separate rooms, in which both room have different space heating loads, the user must select what room has the highest priority. This way, the HEMS will always try to turn off the heating loads in the low-priority room before the loads in the high-priority room. This can for instance be the living room and the bathroom. Most people utilize their living room more than the bathroom, so if the temperature would decrease in the bathroom, it would not necessarily be noticed. This could be one argument to put the space heating loads in the living room at higher priority than those at the bathroom. Also, if the bathroom uses floor heating cables and the living room uses electrical radiators for heating, the bathroom temperature would decrease slower, thus it would be better off with a lower priority than the living room. The load priority, given as LP, will be 1 for the load with highest priority, 2 for the load with second highest priority and so on. If the system consist of n loads, the lowest priority load will have LP=n.

As the PV production in general is low during the winter, the PV produced energy should be carefully utilized to provide the most comfort for the user. When subject to a capacity-based grid tariff, the PV produced energy should only be used when the total grid-supplied load exceeds the demand limit. In addition to this, the PV produced energy should also be used only to prevent loads of a certain priority to turn off. The user should have the option to decide which flexible loads that can be supplied by the produced PV energy. That means that if the total household load exceeds the demand limit, the HEMS will not necessarily use the PV produced energy to reduce the demand for grid electricity. E.g. for the two rooms, living room and bathroom, with different priorities. The HEMS could try to turn off the loads at the bathroom before utilizing the PV produced energy(coming either directly from the PV panels or from the battery). This means that the energy produced by the PV will only be used to prevent the heating loads at the living room from turning off. This will provide a higher comfort level in the living room, while the comfort level could be reduced in the bathroom. The disadvantage of this is that if the demand limit is set so high that the HEMS would never have to turn off the living room heating loads, the PV produced energy would be unused. In comparison, if the produced energy had been used to prevent all loads from turning off, the PV produced energy could be spent rapidly, only supplying low-priority loads. The user could experience this as a waste of power, and would rather that the small amount of PV produced energy should be used to cover the high prioritized loads. Because of this, a priority threshold for the utilization of PV and battery, LP_{BESS} is implemented into the algorithm, and the PV/BESS will only be used to supply power if the loads of lower priority than the priority threshold are turned off or have been requested to turn off.

5.5 Control system structure

5.5.1 System constants and variables

As stated in section 5.2, the real-time event-based control structure presented by Pipattanasomporn et al. has been used as a starting point when developing the HEMS algorithm. The actual load control will only involve space heating loads that all have their priority set by the user. For the HEMS to perform real-time management of the loads and battery, it will need to have available data about the system, both constants and real-time system data.

Predefined constants

The load demand limit P_{max} given by the capacity based grid tariff must be defined, and all loads must also be defined. Load n is denoted L_n. For all controllable loads governed by the load control, the system must know load n's nominal power P_n, its priority level LP_n, the room/zone Z_n in which gives the comfort conditions for the load. For room/zone z, hereby referred to only as zone, the $T_{ref,z}$, $\Delta T_{comfort,z}$ and $\Delta T_{critical,z}$ must also be predefined by the user. If the EWH is implemented in the load control, the EWH would be defined as an own zone with own specified comfort conditions. This also goes for the EV. In addition, defining the minimum and maximum allowable BESS state of charge, SOC_{min} and SOC_{max}, as well as the priority threshold for BESS utilization, LP_{BESS}, is also mandatory. All predefined constants are also showed in Table 5.3.

Real-time system data

The HEMS must also be able to access real-time system data, provided by different sensors. The AMS would need to provide the total grid-supplied household load, P_{grid} and the instantaneous PV production P_{PV}. To be clear, P_{grid} is the household load supplied by the grid, without taking the BESS supply into account. As the capacity-based grid tariff charges for the grid-supplied power, that is the power that needs to be controlled. In addition, the temperature sensors must provide the temperatures in all zones z, $T_{m,z}$.

Predefined constants	Description
P_{max}	Load demand limit given by the capacity-based grid tariff
P_n	Nominal power for load n
LP_n	Priority level of load n. Note that the lowest prioritized load will have the largest LP
Z_n	The zone/room in which gives the comfort conditions for load n
$T_{ref,z}$	The reference temperature in room/zone z
$\Delta T_{comfort,z}$	See Table 5.1, applicable for room/zone z
$\Delta T_{critical,z}$	See Table 5.1, applicable for room/zone z
P_{BESS}	Nominal output power from the battery
LP_{BESS}	The BESS will only be utilized if loads with $LP > LP_{BESS}$ have been tried turned off
SOC_{min}	Minimum required SOC
SOC_{max}	Maximum allowable SOC

Table 5.3: All constants that must be predefined for the HEMS load control.

The BESS should provide its SOC, SOC, and its status, S_{BESS}, which would be 1 when discharging and 0 when charging. Also, the relays must be able to give the status of each load n, S_n, that would be 1 if on and 0 if off.

System variables	Description
P_{grid}	The household load that is supplied by the grid, measured by the AMS in real-time
P_{PV}	Output power from the PV production system
$T_{m,z}$	Measured temperature in zone z
SOC	State of charge for the BESS
S_{BESS}	Status(charging/discharging) of the BESS
S_n	Status(on/off) of controllable load n

Table 5.4: All system variables provided by the sensors.

Regarding the logical constraints of this, all the sensors that are used must be compatible with the same information architecture, meaning they must all use the same protocol[42]. This will allow the sensors to send information to a bus in which the HEMS can access. E.g. for the Smart House at NTNU in Trondheim, which has previously been used for testing [42], the used architecture is KNX. Even though the physical implementation is out of scope for this thesis, it is important to keep in mind when designing the HEMS.

5.5.2 HEMS outer loop control

The HEMS will consist of an outer loop and an inner loop. In the outer loop, the HEMS periodically checks if there are any comfort violations or demand limit violations in the system. First, it will check if the comfort condition in any zone is violated. For all zones, the system will check if the measured temperature in the zone z, $T_{m,z}$ is below $T_{ref} - \Delta T_{comfort}$. If this is the case, the system will request to turn on the heating loads in this zone. This type of request will be called R1, and is sent to the inner loop, also called the load control loop. This loop will be presented in subsection 5.5.3. If there are multiple loads in the violated zone, e.g. two types of space heaters in the same room, the outer loop first request to turn on the lowest priority load in the zone. After that request is handled, the outer loop will request to turn on the second lowest prioritized load in the zone etc. When the inner loop has run, the load status and the grid-supplied load will be updated. From there the system will check if the total grid-supplied load exceed the demand limit, that is if $P_{grid} > P_{max}$. The system will also directly check this if no comfort violations are present. If the total load exceeds the limit, the system will send another request into the inner loop. This type of request is called R2. Then, the load control loop will again run, and try to switch off loads and/or utilize the PV and BESS to reduce the grid-supplied power. After that, the system will update the measurements, and run the outer loop again. Figure 5.4 illustrates the outer loop.

5.5.3 Load control loop

At two occasions can the inner loop(the load control loop) be run: When the outer loop detects comfort level violations(request R1) or when the grid-supplied load exceeds the demand limit(request R2). The flowchart of the inner loop is illustrated in Figure 5.5.

Request R1

When request R1 is sent to the inner loop, the load that is requested on is also provided to the inner loop. That way the inner loop "knows" what load should be attempted turned on. This load is also called the requested load, for simplicity. The inner loop parameters P_{load} and LP_{load} is set according to the nominal power and load priority of the requested load. The process of turning of loads happens in a "while"-loop, where i is the decremental variable. i is at first set equal to the number of controllable loads in

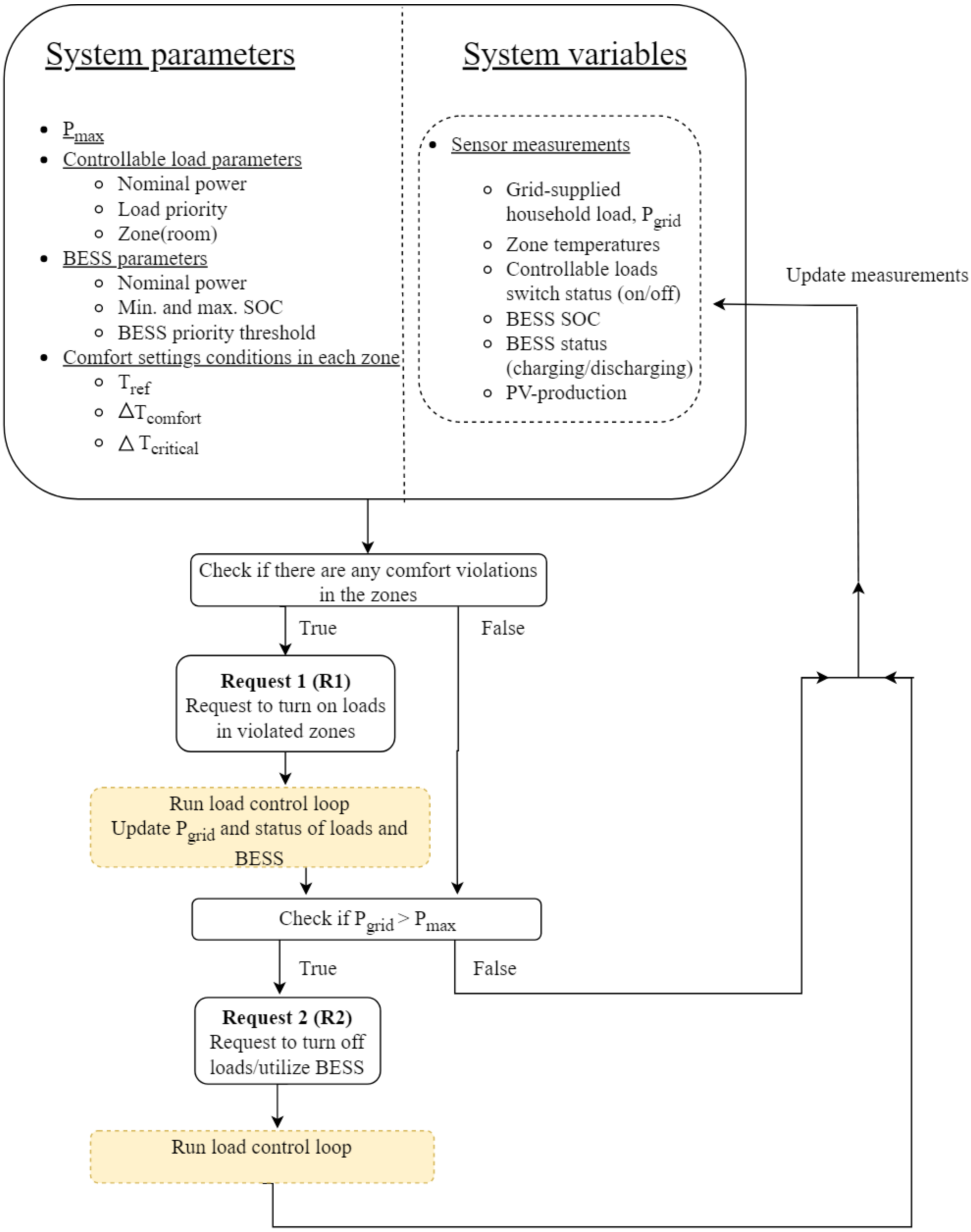

Figure 5.4: Flow chart for the outer loop of the HEMS control system.

the system, and will decrement after every load that is attempted to turn off. At first, it will check if the requested load can turn on, which is done by checking if the statement

$P_{grid} + P_{load} > P_{max}$ is true or false. If it is false, the requested load is turned on, and the inner loop can return to the outer loop. If it is false, the load control will try attempt to turn off other loads or utilize the BESS. It will start by finding the load k, L_k, with LP_k=i. This means that for the first iteration, it will find the load that has the lowest priority. When load k is found, the algorithm will check if L_k is on (S_k=1). If it is not, the algorithm will decrement i and try with the second lowest prioritized load. If L_k is on, the algorithm will check if L_k is allowed to be turned off. Loads will be allowed to turn off as long as the critical comfort condition is not violated, as explained in section 5.3. If it is OK to turn of L_k, it will lastly check if the priority of L_k is lower than the requested load (if $LP_k > LP_{load}$). If it is true, finally L_k will be turned off, and i will decrement. Then it will again check if the load demand limit is exceeded, and the loop will go again, now with a new value for i.

If the decrement variable i equals the priority threshold for BESS utilization, the algorithm will check if the priority of the requested load is higher or equal to the priority threshold for the BESS. This will in other words happen when all loads with lower priority than the BESS priority threshold is attempted turned off, but the demand limit still is violated. If the priority of the requested load is higher or equal to the BESS priority threshold, the algorithm will check if the discharge conditions for the BESS is OK and if the BESS is not discharging already. If both of these conditions are OK, the BESS will start to discharge, and the instantaneous PV production will also be used to supply the total load. After this the P_{grid} is again updated, and the loop will again run for $i = LP_{BESS}$. This is because if the demand limit still is violated, the algorithm will try to turn off the load with the same priority as the battery priority threshold.

When the increment variable has reached zero, it will check if the critical comfort condition is violated for the requested load. If it is violated, the requested load will turn on, even though this means that the demand limit is exceeded.

Request R2

When the outer loop requests that loads must be shut off in order to meet the demand limit, the inner loop recieves this request, but no requested load as in R1. Therefore the P_{load} and LP_{load} will both be set to zero. This way, the R2 request is actually a request to turn on a load with highest priority (LP = 0) and that has a nominal power equal 0. The algorithm will try to turn off loads until 1) P_{grid} does not exceed the limit or 2) all loads are attempted turned off and BESS is discharging, but P_{grid} still exceeds the limit. By this the inner loop will execute almost everything like in R1, with some small modifications:

- if P_{grid} is less than P_{max}, the algorithm will return directly to the outer loop again, instead of turning on the requested load
- if i=0 and P_{grid} still exceeds P_{max}, it will return directly to the outer loop.

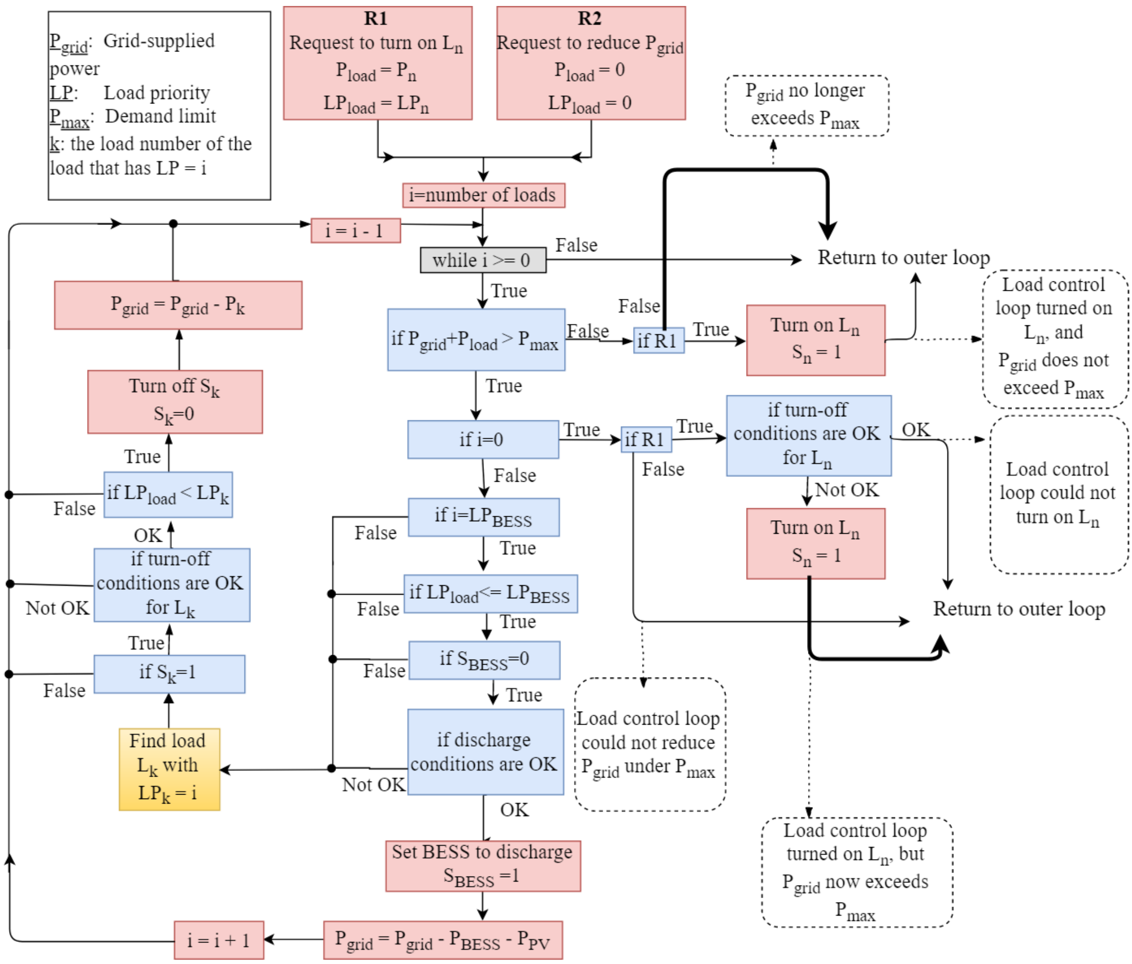

Figure 5.5: Flow chart for the inner loop of the HEMS control system.

5.5.4 BESS charging/discharging

As the inner loop only turns on the BESS, and never turns it off, the BESS must periodically set to charge/stay idle in the outer control loop. This can be done frequently, because by the next time the inner loop runs a request, the BESS will again be turned on if it is required and allowed. This way the BESS discharging will be turned off when the conditions that allow it to discharge ceases.

If the HEMS can access day-ahead data on the next-day PV production prediction, another functionality may be implemented. If the battery priority threshold is set too high, so that the PV generated energy is not fully used, the BESS will save the energy for the next day. This is a problem if the BESS does not have the capacity to store the PV produced energy the next day. This could cause that the BESS is fully charged by e.g. 12h, and that the PV produced energy is supplying the low-load period from 12h and on. The better option would could be to program the HEMS to always discharge the battery from 7h-9h, during the morning peak, to the point where the BESS has enough available storage capacity to store the predicted PV generation. This function is implemented to the HEMS, but because the PV production is relatively modest during the winter, this is not expected to be a problem.

5.6 Scheduled events

The HEMS can also be programmed to schedule certain events during the day. Even though scheduling often needs to be optimized, it can also be chosen by the user. Certain things, like lowering the temperature at times when there is no users in the house could be chosen to reduce energy consumption. In general, this is done during the night when the users sleep, and also during mid-day when there is no one home. These periods can be called "save-mode" periods. For this HEMS, it can be done by defining two reference temperatures in each zone: $T_{ref,comfort}$ and $T_{ref,save}$. Then, the HEMS can be programmed to utilize $T_{ref,save}$ at night and mid-day, and $T_{ref,comfort}$ at all other times. If the HEMS controls every space heating load in the system to reduce its reference temperature at a certain time, all space heating loads will immediately be turned off. They will also remain off for some time, depending on the thermal storage capability and the thermal insulation of each zone. They will remain off until the measured zone temperature T_m has reached $T_{ref,save}$-$\Delta T_{comfort}$, in which the HEMS will request the loads to be turned on again. The energy consumption of the space heating loads during the "save-mode"-period will also decrease. This can be utilized to reduce peak loads, e.g. by combining "save-mode"-periods with EV charging. EV charging demands, as explained, significant amounts of power. By scheduling the EV charging and the saving period at the same time, the household can reduce the amount of capacity-based over-consumption, and thus decrease the grid tariff cost.

Chapter 6

Simulation model for testing of the HEMS control structure

To test the HEMS algorithm developed in chapter 5, a simulation model is developed in MATLAB/Simulink. The simulation model should be designed to represent a typical Norwegian household with electric space heating loads, and also include rooftop PV panels, a BESS and an EV. The households electricity consumption should be simulated during a cold winter day with a small amount of PV production. The simulation model is designed so that the space heating loads can be controlled by the HEMS according to chapter 5, and the thermal system of the household apartment is simplified with the goal of simulating the dynamics between the space heating loads and the indoor temperature. *Note that for all 1 hour average load profiles provided, the load profile are delayed 1 hour because of computational delay in Simulink.*

6.1 Thermal model of a room

The simulation model of the house must be able to model the dynamic behaviour between the status of a space heating load in a room and the room temperature. As the room temperatures are vital for the load control, it is important that the simulation model can somewhat model the temperatures properly. The thermal dynamic model of a house can be approached in a complex manner, but for the purpose of this thesis, the model itself will be greatly simplified. It will be based on MATLAB/Simulink's "Thermal model of a house"[57]. Here, a house consist of four side walls, one floor and one roof. Therefore it can be regarded as a single room. Inside the room there is one temperature

T_{in}, and outside the room there is outdoor temperature T_{out}. The room is filled with air, with specific heat capacity c_{air}. The side walls, floor and roof are made of materials with thermal conductivity λ, and has a thickness of d. The room and air volume is determined by its length l, width w and height h. It also consists of n windows of length l_w, height h_w and thickness d_w and with thermal conductivity λ_w. The total wall area (of side walls, roof and floor), A_{walls}, and the total window area, A_{win}, is calculated, and from these the absolute thermal resistances for the total wall area, R_{walls}, and window area, R_{win}, are obtained, as by Equation 6.1.

$$R_{walls} = \frac{d}{\lambda \cdot A_{walls}} \left[\frac{°\mathrm{C}}{W}\right] \qquad R_{win} = \frac{d_w}{\lambda_w \cdot A_{win}} \left[\frac{°\mathrm{C}}{W}\right] \tag{6.1}$$

Windows have a larger thermal conductivity than walls, making the heat losses through the windows a huge contributor for the overall heat loss. The absolute thermal resistance can also be calculated by the thermal transmittance (U-value) for the walls and windows, see Equation 4.3 . From the thermal resistances of the walls and windows, the equivalent thermal resistance of the house is obtained by Equation 6.2

$$R_{eq} = \frac{1}{R_{walls}} + \frac{1}{R_{win}} = \frac{R_{walls} \cdot R_{win}}{R_{walls} + R_{win}} \tag{6.2}$$

By the equivalent thermal resistance, the lumped heat loss rate, $\frac{d}{dt}Q_{loss}$ through the side walls, floor, roof and windows can be calculated by Equation 6.3.

$$\frac{d}{dt}Q_{loss} = \dot{Q}_{loss} = \frac{T_{in} - T_{out}}{R_{eq}}[W] \tag{6.3}$$

Because the equivalent thermal resistance accounts for heat losses through all surfaces, when the outside temperature and outside temperature are the same for all surfaces. This is a simplification, as the floor often is in contact with the ground which holds a different temperature than the outside air. In addition to this, the model does not account for the heat flow given by solar irradiance on the walls and through the window. These factors are not implemented in the model.

Inside the house there is a heater that provides a heat flow of $\dot{Q}_{heater}$. The temperature change in the house is then given by

$$\frac{d}{dt}T_{in} = \frac{1}{M_{air} \cdot c_{air}} \cdot (\dot{Q}_{heater} - \dot{Q}_{loss}) \tag{6.4}$$

This is valid when the room is only filled with air, with a total air mass of $M_{air} = l \cdot w \cdot h \cdot \rho_{air}$, where ρ_{air} is the air density. Based on Equation 6.3 and Equation 6.4, the Simulink block scheme for the indoor temperature can be arranged as shown in Figure 6.1

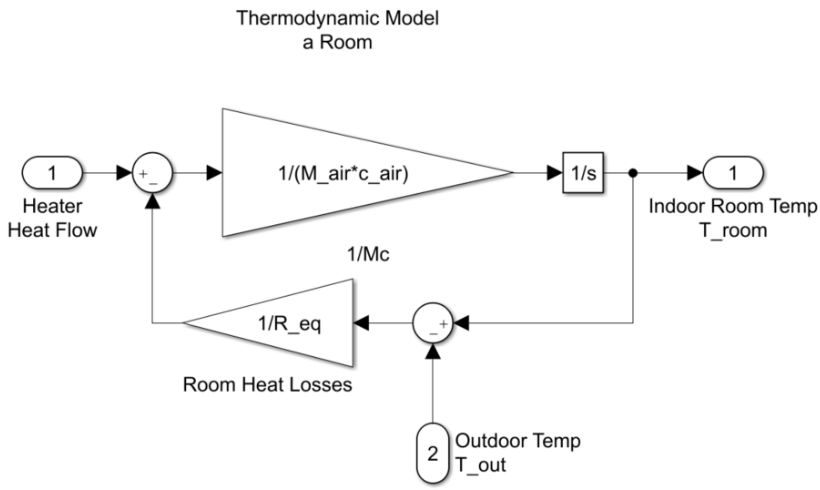

Figure 6.1: Simulink model for dynamics between heater heat flow, room heat loss and indoor temperature.

6.2 The Norwegian household model

The model explained in section 6.1 is used to form a model representing a Norwegian household. The modelled apartment will consist of three rooms of different sizes. The house consists of one room of combined living room and kitchen, one room for entrance and hallway and one bathroom. The model will not simulate heat flows from one room to another, and each room will be modelled as having a specified outdoor temperature. As the modelling of a house/apartment is complex, the main model functionality will be to replicate the heating needs for a typical household. The heating needs for a household will depend very much of the insulation standard of the house/apartment and the type of apartment (detached dwelling, apartment in an apartment block, semi-attached house etc.). The model will therefore be designed to have approximately the same heating needs as a typical household, but can not be considered as a physical replication of an apartment.

As presented previously, the space heating demand is assumed to cover 80 % of the total electricity consumption during a cold day. The households total daily electricity consumption is designed to be approximately 62-77 kWh , which yields a space heating demand of approximately 52 - 62 kWh. The load profile for non-deferrable loads will also be presented, and should accumulate to 20 % of the total electricity consumption.

6.2.1 U-values for windows and walls

The U-values used for the room walls is taken from the TEK-97 regulation, that states that the U-value for outer walls should be less than 0.18 $\frac{W}{m^2K}$, so 0.18 is used. By using a standard that require even better insulated walls, like the TEK-17, the heat loss through the walls would be substantially lower. This would also reduce the need for heating, which would not be beneficial for this model. The modelled apartment should have a relatively large space heating demand, which is obtained by having poorly insulated modelled walls. For the windows in the rooms, an U-value of 5.7 [$\frac{W}{m^2K}$], which is the U-value of ordinary glass. This is more than what the regulations require for windows(1.2 $\frac{W}{m^2K}$). This difference means that the total window area is less in the model than it would have been in reality, for the same amount of window heat loss.

6.2.2 The rooms

The three modelled rooms are designed to provide different amounts of flexibility. In the kitchen/living room and entrance/hallway, there are both heating foils and electrical radiators, while for the bathroom only floor heating cables are used. This means that it is not only air that is heated up in every room, and thus the contents of the room must be modified to showcase this difference in heat capacity. The heat capacity in each room us therefore modelled as defining the contents of the room to be a mix of air and wood (heating foils) or concrete (heating cables). This way the absolute heat capacities of the rooms will be higher than if it was only air that was being heated. By doing this, the model treats the content of the rooms to be a perfect mix of air and wood/concrete. As unrealistic as this is, it still serves the purpose of showcasing the different flexibility present in each room. The equivalent mixed material heat capacity for a even mixture of material 1 and 2, respectively with mass m_1 and m_2 and specific heat capacity c_1 and c_2 is calculated by Equation 6.5

$$c_{eq} = (\frac{m_1}{m_1 + m_2}) \cdot c_1 + (\frac{m_2}{m_1 + m_2}) \cdot c_2 \tag{6.5}$$

The model will not differentiate between the space heating loads in the same room. A fully realistic model would show a different temperature response when a floor heating load of 1 W is used versus an electrical radiator of 1 W, because the the two loads heat up different materials. The model presented thereby does not differentiate between the different space heating loads, as the model is simplified beyond this.

Kitchen/Living room (Zone 1)

The living room/kitchen is designed to be the biggest room in the apartment, and the room with the highest demand for heating and heat losses. This is the room that is the most used, in which a temperature loss will provide the biggest comfort loss. The kitchen/living room is defined as the highest priority zone, and will have to types of electrical space heaters. One electrical radiator and heating foils in the floor. As stated, these two heating loads provide different amount of flexibility/heat storage capability. As the electrical radiator heat up air, while the foil heats up wood, the room content is defined to be 1.5 % wood and 98.5 % air. These two space heating loads are referred to as "Heater 1" and "Heater 2" in the model, and has nominal power of 1680 W and 1440 W. The room parameters in the simulation model is designed to be as shown in Table 6.1.

Parameter	Kitchen/Living room
length	6.5 m
width	5.5 m
height	3 m
air content	98.5 %
wood content	1.5 %
concrete content	0 %
total window area	5 m^2
total wall area	138.5 m^2

Table 6.1: The model parameters for the kitchen/living room.

The outdoor temperature for this room is modelled as a shifted sinusoidal wave with a period of 1 day, going from -10 at 0h to -6 at 12h, as shown in Figure 6.2. The outdoor temperature of the room is set as the lowest for all the rooms in the model, to simulate that this is the room with most area bordering to the outside. The reference temperature for the kitchen/living room is set to 22 °C, and the thermostat will allow a deviation of $\pm\ \Delta T = 0.5\,°\mathrm{C}$. For the HEMS control, this room will be implemented as zone 1.

Figure 6.2: Outdoor temperature for kitchen/living room.

The entrance/hallway (Zone 2)

The entrance/hallway is a smaller room than the kitchen/living room, and will be designed to have both less heating demand and less heat loss because it is thought to have most of its bordering area to warmer areas, e.g. a neighbouring apartment or the kitchen/living room. The hallway/entrance will also have two heaters, which is thought to be one electrical radiator and floor heating foils, as the kitchen/living room. The two heaters will be referred to as "Heater 3" and "Heater 4", with nominal power of respectively 720 W and 240 W. The entrance/hallway is defined to be the zone with second highest priority, and is defined to be zone 2 in the HEMS control. The model parameters is shown in Table 6.2.

Parameter	Entrance/hallway
length	3 m
width	3 m
height	3 m
air content	98.5 %
wood content	1.5 %
concrete content	0 %
total window area	2.5 m^2
total wall area	51.5 m^2

Table 6.2: The model parameters for the entrance/living room.

The outdoor temperature for the entrance/hallway model follows the same shifted sinusoidal wave as for the kitchen/living room, going from its minimum of 7 °C at 0h to its maximum of 9 °C at 12 h. As the kitchen/living room, the reference temperature will be set to 22 °C, and the thermostat will allow a deviation of $\pm\ \Delta T = 0.5\,^{\circ}$C.

The bathroom (Zone 3)

The bathroom will be of similar size as the entrance hallway, with the same heating losses. That means it will be modelled as having the same outdoor temperature as the entrance/hallway, and also have the same amount of window area. The bathroom is modelled with electrical floor heating cables, referred to as ”Heater 5”, with a nominal power of 900 W. Because of this, the content in this room is set to be 98.5 % air and 1.5% concrete. This makes the lumped heat capacity in the room greater than for the entrance/hallway, allowing a slower temperature decrease when the floor heating is turned off. Also, because of this, the bathroom is set to be the third highest priority, which is also the lowest in the system. Of the three rooms, the bathroom is maybe used the least, and combining this with the higher heat capacity it is well-suited for load control purposes. The bathroom model parameters are shown in Table 6.3

Parameter	Bathroom
length	3 m
width	3 m
height	3 m
air content	98.5 %
wood content	0 %
concrete content	1.5 %
total window area	2.5 m^2
total wall area	51.5 m^2

Table 6.3: The model parameters for the bathroom.

The reference temperature for the bathroom is set to 24 °C, with the thermostat allowing a deviation of $\pm\Delta T = 0.5\,^{\circ}$C.

6.2.3 Modelling the EWH

Modelling the EWH would require a model that can simulate the EWH in-tank temperature as a function of inlet water(flow and temperature), outlet water(flow and temperature), the heat loss of the tank and the heating load inside the tank. The development and implementation of this model into the household model was attempted, on the basis of the EWH differential equations presented in [53]. The development of the EWH model was unsuccessful and provoked simulating faults. Because of this, it is neither used for the final simulations of the model, nor implemented in the load control algorithm.

6.2.4 The load profile of the modelled household

For the heat flow provided by the all space heating loads, the efficiency is assumed to be 100 %. That means that for a space heating load of 1 W, it is assumed to provide 1 W of heat flow to the room. When running the simulation of the three rooms with the mentioned parameters and no control of the loads other than ordinary thermostat control, the energy demand for heating for 24 hours reaches approximately 55.5 kWh. This is in accordance with the assumed heating demand for a typical household.

Assuming the space heating demand to be 80 % of the total demand, this yields that the total daily demand should be $\frac{55.5}{0.8}$ kWh $\approx$ 70 kWh. That means that the remaining 20 % , approximately 14 kWh, should be modelled as non-deferrable load demand. This includes the demand for water heating, as the EWH is not a part of the load control. The non-deferrable load demand is assumed to follow approximately the same shape as the load profile from Figure 4.5, assuming that the demand for space heating stays relatively constant through the day. Therefore, the non-deferrable load profile is modelled to follow the same trends, with a smaller peak at morning and a bigger peak during 17h-19h. The non-deferrable load is modelled to be very low during 0h to 6h, and from 9h to 15 h, because of no acticity in the house. The demand during this time is representing the demand for lighting, refrigerator etc., which runs the entire day. The load curve is also designed to vary within each hour, to represent that the demand can be very high for shorter periods, because of short-timed heavy loads like coffee maker, water boiler, hair dryer etc. The non-deferrable load profile calculated at 15 minute and 1 hour intervals is shown in Figure 6.3. Note that the plot for the 1 hour interval is shifted by 1 hour.

6.2.5 EV charging

The non-deferrable load presented is not accounting for the EV charging, thus the demand for EV charging is modelled as an additional load. Based on the numbers pre-

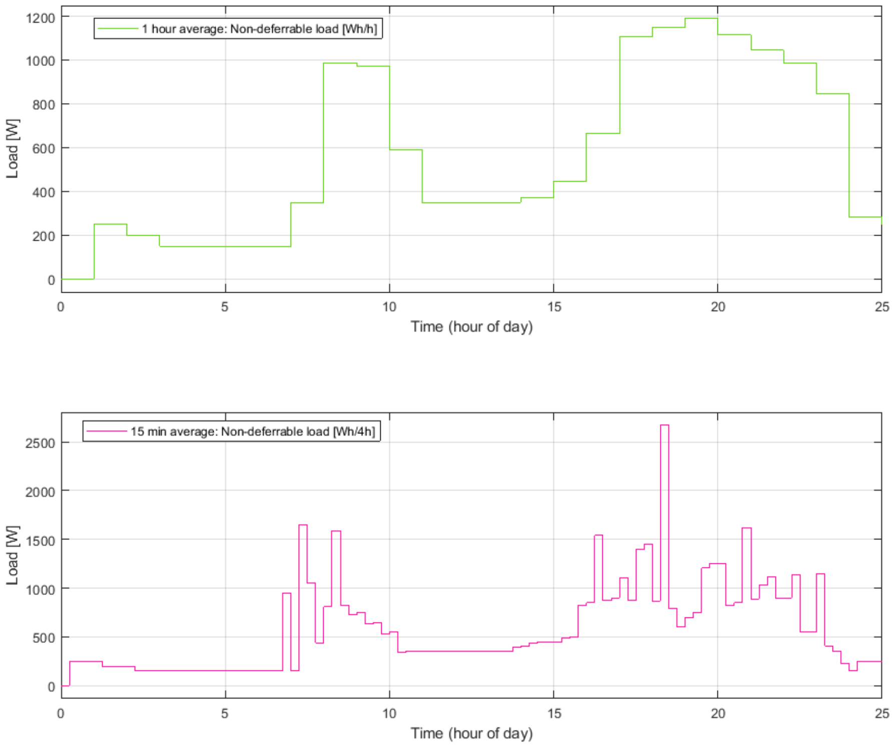

Figure 6.3: The non-deferrable load measured at 15 minute intervals and 1 hour intervals. The measurement for the 1-hour average is delayed by one hour, which is why it is zero the first hour.

sented in subsection 4.2.2, it is assumed that the EV charging will demand approximately 8.25 kWh of electricity every day, and that is is charged at 3.7 kW (16 A fuse). For the simulation, the EV load is modelled as a 3.7 kW load for 2.25 hours (two hours and 15 minutes). For the simulations, the EV charging can either be dismissed, unscheduled or scheduled. When dismissed, the EV load is not a part of the household load. When it is charged, but not scheduled, the EV will be charged from 21:30 to 23:45. At this point, many EV owners don't use the EV for the rest of the day. This is also shown at Figure 4.3, where approximately 20% of EV owners charge during these hours. When the charging is scheduled, the EV will be charged from 00:00 to 02:15. The total household grid-supplied power demand for the three EV scenarios is shown in Figure 6.4.

6.3 PV production and BESS modelling

As the simulations should replicate conditions during winter time, the potential for PV production is not ideal. Because of this, it is assumed that the household have installed a relatively large PV production system, at 5 kWp. This is 20 panels of 250 kWp. It is also assumed that the PV panels' angle are optimized, the PV technology is crystalline silicon, and that there is a loss of 14 % from production to utilization of the energy[58]. The daily PV generation for such a system is found from the Photovolatic Geographical Information System (PVGIS) of the European Commission Joint Research Centre [58]. For the purpose of properly testing the load and BESS management, the PV production data in Trondheim, Norway, during February is used. The daily PV production is estimated to be 7.08 kWh. Based on data from the Norwegian Meteorological Institute[59], the typical February sunrise in Trondheim is at 8h, and sunset is at 17h. Based on these data, the PV production curve for the PV system is designed. It is designed to follow one 9-hour-period of a cosine wave shape shifted π radians, starting at 8h and ending at 17h. The total daily production is approximately 7.08 kWh. The production curve is shown in Figure 6.5.

The BESS is modelled as a simple battery storage with 90 % efficiency and 14 kWh storage capacity[60]. As the PV production is so low, the BESS storage capacity will not be regarded as a limitation for the simulations. The BESS discharging power is determined to be strict 1.5 kW, and the BESS is allowed to fully charge and discharge.

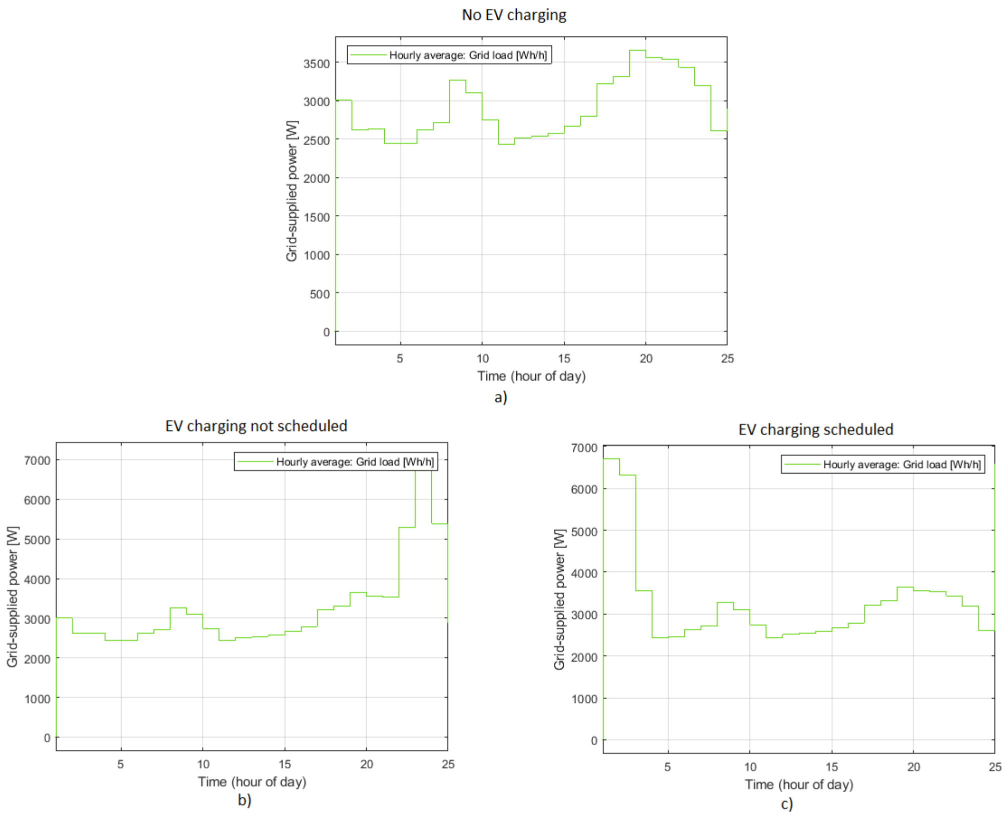

Figure 6.4: The grid-supplied power demand for the household when the EV charging is not present(left), not scheduled (middle) and scheduled (right). Note the different axis resolution.

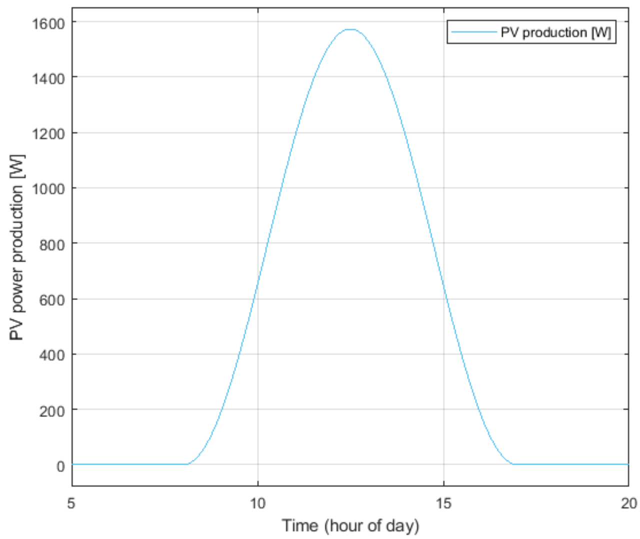

Figure 6.5: The power produced by the PV production.

6.4 Parameters for the HEMS control

When controlling the household loads by the energy management control structure presented in chapter 5, certain constants must be defined. The space heating loads are defined as shown in Table 6.4. If there are two loads in the same zone, the load with the higher nominal power is prioritized highest. The loads are also prioritized with respect to the user's comfort preferences for each zone.

Load name	Load	Nominal power(P) [W]	Zone(Z)	Priority (LP)
Heater 1	L_1	1680	1 (Kitchen/Living room)	1
Heater 2	L_2	1440	1(Kitchen/Living room)	2
Heater 3	L_3	720	2(Entrance/hallway)	3
Heater 4	L_4	240	2(Entrance/hallway)	4
Heater 5	L_5	900	3 (Bathroom)	5

Table 6.4: Load constants for the controllable loads.

The pre-defined temperature constants are as shown in Table 6.5. When the temperature is 1 °C under the reference temperature, the loads in the zone will be requested to turn on. The critical comfort condition for the kitchen/living room is 3 °C under the reference temperature, while it is 5 °C for the lower priority zones. This means that the HEMS will allow a temperature over 19 °C, 17 °C and 19 °C for zone 1, zone 2 and zone 3, respectively. The $T_{ref,save}$ temperature is programmed to be set to 15 °C for all zones.

Room	Zone	$T_{ref,comfort}$[°C]	$T_{ref,save}$[°C]	$\Delta T_{comfort}$[°C]	$\Delta T_{critical}$[°C]
Kitchen/living room	1	22	15	1	3
Entrance/hallway	2	22	15	1	5
Bathroom	3	24	15	1	5

Table 6.5: Temperature constants used in the load control.

The "save-mode" are defined to happen in two periods: At night, and at mid-day. The periods in which the HEMS lower the temperatures are defined in Table 6.6. When the "save-mode"-periods end, the reference temperature will increase for the zones, causing the space heating loads to turn on. To avoid that all space heating loads turn on/request to turn on at the same time, the "save-mode"-period stops at different hours for each room.

	Save times at night		Save times at mid-day	
Room	Start	End	Start	End
Kitchen/living room	00:00	05:30	09:00	14:00
Entrance/hallway	00:00	04:45	09:00	13:15
Bathroom	00:00	04:00	09:00	12:45

Table 6.6: Starting time and ending time for the "save-mode" periods.

For the BESS, the priority threshold is put at $LP_{BESS} = 2$. This means that the energy stored in the battery will be utilized to prevent the heating loads at the kitchen/living room to turn off. This threshold will also be changed in the simulations, to test how the threshold affect the simulation results.

The Simulink model is set to run the outer loop control every 15 seconds, so this is the frequency in which the loads are controlled and the variables are updated.

Chapter 7

Points of interest and scenarios regarding the simulations

When testing the developed control structure for load and BESS management, certain simulation results must be investigated. In this chapter these will be explained briefly.

7.1 Economic benefit

The grid tariff cost will be investigated. The three proposed tariff structures, the capacity-based (CB), the ToU-based and the measured power peak (MPP) grid tariff will be investigated for all scenarios. As the control structure is developed by the intention of reducing over-consumption by the capacity-based grid tariff, it is also interesting to see how the control structure would perform during the two other grid tariff regimes.

When calculating the grid tariff cost for each simulation, the grid tariff proposals presented in section 2.5 will be used, and the cost for each proposed tariff structure will be calculated. The fixed costs for each tariff will be scaled as to be evenly distributed on all 365 days of the year, so the total fixed costs will be calculated based on the length of the simulation.

The proposed grid tariff structures are based on hourly average measurements of the household's energy demand. These will be investigated. Regarding the CB tariff, the impact of more frequent power measurements will be investigated as well. If the consumption exceeds the demand limit by 1 kW for the first 30 minutes of an hour, while the next 30 minutes the consumption is 1 kW under the demand limit, the first half hour over-consumption will not be penalized with 1 hour measurements. Because of this, regarding the capacity-based grid tariff, the cost will be investigated if the measurements were done every 15 minutes and every minute. The prices are adapted as so the hourly over-consumption term is divided on 4 for the 15-minute measurements, and is divided on 60 for the 1-minute measurements. By averaging the load over a shorter time period, it is more likely that high power loads that is on for short duration will be penalized. The measured power peak grid structure and ToU is only calculated based on 1 hour measurements.

If the PV produced electricity is not charged to a battery, but directly supplying the household demand as it is produced, some of this electricity might be supplied back to the grid if the production exceeds the household demand. The economic compensation for feeding electricity back to the grid will be calculated based on the spot price for electricity in Trondheim during February 2019. From Nord Pool's website, it is found to be 0.443 $\frac{NOK}{kWh}$, based on an EURO to NOK ratio of 9.78 $\frac{NOK}{EURO}$[61].

7.2 Measuring the comfort loss

The loss of comfort in each zone while the zones are in use will also be investigated. This is done by checking the zone temperatures from 6.5h to 9h and from 15.5h to 24h, and measuring how often the zone temperature reaches 1 °C under the reference temperature for the zone. This will be indicated by the variable *violation*, which will be given in percent. This percentage indicates how long the zone temperature has been more than 1 °C below the reference temperature during the time interval t $\in$ [06:30, 09:00] $\vee$ [15:30, 00:00]. During this time interval there is activity in the apartment, thus it is during these periods the comfort loss will be experienced.

If the zone temperature is 1 °C below the reference temperature for the entire time period, *violation* for the zone will be 100 %. If the zone temperature never decreases to T_{ref}-1 °C during the time period, the *violation* for the zone will be 0 %.

7.3 Other points of interest

Other criteria that will be investigated are:

- in what degree the modelled space heating loads are able to reduce demand at certain times, and what level of flexibility they offer.

- how the management of BESS and scheduling of EV affects the grid tariff cost
- if the energy management will reduce the peaks measured at 1-minute, 15-minute and 1-hour intervals

7.4 Investigated scenarios

The model will be simulated for multiple different scenarios, to investigate the mentioned criteria. For all scenarios the "save-mode" will be utilized for both night and mid-day, and battery priority threshold is set to $LP_{BESS} = 2$, unless stated otherwise. For all scenarios it will be stated if the load control algorithm is being utilized to control the loads. If the load control is not used, the space heating loads are only controlled by the thermostats. The model will be tested both with and without PV production. When the PV production is added in the simulation, the BESS will be utilized only when the HEMS is used. The impact of the load and BESS control will also be tested when adding the EV-load to the simulation. See Table 7.1

Variable		**Description**
P_{max}		Demand limit
PV	= 0(Disabled)	Model is not simulated with PV production
	=1(Enabled)	Model is simulated with PV production
HEMS	=0(Disabled))	The space heating loads are only controlled by thermostat If PV=1, the BESS is not utilized
	=1(Enabled)	The space heating loads are controlled by the HEMS. If PV=1, the BESS management is utilized
EV	=0(Disabled)	The EV load is not part of the simulation
	=1(Unscheduled)	The EV load is part of the simulation, and it is not scheduled
	=2(Scheduled)	The EV load is part of the simulation, and it is scheduled

Table 7.1: Description of nomenclature for simulation scenarios

Chapter 8

Results

For each simulation case, it is first simulated without the HEMS controlling the loads(HEMS=0). When HEMS=0, this means that the space heating loads are only controlled by the thermostats, and that, if PV is included, the PV produced power is not charged to the battery. These cases are called the base cases. The base cases will be simulated for multiple demand limits to calculate what the cost of the CB grid tariff would be for every demand limit in absence of the load control. The CB tariff cost is calculated with respect to 1-hour measurements(CB_{60m}), 15-minute measurements (CB_{15m}) and 1-minute measurements (CB_{1m}). In the base case simulations, the ToU tariff cost and the MPP tariff cost will be equal for all demand limits P_{max}. This is because the demand limit does not affect these tariffs when there is no HEMS controlling the loads. For all cases, the grid-supplied peak power is presented from the 1-hour measurements ($P_{peak,60m}$), 15-minute measurements ($P_{peak,15m}$) and 1-minute measurements ($P_{peak,1m}$). For the base cases, the grid tariff cost and the power peak values are presented as absolute values, while for the simulations with load control the values are also presented as percentages of the base case results. This is to clearly present the reduction (or increase) compared to the base case with the same demand limit. The comfort losses given by the *violation* measurement will also be provided for all simulations where the HEMS is active (HEMS=1). For the simulations that the HEMS is active, the demand limit in the load control will be the same as for the demand limit given by the CB tariff.

Case 1 will simulate the model without PV and EV. This is to test the effect of controlling the space heating loads to reduce over-consumption by the CB tariff regime. Case 2 will involve the PV panels, but not the EV. Case 2 is simulated to check the effect of the HEMS combined management of the space heating loads and the BESS. For Case

3, both the PV and EV are involved. Case 3 will simulate the overall performance of the HEMS, with both space heating load control, BESS management and scheduled EV charging.

All simulations are run over 48 hours, and the grid tariff cost will be calculated for the entire 48 hours. If the plots only contain 24 hours, it is because the results shows little to no change between the first 24 hours and the last 24 hours of the simulation.

The results are also given in Appendix A.

8.1 Simulation case 1: Simulating scenario without EV and PV

In this simulation case, the difference between load control and no load control is simulated for different demand limits. PV and EV are not included.

8.1.1 Case 1: Base case

PV=0, EV=0, HEMS=0

In Figure 8.1 the grid-supplied load is shown together with the temperatures of all zones. Because there is no HEMS performing load control, all the space heating loads are only controlled by thermostats.

Base case: Grid tariff cost

The cost for the different grid tariff structures in the base case is shown in Table 8.1. For the CB_{60m} tariff, the cost stays relatively constant for all demand limit levels. When the measurement-period decrease, the CB tariff increases.

Base case: Peak measurements

In Table 8.2 the measured peaks of grid-supplied power is presented. It is observed that the peak measurement increase as the measuring intervals decrease.

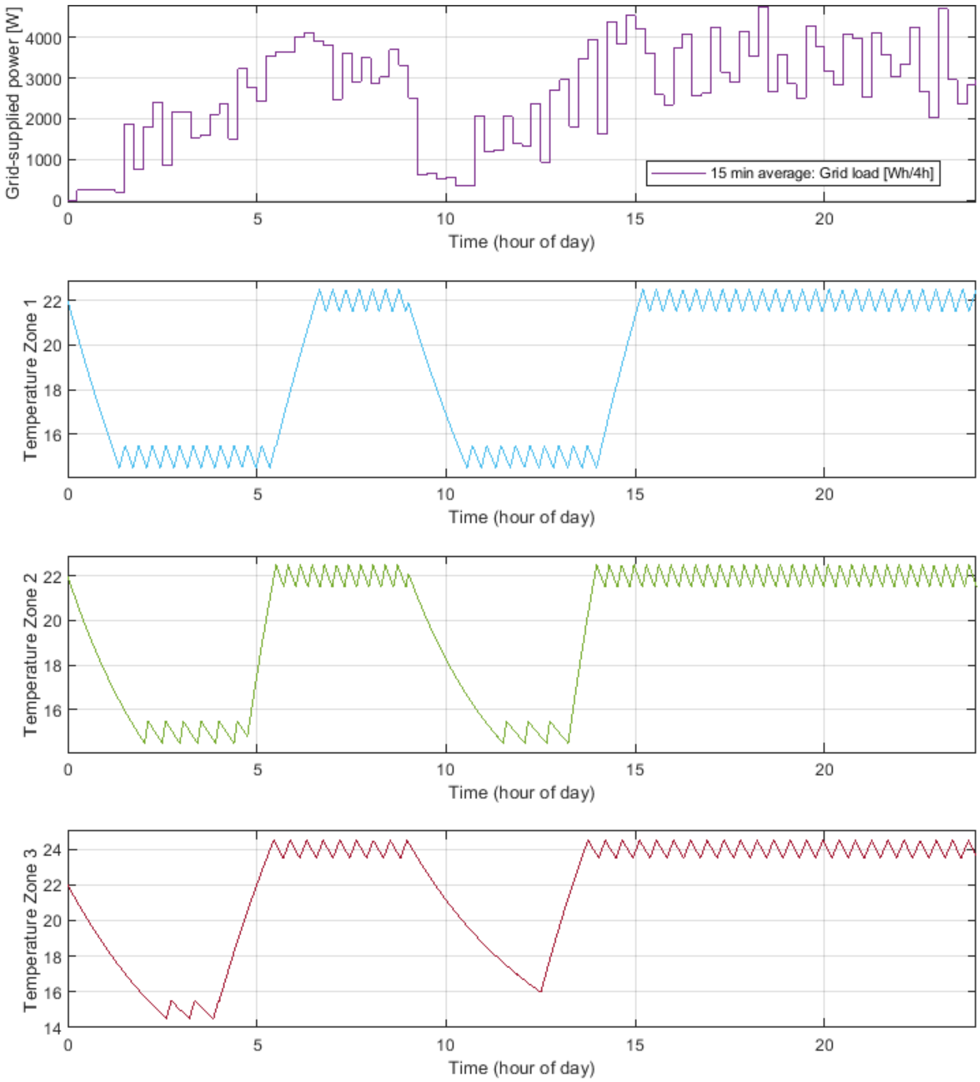

Figure 8.1: Base case 1: Plots of 15-minute grid supplied load, and zone temperatures.

		Grid tariff cost [NOK]				
		CB_{60m}	CB_{15m}	CB_{1m}	ToU	MPP
$P_{max}[W]$	3250	30.36	35.61	49.86	46.91	31.55
	3500	27.48	32.39	45.95		
	3750	27.26	30.30	42.70		
	4000	27.71	29.29	39.70		
	4500	29.13	29.55	35.53		

Table 8.1: Case 1: Base case grid tariff cost for different grid tariff structures.

Grid-supplied power peak measurement [W]		
$P_{peak,60m}$	$P_{peak,15m}$	$P_{peak,1m}$
4326	5420	8130

Table 8.2: Case 1: Base case power peaks measurements.

8.1.2 Case 1: With HEMS control

PV=0, EV=0, HEMS=1

Case 1 is simulated again, but now with the HEMS activated. The case is simulated for the same occurrences of P_{max}, and the HEMS will for every P_{max} manage the system with respect to this demand limit.

Grid tariff cost and reduction

		Grid tariff cost[NOK] / reduction compared to base case[%]				
		CB_{60m}	CB_{15m}	CB_{1m}	ToU	MPP
$P_{max}[W]$	3250	26.15/14.5%	26.72/25.0%	27.30/45.2%	44.93/4.22%	28.87/8.49%
	3500	25.15/8.48%	25.22/22.1%	25.40/44.7%	45.40/3.22%	28.45/9.83%
	3750	26.16/4.05%	26.15/13.7%	26.18/38.7%	45.83/2.30%	29.00/8.08%
	4000	27.17/1.95%	27.17/7.24%	27.17/31.6%	46.36/1.17%	30.03/4.82%
	4500	29.10/0.103%	29.10/1.52%	29.10/18.1%	47.70/-1.68%	31.72/-0.539%

Table 8.3: Case 1: With HEMS control - grid tariff cost reduction for different grid tariff structures and with different demand limits

Grid-supplied peak power reduction

Table 8.4 shows how much the measured grid-supplied power peaks is reduced when the HEMS perform load control. For all the measurements, the peak is reduced more when the demand limit is 3500 W than for 3250 W. The peak reduction is also most significant for the 1-minute measurements.

Comfort violations

In Table 8.5, the comfort loss is given with regards to how long each zone had a temperature at 1 °C under the reference temperature. It is evident that the demand limit at 3250 W causes major comfort losses for the household, with zone 1 and zone 3 constantly violating this limit. It is observed that for all the demand limits up to 4000 W, the comfort loss in zone 3 is significant.

		Grid-supplied power peak reduction [%]		
		$P_{peak,60m}$	$P_{peak,15m}$	$P_{peak,1m}$
P_{max}	3250	16.2%	18.3%	31.3%
	3500	19.0%	34.1%	48.3%
	3750	16.1%	31.9%	50.2%
	4000	10.0%	27.5%	50.9%
	4500	-0.5%	19.0%	44.9%

Table 8.4: Case 1: With HEMS load control - Reduction of measured peak in grid-supplied power compared to base case.

		violation [%]		
		Zone 1	Zone 2	Zone 3
P_{max}	3250	99.9 %	68.1 %	99.9 %
	3500	19.7 %	23.5 %	99.4 %
	3750	1.8 %	4 %	91.7 %
	4000	0 %	0 %	39.4 %
	4500	0 %	0 %	1.6 %

Table 8.5: Case 1: With HEMS load control - measuring the comfort loss in each zone

Results when P_{max}= 3500 W

Figure 8.2 presents the simulation results for case 1 with the HEMS performing load control at a demand limit of 3500 W. As can be seen from both the figure and Table 8.5, there are significant comfort losses in all zones. The temperature in the kitchen/living room does not reach its reference temperature until around 23h. The bathroom is never allowed to fully heat up because of the constant stress on the demand limit, while the entrance/hallway suffers a big temperature dip in the morning.

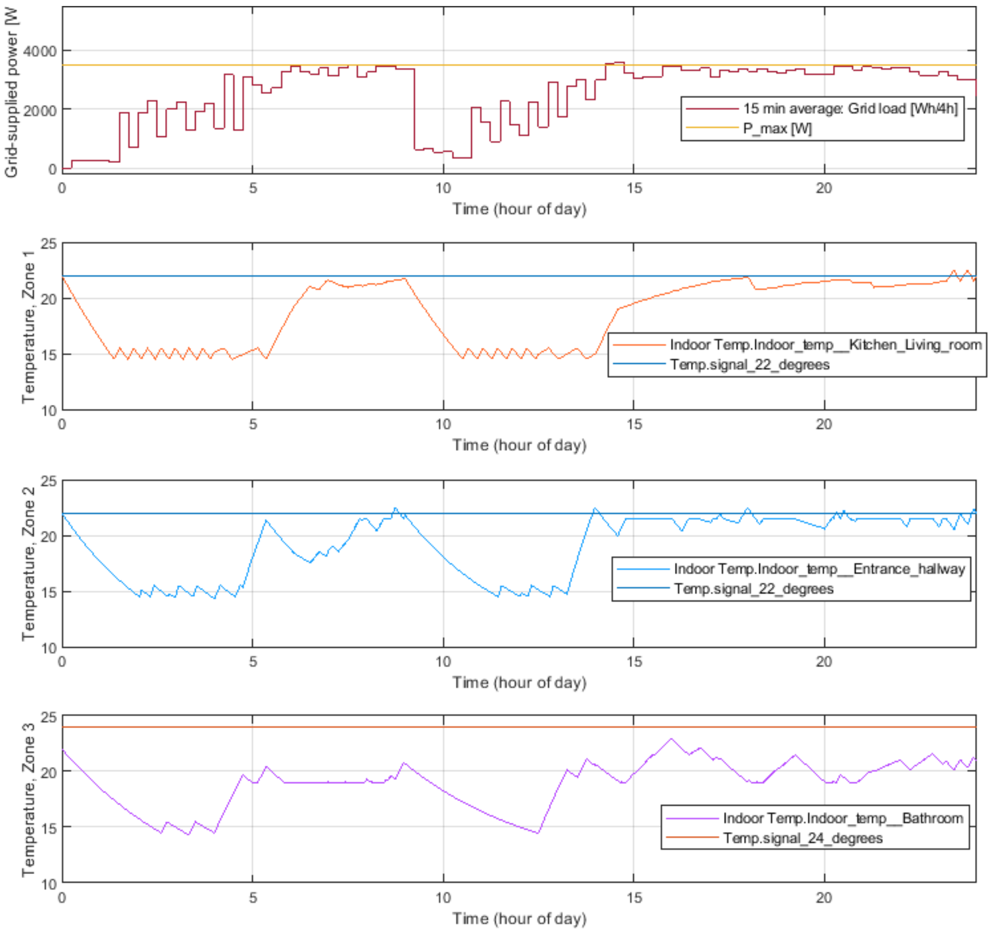

Figure 8.2: Case 1: With HEMS(P_{max}=3500 W). Plots of 15-minute grid supplied load, and zone temperatures.

Results when P_{max}= 3750 W

The simulation results for case 1 with the HEMS performing load control with P_{max}=3750 W is shown in Figure 8.3. As also given by Table 8.5, the bathroom temperature seldom reaches its comfort condition. The entrance/hallway temperature shows some minor periods where the space heating loads in the room is turned off for a significant time. The temperature in the kitchen/living room stays relatively constant around the reference temperature, and only has a *violation* of 1.8 %.

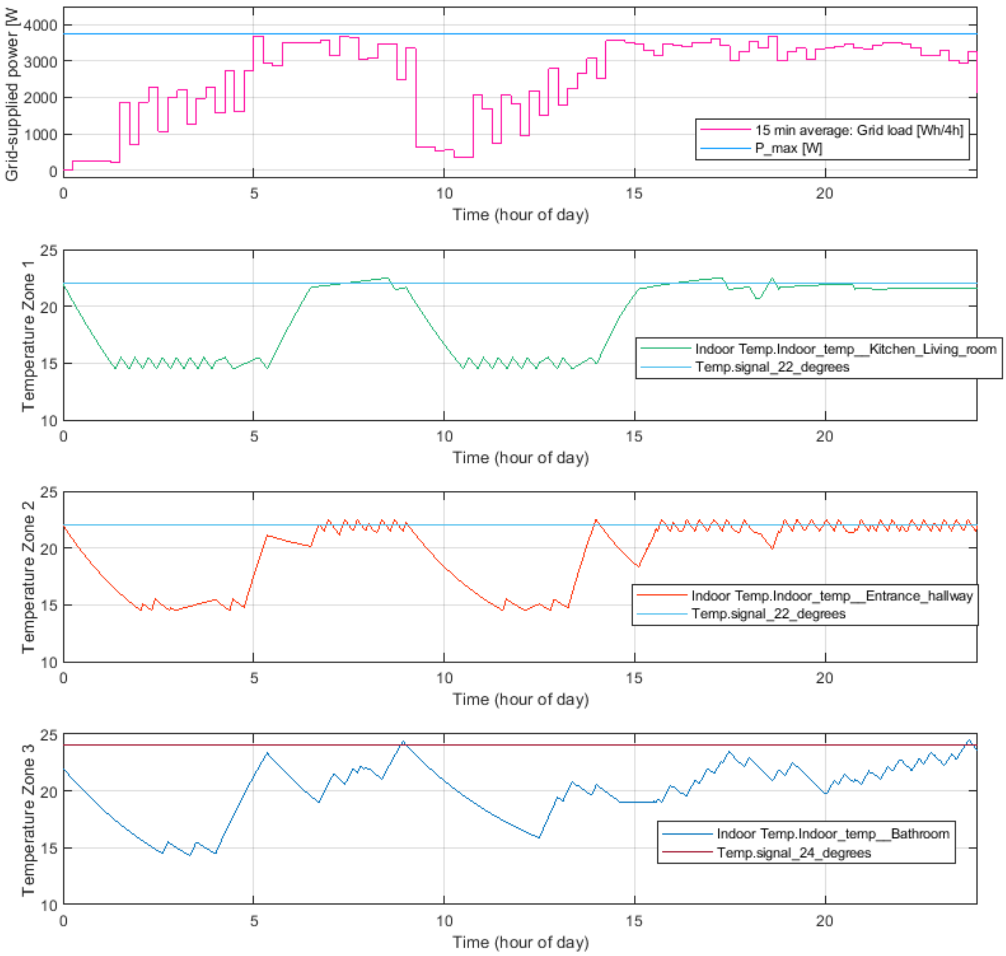

Figure 8.3: Case 1: With HEMS(P_{max}=3750 W). Plots of 15-minute grid supplied load, and zone temperatures.

8.2 Case 2: Simulating scenario with PV production BESS

In this simulation case, the difference between load control and no load control is simulated for different demand limits when the household has a PV production system and a BESS. The EV load is not included in the simulation. Case 2 is simulated with the demand limits of 3250 W, 3500 W and 3750 W.

8.2.1 Case 2: Base case

PV=1, EV=0, HEMS=0

Figure 8.4 shows the load profile for the base case, and the PV produced power. As there is no load control, the BESS is not utilized either, and the produced energy goes directly to supply the household or back to the grid. This can be seen by the grid-supplied power decreases mid-day compared to case 1 shown in Figure 8.1. The power that is fed back to the grid is calculated and worth 1.34 NOK.

Base case: Grid tariff cost

The grid tariff cost for the base case is presented in Table 8.6. It shows the ToU cost, the MPP cost as well as the CB cost for different demand limits and for different power measurement intervals.

<table>
<tr><td></td><td></td><td colspan="5">Grid tariff cost [NOK]</td></tr>
<tr><td></td><td></td><td>CB_{60m}</td><td>CB_{15m}</td><td>CB_{1m}</td><td>ToU</td><td>MPP</td></tr>
<tr><td rowspan="3">$P_{max}[W]$</td><td>3250</td><td>27.84</td><td>32.77</td><td>45.78</td><td rowspan="3">42.65</td><td rowspan="3">29.14</td></tr>
<tr><td>3500</td><td>25.45</td><td>30.00</td><td>42.60</td></tr>
<tr><td>3750</td><td>25.74</td><td>28.59</td><td>39.75</td></tr>
</table>

Table 8.6: Case 2: Base case grid tariff cost for different grid tariff structures.

Base case: Peak measurements

The grid-supplied power peak measurements are shown in Table 8.7. The 1-hour power peak have decreased compared to case 1. This is because the peak happens around 15h,

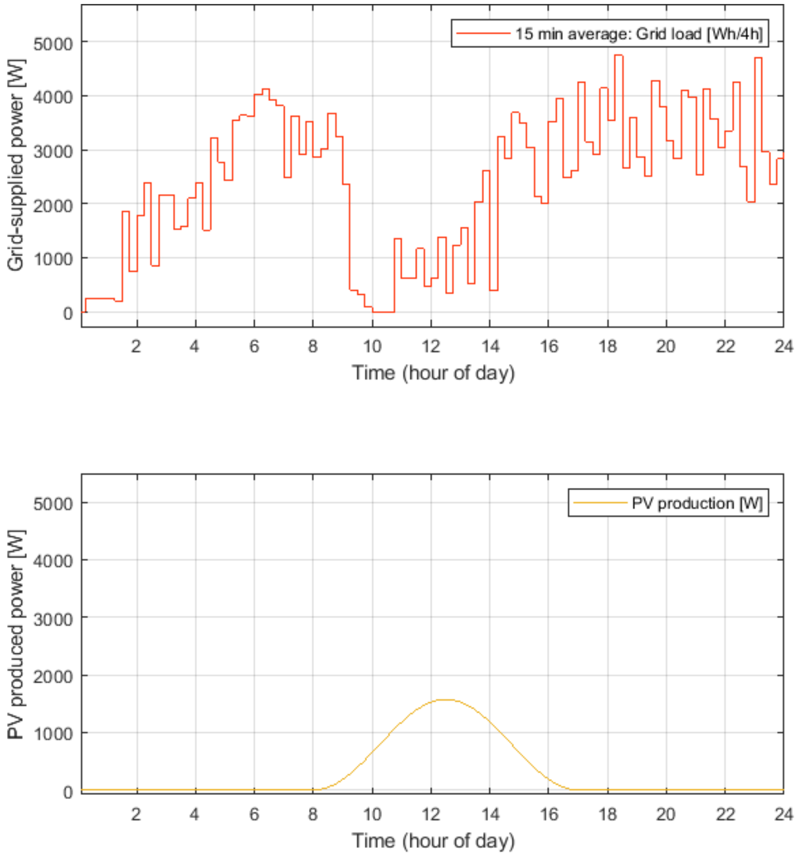

Figure 8.4: Case 2: Base case - Plots of 15-minute grid supplied load, and PV produced power.

mostly because heating loads are turned on after the "save-mode"-period, simultaneously as the PV production reduces the demand for grid-supplied power.

Grid-supplied power peak measurement [W]		
$P_{peak,60m}$	$P_{peak,15m}$	$P_{peak,1m}$
3705	5420	8130

Table 8.7: Case 2: Base case power peaks measurements

8.2.2 Case 2: With HEMS control

PV=1, EV=0, HEMS=1

Case 2 is simulated with the HEMS controlling the BESS and the loads. The energy stored on the battery was fully used in the scenarios with demand limits of 3250 W and 3500 W. For the scenario with the demand limit at 3750 W, the battery did not discharge fully, and ended the simulations with approximately 2.5 kWh of energy stored.

Grid tariff cost and reduction

The grid tariff costs and reductions are presented in Table 8.8.

		Grid tariff cost[NOK] / reduction compared to base case[%]				
		CB_{60m}	CB_{15m}	CB_{1m}	ToU	MPP
$P_{max}[W]$	3250	24.62/11.6%	25.28/22.9%	25.80/43.6%	39.79/6.71%	27.96/4.05%
	3500	24.5/3.73%	24.51/18.3%	24.60/42.3%	40.72/4.52%	27.74/24.80%
	3750	25.62/0.46%	25.62/10.4%	25.62/35.5%	42.55/0.23%	28.52/2.12%

Table 8.8: Case 2: With HEMS control - grid tariff cost reduction for different grid tariff structures and with different demand limits

Grid supplied peak power reduction

Table 8.9 presents the percentage reductions in the grid-supplied peak power measurements compared to the base case. The peaks have decreased the most for the 1-minute measurements, and the reduction for the 15-minute measurements are also significant. The reductions for the 1-hour measurements are less significant. It is also observed that the peak reductions at P_{max} =3250 W are less than for P_{max} =3500.

		Grid-supplied power peak reduction [%]		
		$P_{peak,60m}$	$P_{peak,15m}$	$P_{peak,1m}$
P_{max}	3250	5.80%	28.6%	31.8%
	3500	8.04%	34.4%	53.4%
	3750	3.64%	31.9%	52.8%

Table 8.9: Case 2: With HEMS load control - Reduction of measured grid-supplied power peak compared to base case.

		violation [%]		
		Zone 1	Zone 2	Zone 3
P_{max}	3250	87.5 %	69.0%	99.9 %
	3500	4.8 %	26.7 %	78.4 %
	3750	0 %	13.3 %	44.2 %

Table 8.10: Case 2: With HEMS load control - measuring the comfort loss in each zone

Comfort violations

The comfort violations when simulating case 2 with load control is shown in Table 8.10. The demand limit of 3250 W forces major comfort losses in all zones. For this demand limit, the comfort loss is also more for zone 1 than for zone 2, even though zone 1 has the highest priority.

Results when P_{max}=3500 W

Figure 8.5 shows the results for the simulation of case 2 with the HEMS performing load control and BESS management. The temperature at the kitchen/living room suffers from the defined comfort loss at 4.8 % of the time, which is better than the results from case 1 for the same demand limit. As can be seen, the bathroom is suffering significant comfort losses, and the temperature stays at the critical comfort limit during 6h-9h. At this time the household demand is very high, and the entrance/hallway suffers from a dip in the temperature during this time. Most importantly, the comfort is preserved at the living room/kitchen during this time. The dynamic behaviour of the different zone temperatures as a response to the household load demand can easily be seen in the figure.

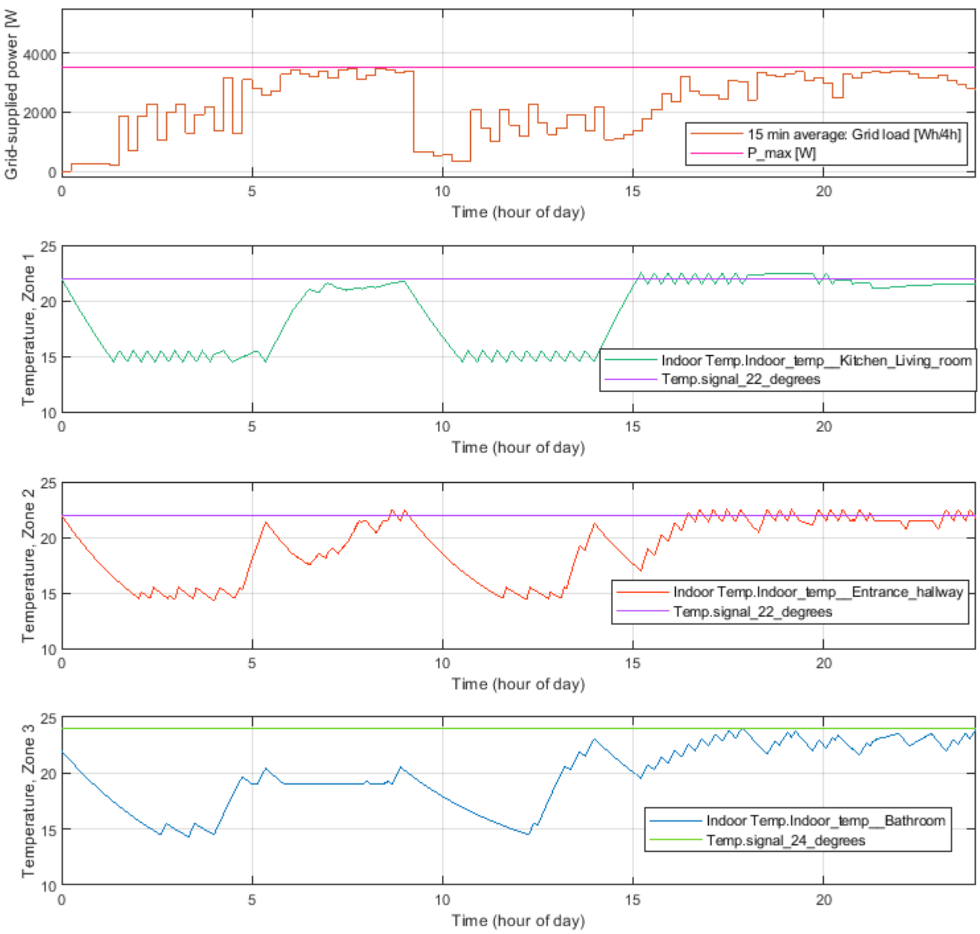

Figure 8.5: Case 2: With HEMS load control (P_{max}=3500 W). Plots of 15-minute grid supplied load, and zone temperatures.

8.3 Case 3: Simulating scenario with PV production and EV

The last simulated case will be for a household that has installed PV production and has an EV. For the base case, PV produced power will not be stored on the battery, and the EV charging will not be scheduled. For the simulations with HEMS, the load control (including BESS management) will be performed, and the EV charging will be scheduled. The simulations are simulated for demand limit of 3250 W, 3500 W, 3750 W and 4000 W.

8.3.1 Case 3: Base case

PV=1, EV=1, HEMS=0

Figure 8.6 shows the grid-supplied load for the case 3 base case. The temperatures are not shown, but are equal to what is shown in Figure 8.1. As in case 2, the PV power that is fed back to the grid is worth 1.34 NOK.

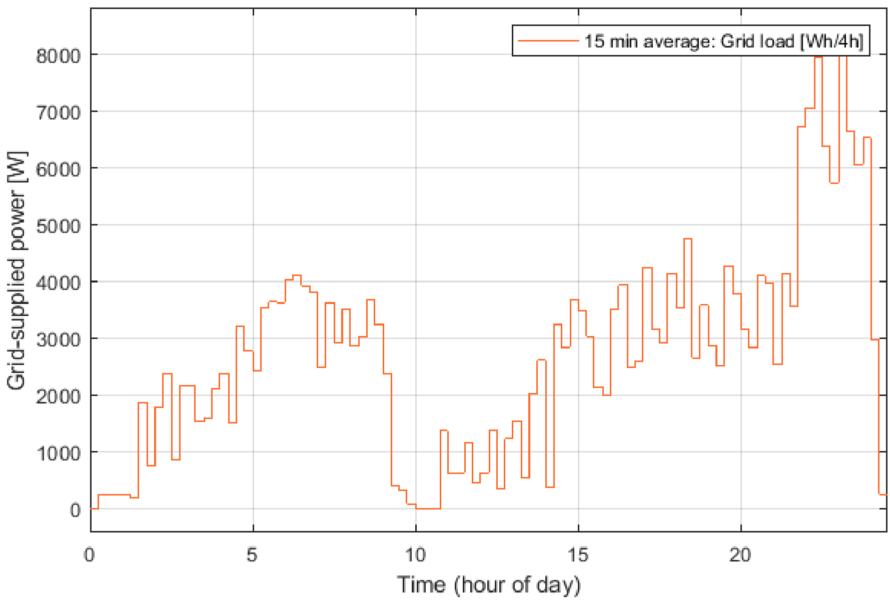

Figure 8.6: Base case 3: Plots of 15-minute grid supplied load.

Base case: Grid tariff cost

The grid tariff costs for the base case are presented in Table 8.11.

<table>
<tr><td colspan="2"></td><td colspan="5">Grid tariff cost [NOK]</td></tr>
<tr><td colspan="2"></td><td>CB_{60m}</td><td>CB_{15m}</td><td>CB_{1m}</td><td>ToU</td><td>MPP</td></tr>
<tr><td rowspan="4">$P_{max}[W]$</td><td>3250</td><td>44.41</td><td>48.49</td><td>59.54</td><td rowspan="4">45.05</td><td rowspan="4">42.67</td></tr>
<tr><td>3500</td><td>41.16</td><td>45.06</td><td>55.80</td></tr>
<tr><td>3750</td><td>39.96</td><td>42.78</td><td>52.32</td></tr>
<tr><td>4000</td><td>39.41</td><td>41.36</td><td>49.20</td></tr>
</table>

Table 8.11: Case 3: Base case grid tariff cost for different grid tariff regimes

Base case: Peak measurements

In Table 8.12 the measured peaks of grid-supplied power are presented. All peak measurements have increased significantly compared to the two other cases because of the additional EV load.

Grid-supplied power peak measurement [W]		
$P_{peak,60m}$	$P_{peak,15m}$	$P_{peak,1m}$
7117	8400	10330

Table 8.12: Case 3: Base case power peaks measurements

8.3.2 Case 3: With HEMS control and scheduled charging

PV=1, EV=2, HEMS = 1

Case 3 is simulated with HEMS control and scheduled EV charging. That means that the EV-load is scheduled to charge from 00:00 to 02:15. During the simulations for the demand limits of 3750 W and 4000 W, the battery had respectively 0.8 kWh and 3.7 kWh stored when the simulation ended.

Grid tariff cost and reduction

The grid tariff cost and reduction for each demand limit are presented in Table 8.13.

		Grid tariff cost[NOK] / reduction compared to base case[%]				
		CB_{60m}	CB_{15m}	CB_{1m}	ToU	MPP
$P_{max}[W]$	3250	28.83/35.1%	30.27/37.6%	30.82/48.2%	42.31/6.1 %	32.52/23.8%
	3500	27.00/34.4%	27.87/38.1%	28.03/49.8%	43.12/4.3 %	30.72/28.0%
	3750	26.88/32.7%	27.70/35.3%	27.72/47.0%	45.28/-0.5%	30.90/27.6%
	4000	27.47/30.3%	27.79/32.8%	27.82/43.5%	45.60/-1.2 %	30.98/27.4%

Table 8.13: Case 3: With HEMS control - grid tariff cost and reduction for different grid tariff structures and with different demand limits. The reductions are calculated compared to the base case with the same demand limit.

Grid-supplied peak power reduction

The reduction in the grid-supplied peak power is presented in Table 8.14. It can be observed that the peak is reduced significantly for all measurements intervals and demand limits.

		Grid-supplied power peak reduction [%]		
		$P_{peak,60m}$	$P_{peak,15m}$	$P_{peak,1m}$
P_{max}	3250	36.8%	39.4%	42.0%
	3500	43.9%	39.9%	47.2%
	3750	43.9%	39.9%	47.2%
	4000	43.9%	39.9%	47.5%

Table 8.14: Case 3: With HEMS load control - Reduction of measured peak in grid-supplied power compared to base case.

Comfort violations

The *violation* in each zone for all demand limit simulations is presented in Table 8.15.

Results when $P_{max} = 3750$ and LP_{BESS}=2

As can be seen from Figure 8.7, the results presented are for the entire 48 hour simulation. The is because the system response changes from the first day to the other. As the BESS is not charged at the start of the simulation, the EV load forces the demand over the demand limit. Because the battery priority threshold is set only to supply comfort for zone 1, and the need to turn off both space heating loads in zone 1 seldom occur, the

		violation [%]		
		Zone 1	Zone 2	Zone 3
P_{max}	3250	87.5 %	75.0 %	99.9 %
	3500	4.1 %	24.7 %	89.4 %
	3750	0 %	9.9 %	40.5 %
	4000	0 %	1.6 %	43.7 %

Table 8.15: Case 3: With HEMS load control - measurements of the comfort loss in each zone

BESS does not utilize all the PV produced energy. Instead, it is used the next night to supply the EV load when the demand exceeds the demand limit. Later, the same scenario is tested with a battery priority threshold of 5.

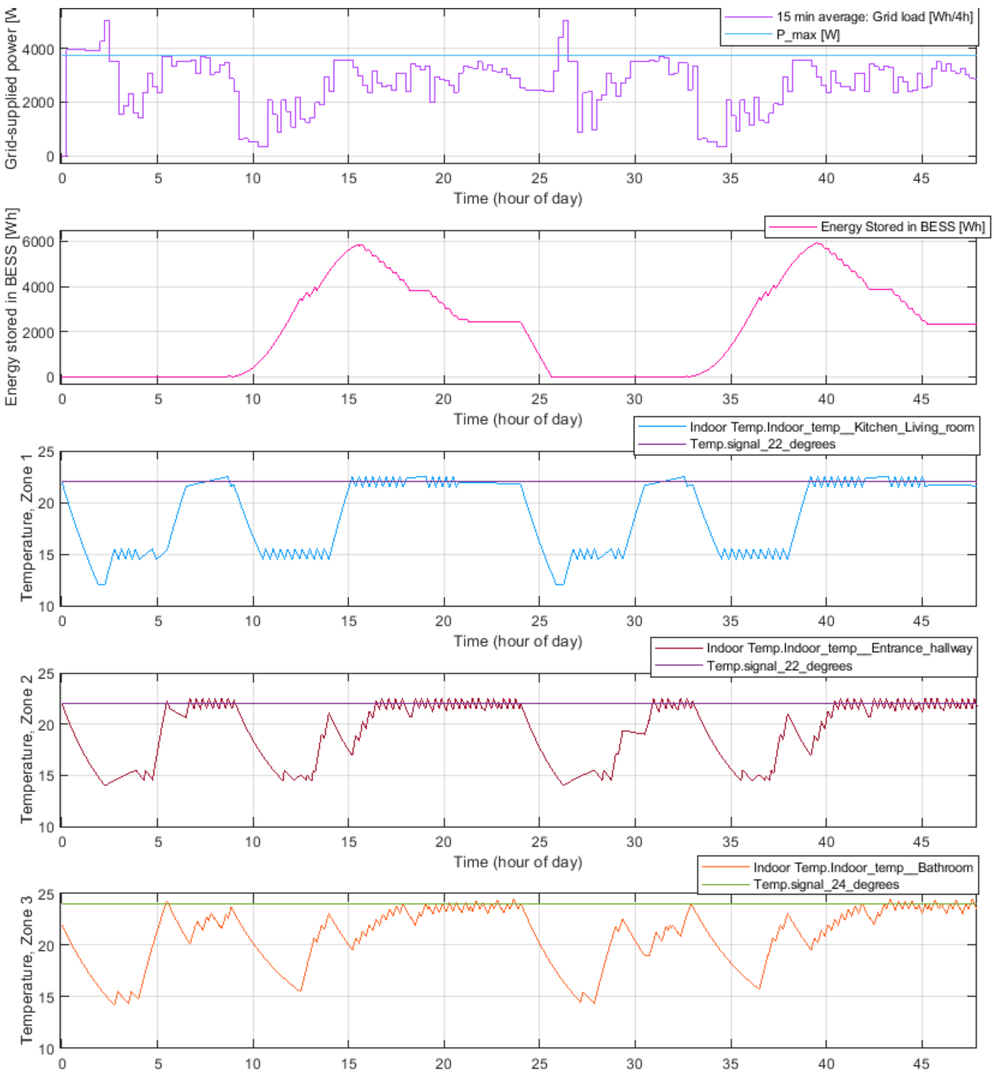

Figure 8.7: Case 3: With HEMS load control (P_{max}=3750 W) and $LP_{BESS} = 2$. The figure shows the plots for 15-minute grid supplied load, energy stored in BESS and zone temperatures.

Results when P_{max} = 3750 and LP_{BESS}=5

For this simulation, the load priority threshold for the BESS was changed to 5, which is the lowest priority in the system. This means that the BESS can be utilized to supply power for all the space heating loads. This way the BESS will be utilized as the first step in the load control, before any of the space heating loads are turned off. The simulation results are presented in Figure 8.8. As can be seen, and also presented in Table 8.17, the zone temperatures in zone 1 and zone 2 is never under the *violation* limit, and in zone 3 the *violation* is now 21.6 %. This is a reduction compared to when the battery priority threshold was equal to 2, where the zone 2 *violation* was 9.9 % and 40.5 % in zone 3. The cost is presented in Table 8.16. It shows that the cost for the CB tariff and MPP tariff increases fractionally compared to the scenario with lower priority threshold, while the ToU tariff decreases by 3.5 %.

		Grid tariff cost[NOK] for LP_{BESS}=5				
		CB_{60m}	CB_{15m}	CB_{1m}	ToU	MPP
$P_{max}[W]$	3750	27.34	27.97	27.98	43.7	31.16

Table 8.16: Case 3: With HEMS control (P_{max}= 3750 W) and LP_{BESS}=5 - Grid tariff costs for the scenario

		violation [%]		
		Zone 1	Zone 2	Zone 3
P_{max}	3750	0 %	0 %	21.7 %

Table 8.17: Case 3: With HEMS control (P_{max}= 3750 W) and LP_{BESS}=5 - measurements of the comfort loss in each zone

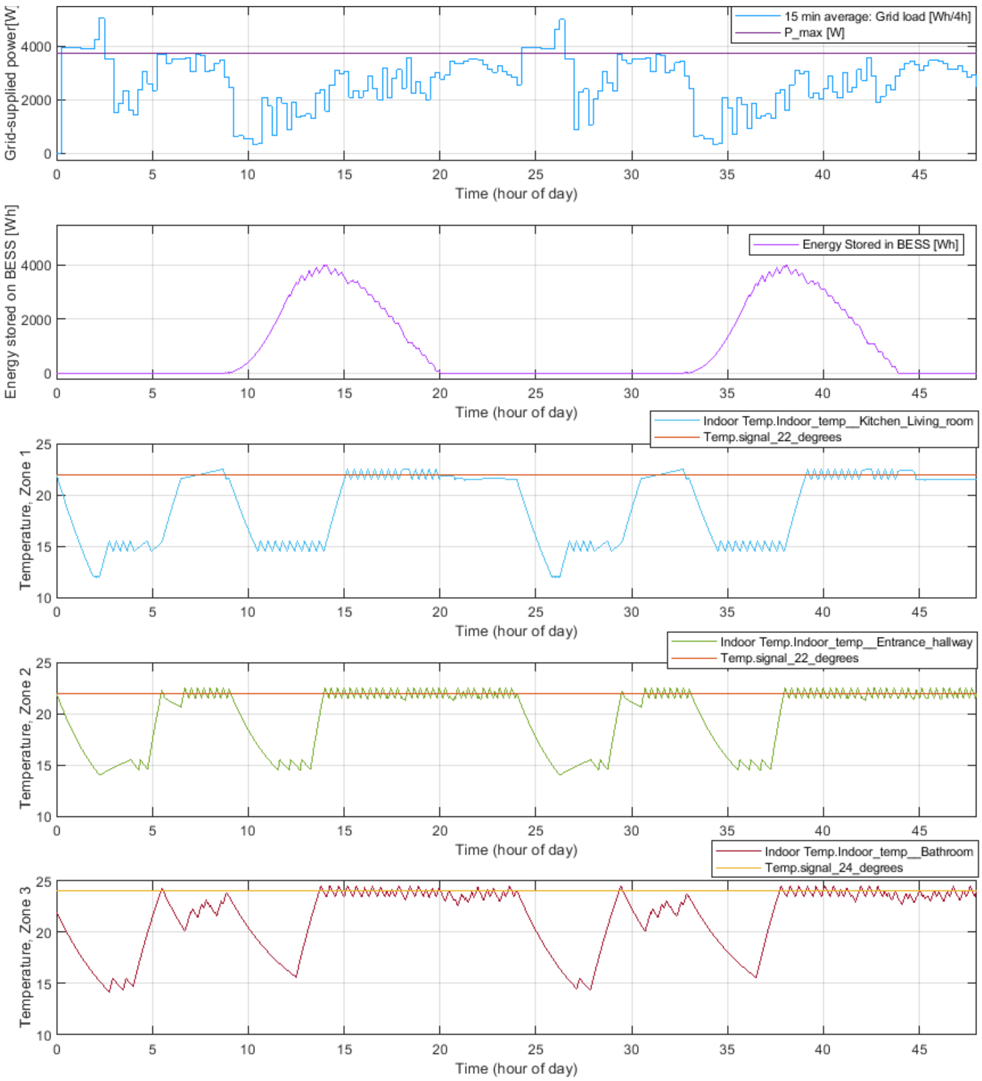

Figure 8.8: Case 3: With HEMS load control (P_{max}=3750 W) and LP_{BESS} = 5. The figure shows the plots for 15-minute grid supplied load, energy stored in BESS and zone temperatures.

Chapter 9

Analysis and discussion

In this part the results presented in the previous chapter will be analyzed and discussed, as well as the overall performance of the HEMS control and the reliance of the model.

9.1 Reviewing the economic benefit versus comfort loss

9.1.1 Case 1

The purpose of simulating case 1 was to test in what level the modelled space heating loads alone could impact the grid tariff cost and peaks of grid-supplied power, and at what cost regarding comfort loss.

The results for the case 1 base case (BC1) shows that for the conventional 1-hour power averaging that is used today, the ToU tariff is significantly higher than the CB and MPP tariff. The ToU tariff is only based on energy consumption during specific hours, with high tariff rates at winter, especially between 6h-20h. That way a big part of the energy consumption in this model is being charged at the highest rate. "Save-mode" during the night can cause negative results, if the reheating of the apartment happens after 6h. In this model, the reheating of zone 1 happens during 6h and onwards, so it is likely that this causes a higher ToU cost. The cost for the 1-hour CB tariff and MPP tariff are comparably low, and this is because these measurements do not get affected by short-timed heavy loads. This can also be seen in Figure 6.3, where the hour-by-hour household demand curve (without EV) is seldom over 3500 W. Because of this, the 1-hour MPP and CB tariff is notably small in case 1.

Investigating the 1-minute measurements, it is clear that the CB tariff increases significantly when decreasing the measurement interval. The 1-minute CB is able to penalize short timed loads that cause the demand to exceed the demand limit for short periods. This can also be seen from Table 8.2, where the measured 1-minute peak is 187 % of the 1-hour peak. At 15-minute measurements, the CB tariff increases slightly, but is still in reasonable limits under the ToU tariff.

When running the case 1 with HEMS control, the result of setting the demand limit too low can be observed. For a limit of 3250 W, the measured peaks are reduced, but less than for the 3500 W demand limit. This is interesting, as it is expected that a lower demand limit would cause lower measured peaks. This is not the case, because the demand limit is so low that it causes problems for the loads in zone 1. The nominal power of the loads in zone 1 adds up to 3120 W. And with a non-deferrable load of minimum 200 W (see Figure 6.3), this means that the two heating loads in zone 1 never can be on at the same time without breaching the limit. This causes zone 1 to never fully reheat after the "save-mode"-periods. The HEMS will continue to try to turn off the other loads in order to turn on both the zone 1 loads, but it never allows the loads to turn on unless the critical comfort conditions are violated. Based on this, the HEMS is not able to perform an efficient load control.

It can be observed that for the demand limit of 3500 W, the HEMS perform a lot better. It manages to reduce the 1-hour peak of grid-supplied power significantly for all measurements intervals. Even though the HEMS is not directly programmed to reduce the peaks, peak reduction is beneficial from the grid operator's point of view and also regarding the possible MPP tariff. Even though it does not involve as much comfort loss as for the demand limit of 3250 W, it is still a significant comfort loss of 19.7 %, 23.5 % and 99.4 % for zone 1,2 and 3, respectively. Even though this limit provides the lowest CB tariff cost, these comfort losses will rarely be accepted, and users would probably choose to pay a little bit more to remain comfortable.

For the demand limit of 3750 W, which is the second-best alternative regarding the CB grid tariff, the comfort losses in zone 1 and 2 decrease to 1.8 % and 4 % respectively. The comfort losses in zone 3 remain very high and the temperature deviates more than 1 °C from the reference temperature more than 90 % of the time. As can be seen from Figure 8.3, the temperature is often over 20 °C. For some users, this might be good enough knowing that it reduces their electricity bill. For the 1-hour measurement, the CB tariff is reduced by 4 %, which might not be a significant reduction compared to the zone 3 comfort losses of over 90 %.

With a demand limit of 4500 W, and the HEMS performing the load control, it might result in a bigger grid tariff than in the BC1. The 1-hour peak increased during this simulation, mostly because the demand limit was set higher than the BC1 1-hour peak. On the other side, the HEMS still manage to reduce the 1-minute peak by 44.9 %, and if the CB_{1m} was current, the grid tariff cost would be reduced by 18.1 %. This would be appealing for users, as the 4500 demand limit impose nearly no comfort loss for any of the zones.

The bathroom (zone 3) suffers from significant comfort losses for all demand limits up to 4000 W. This is mainly because it is the lowest prioritized zone, and also partly because it provides a significant amount of flexibility. The modelled concrete in the bathroom shows its huge heat storage capacity, and for the demand limit of 3750 W, in most cases it is enough to turn off the 800 W bathroom heating cables to remain under the limit.

It is observed that with the HEMS controlling the loads, the CB tariff stays somewhat constant for all measurement intervals. This implies that the HEMS is able to force the 1-minute measured load to stay under the demand limit at all times. This is done because the HEMS is programmed to update every 15 second. One could argue that the HEMS also could update faster, to prevent even shorter periods of over-consumption. This would, on the other hand, cause a lot of frequent switching on/off of appliances, which might cause problems for the voltage quality if the switched loads require a lot of power. A resolution of 15 seconds might also be enough to cause this.

Based on the overall results from case 1, the management of space heating loads, with the goal to reduce the CB grid tariff, is not very efficient when dealing with 1-hour measurements of grid-supplied power. The space heating loads are not able to reduce the grid tariff cost without extensive loss of comfort for the user. These loads are not flexible enough to shift consumption from one hour to another without significant comfort loss. Regardless, the space heating loads provide enough flexibility to counter-act short periods of high consumption, which can give huge economic benefits if dealing with a CB grid tariff based on shorter measurement intervals.

9.1.2 Case 2

Case 2 was simulated to investigate how the BESS management could increase the comfort level of the zones. For all demand limits simulated in case 2 with HEMS, the BESS management was operated with a battery priority threshold equal to 2.

For the case 2 base case (BC2) simulations, some of the PV produced energy was fed back to the grid, and this energy was calculated to be worth 1.34 NOK. This must be accounted for when evaluating the economic benefit of the HEMS control. In addition to this, the calculation of the BC2 MPP grid tariff is surprisingly low, compared to in the BC1. Seemingly, the 1-hour measurement power peak for the BC1 happens around 15h, because of the reheating after the "save-mode"-period. This peak is reduced in BC2, because of the PV produces power at this time. Because of this, the MPP grid tariff is reduced when comparing the BC2 with BC1.

Analyzing the comfort losses for the case 2 with HEMS control, it is observed that for all three demand limits simulated, the comfort losses are generally reduced when comparing each demand limit simulation in case 2 with the respective simulation for case 1. E.g., the *violation* for zone 1, 2 and 3 are respectively 19.7 %, 23.5 % and 99.4 % for $P_{max} = 3500$ in case 1. For case 2 with the same demand limit, the zone 1, 2 and 3 *violation* are 4.8 %, 26.7 % and 78.4 % respectively. The comfort loss in zone 1 and 3 have been reduced significantly by utilizing the PV produced energy. This shows the effectiveness of utilizing the BESS to reduce the time the loads in zone 1 are turned off.

Figure 8.5 shows the system response when the demand limit is 3500 W. The figure showcase the importance of scheduling different reheating starting times for each zone. Zone 3 starts the reheating 45 minutes before zone 2 and 90 minutes before zone 1. This allows zone 2 and 3 to have a temperature increase before zone 1 starts the reheating. When zone 1 reheats, all other space heating loads are turned off to not exceed the demand limit. In addition, the BESS is utilized to allow both the heaters in zone 1 to be turned on. As can be seen from Figure 8.2, both heaters were never allowed to be turned on simultaneously during the reheating process. This shows how the BESS is utilized to only provide more comfort for zone 1. The BESS priority threshold will be discussed in section 9.2.

9.1.3 Case 3

Case 3 was simulated to test how the HEMS performed when involving space heating loads and BESS control, PV and EV charging.

The simulations involving EV shows that the measured power peaks increase when adding the unscheduled EV charging. This is because of its huge load of 3.7 kW. Comparing the grid tariff costs in case 3 base case (BC3) with BC2, the results show that the BC3 receives larger grid tariff costs than BC2, also for the ToU. The increase in the ToU grid tariff is not very large, mainly because the EV charging happens after 20h, and thus it is not charged by the increased energy price. For the CB grid tariff, and for all measurement intervals, the increase from BC2 is significant. This shows that when a heavy load as the EV is not scheduled, the cost of the CB tariff can increase dramatically.

When simulating case 3 with the HEMS activated and the EV charging scheduled, the CB tariff cost is reduced significantly, also for the 1-hour measurement intervals. The CB_{60m} is reduced between 30-35 %, and this reduction is mainly because of the scheduled EV charging. For the CB_{1m}, the reduction is between 40 - 50% for all demand limits. This shows the great potential for scheduled EV charging. If the car is not used after 21:30 anyways, it would not cause any comfort loss for the user to schedule the charging to the night. This way, scheduled charging can cause major economic benefits with no associated loss of comfort and convenience.

9.1.4 Conclusive thoughts on the affect of HEMS on the grid tariff costs

As the developed model of the apartment is simplified in terms of its thermal characteristics, any absolute conclusions regarding the effectiveness of the HEMS can not be drawn based on the results of these simulations. Any conclusions will only be valid for the developed model.

It is observed that the HEMS control do not contribute to any major reduction of the ToU tariff in the modelled environment, mainly because it is not programmed to shift or reduce large parts of the demand during the 6h-20h period. Results also showed that the ToU-grid tariff might be increased with HEMS control, when the demand limit is set high. This HEMS is therefore not a suitable option for reducing a ToU grid tariff.

The results can also imply that the MPP grid tariff can be reduced if the 1-hour measurement of the power peak is reduced. For all scenarios, it is a trade off between comfort level and cost. For a low demand limit, the 1-hour measured peak can be reduced, but the comfort violations will also be high. Still, it is able to reduce the 1-hour peak, and still maintain comfort in the highest priority zone, as is the case in the case 2 simulation with HEMS at a demand limit of 3750 W.

In the modelled environment, the CB tariff, as it is presented by NVE, will only be significantly reduced if big loads are able to be shifted from high-demand periods to low-demand periods. This often means a load shifting over a period of multiple hours. This is what happens in case 3, where the CB_{60m} tariff is reduced greatly. Another load that also can be part of reducing the CB_{60m} tariff is by load shifting of the EWH, because of its high nominal power. In case 1 and 2, the CB_{60m} tariff is not reduced sufficiently, comparing it with the associated comfort losses in the simulations. But if the power measurements are averaged on a 15-minute basis, instead of every 1 hour, the economic benefit of controlling the space heating loads increase. And for a 1-minute basis, the economic saving is the highest. This show that the control of space heating loads might be more suitable when dealing with load shifting on a minute-to-minute basis. They are suitable for evening out the instantaneous demand, but seems more inefficient at load shifting from peak hours to non-peak hours. In Statnett's answer to the NVE grid tariffs proposal [16], the Norwegian TSO argued that the CB tariff would be more efficient for penalizing high instantaneous power demand if the measurment resolution was smaller than 1 hour, and that the grid also would benefit from this. If such a change is being proposed for the next grid tariff structure announcement, the HEMS control structure could impose great economic benefit for the users.

9.2 Efficient utilization of the BESS

The PV produced energy might be utilized poorly if the BESS priority threshold is set too high. Looking back at the simulation in case 1 for P_{max}=3750 W and HEMS=1, the comfort losses in zone 1 were only 1.8 %, while 4 % in zone 2 and 91.7 % in zone 3. In case 2 for P_{max}=3750 W and HEMS=1, the comfort loss in zone 1 is 0 %, 13.3 % in zone 2 and 44.2 % in zone 3. This is interesting, as the comfort losses with PV and BESS management has increased for zone 2, while decreased significantly for zone 3. In addition, the BESS does not fully discharge, and 2.5 kWh of the PV produced energy is not utilized. This is understandable, as the HEMS rarely requested the loads in zone 1 to turn off, as is understood by the low (1.8%) comfort loss in the case 1 simulation. For better utilization of the renewable energy, the BESS priority threshold must be put high if the demand limit is low, and vice verca. For lower demand limits, all loads are usually being used in the load control. For high demand limits, only the low priority loads are being utilized in the load control. More specific, the LP_{BESS} must be put low enough so that the BESS can prevent the loads that actually are being requested to turn off, from turning off. Therefore, the LP_{BESS} should be adjusted to provide comfort only for zone 1 if the zone would suffer significant comfort losses without the extra power supplied by the BESS.

This is tested in case 3, when the simulation with HEMS=1 and P_{max}=3750 W is run for both a threshold of 2 and 5. The results show that the overall comfort level in the system increase a lot when allowing the BESS to be utilized at all times the demand is higher than the demand limit. This does cause some downsides, e.g. that the EV charging is not supplied by the BESS during nighttime, and thus the demand exceed the demand limit. The cost increases because of this, but this increase can be considered small compared to the increased comfort level of zone 2 and 3. In addition, by putting a low threshold for the battery utilization, the PV produced energy is more likely to be used. If not, the battery might be storing energy to the next day. This could also be beneficial, especially when having the EV charging scheduled at night.

9.3 Comfort level settings

As the HEMS functioning is highly dependent on the comfort level conditions and the critical comfort level conditions of the controllable loads, this is a feature that must be discussed. For this model, the maximum allowable temperature decrease from the reference temperature is set to 3 °C for zone 1 and 5 °C for zone 2 and 3. This will ultimately allow the temperature in zone 2 and 3 to be constantly 4 °C under the reference temperature. This is in most cases unacceptable, and one might argue why this limit is set to allow this huge difference in temperature. On the other hand, some users could accept the temperature to decrease for 5 °C in the room, when the colder period is short and it yields economic benefit for the user. The problem occurs when the demand limit is put so low that the household demand constantly exceed the limit, causing the space heating loads to be turned off. Therefore this limit must be carefully chosen.

As can be observed from the results, the bathroom is often suffering a comfort loss. This is because of its low priority, and in some of the cases, the demand limit is never exceeded, primarily due to the flexibility offered by the floor heating cables. Users should be aware of this when defining the priorities for the zones/loads. If the user has defined the bathroom to be the lowest priority, the user must be aware that the bathroom temperature could fluctuate a lot, and that it will not always be warm in the morning or at other times when it is used. Beside this, it is also important that the users understand that the temperature fluctuations happens continuously during the day, also when the bathroom is not in use. By utilizing the flexibility given by space heating loads, the users should experience an economic benefit, and this benefit causes a temperature decrease - sometimes at times when the user will experience it, and sometimes not.

If the allowed temperature deviation had been decreased, the HEMS ability to reduce the demand would also have been decreased. This would in turn result in less comfort loss, but again, the ability to enable the flexibility bound in space heating loads do come at a certain price. In most cases, the loss of comfort is somewhat unavoidable, and the more comfort loss is accepted, the more flexibility can be enabled. The trade off between economic benefit and savings are ultimately dependent on individual preferences, in which makes it difficult to conclude whether a given amount of comfort loss is acceptable or not. Temperature losses in rooms that users actually do not have to use for longer periods should be weighted differently than the rooms users are bound to use, as the living room. It might be reasonable to believe that for some people, a *violation* over 90 % for zone 2 and 3 would be acceptable, as long as the economic benefit is significant and the comfort loss at the kitchen/living room is low. On the other hand, this might not be acceptable at all for others.

If the HEMS could calculate and accumulate the daily comfort loss somehow, like the *violation* value, the load control algorithm could be programmed to not allow more than a certain amount of *violation* in every zone each day. Another possible implementation for decreasing the comfort loss could be a time-varying $\Delta T_{critical}$, as the users could set the HEMS to not allow more than, e.g., 2 °C deviation in the bathroom between 22:00 and 22:30, when the bathroom is likely to be used. This could be a good idea, as the users would know that during this period, the room temperature would be acceptable, and could plan to use the room at that time. This form of specific scheduled room temperatures would require more involvement from the user at implementation, but could be experienced as conveniently predictable in the long run.

9.4 Reliance of the model and result

The results are produced by the model presented in chapter 6. As explained, this model is heavily simplified compared to the realistic scenario. The actual flexibility that is modeled, is based on the heat capacity of the rooms. In the model, these rooms are filled with a mix of air and wood/concrete, to give the room heat storage capabilities. The model is not verified by testing in an real environment, but the temperature dynamics for the rooms are similar to the results obtained in the work of Skulstad [42], which was tested in the Smart House at NTNU.

A sensitivity analysis on the model parameters was not executed, but such analysis could be helpful when discussing the validity of the model. As the rooms' flexibility is modelled as their heat storage capabilities, it would be interesting to see how changes of the in-room heat capacities would affect the simulations. Lower heat capacities would result in more frequent temperature fluctuations, as the room's ability to store the heat would decrease. By this the time it would take to reach the room's critical temperature would also be reduced, and thus also the time the space heating loads could be turned off. Such changes could have given different overall results, as the space heating loads would only be able to shift demand for an even shorter period of time. This would possibly result in an even lower HEMS performance regarding reducing the 1-hour-based CB tariff, and also the 15-minute-based CB tariff. On the other hand, if the heat capacities of the rooms were increased, this would result in increased performance regarding load-shifting on an hour-to-hour basis.

Chapter 10

Conclusion

In this thesis, the development of a load control algorithm is presented, tested and discussed. The overall goal of the algorithm was to reduce a household's grid tariff cost given by the capacity-based grid tariff, while maintaining a sufficient comfort level for the users. The control structure took advantage of the accessible heat storage capacity present in households, as well as the utilization of a PV generation system and a BESS to achieve the overall goal. The testing of the proposed algorithm was done in a Simulink environment, modelling a typical Norwegian household's electricity consumption, the dynamics between space heating loads and indoor temperature and PV/BESS utilization during a cold winter day. The results show that the modelled space heating loads can be controlled in order to achieve short-period load levelling, but the ability to shift loads on an hour-by-hour perspective is not sufficient. As a result of this, simulations show that the capacity-based grid tariff cost for 1-hour measurements of power consumption is reduced, but not sufficiently compared to the associated comfort loss regarding the decreased room temperature.

On the other hand, the control of the space heating loads can give significant reductions in the capacity-based grid tariff if the grid-supplied power is measured (and charged) at smaller intervals. For 15-minute measurements and especially 1-minute measurements, the control of space heating loads alone might provide a grid tariff reduction of respectively 13.7 % and 38.7 % with an associated acceptable loss of comfort (case 1, $P_{max} = 3750$ W).

When involving the control of PV produced energy and the scheduling of EV charging, the modelled load control managed to reduce the 1-hour CB grid tariff by over 30 %, and reduce the 1-minute CB tariff by up to 50 %. This performance was achieved by proper scheduling of the EV charging, and gives clear indications that scheduled charging can be a very efficient measure for reducing the CB grid tariff.

The involvement of the BESS was implemented with the goal of increasing the comfort level in certain high priority zones, and the simulations show that the utilization of the BESS can be inefficient if its priority threshold is not carefully set in accordance with the demand limit for the household.

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Appendix A: Simulation results

	PV	EV	Control	Pmax	LP_BESS	Income PV2Grid	1 hour MPP	1 hour CBT	15 min CBP
Scenario 1-1	0	0	0	3250	2	0	31,55	30,36	35,61
Scenario 1-2	0	0	0	3500	2	0	31,55	27,48	32,39
Scenario 1-3	0	0	0	3750	2	0	31,55	27,26	30,30
Scenario 1-4	0	0	0	4000	2	0	31,55	27,71	29,29
Scenario 1-5	0	0	0	4500	2	0	31,55	29,13	29,55
Scenario 1-6	0	0	1	3250	2	0	28,87	26,00	26,72
Scenario 1-7	0	0	1	3500	2	0	28,45	25,15	25,22
Scenario 1-8	0	0	1	3750	2	0	29,00	26,16	26,15
Scenario 1-9	0	0	1	4000	2	0	30,03	27,17	27,17
Scenario 1-10	0	0	1	4500	2	0	31,72	29,10	29,10
Scenario 2-1	1	0	0	3250	2	1,336	29,14	27,84	32,77
Scenario 2-2	1	0	0	3500	2	1,336	29,14	25,45	30,00
Scenario 2-3	1	0	0	3750	2	1,336	29,14	25,74	28,59
Scenario 2-4	1	0	1	3250	2	0,000	27,96	24,62	25,28
Scenario 2-5	1	0	1	3500	2	0,000	27,74	24,50	24,52
Scenario 2-6	1	0	1	3750	2	0,000	28,52	25,62	25,62
Scenario 3-1	1	1	0	3250	2	1,336	42,67	44,41	48,49
Scenario 3-2	1	1	0	3500	2	1,336	42,67	41,16	45,06
Scenario 3-3	1	1	0	3750	2	1,336	42,67	39,96	42,78
Scenario 3-4	1	1	0	4000	2	1,336	42,67	39,41	41,36
Scenario 3-5	1	2	1	3250	2	0	32,52	28,83	30,265
Scenario 3-6	1	2	1	3500	2	0	30,72	27	27,87
Scenario 3-7	1	2	1	3750	2	0	30,9	26,88	27,7
Scenario 3-8	1	2	1	4000	2	0	30,98	27,47	27,79
Scenario 3-9	1	2	1	3750	5	0	31,16	27,34	27,97

1 min CBP	1 hour ToU	1 hour peak [W]	15 min peak [W]	1 min peak [W]	Z1 Comfort violation	Z2 Comfort violation
49,86	46,91	4236	5420	8130	0,000	0,000
45,95	46,91	4236	5420	8130	0,000	0,000
42,70	46,91	4236	5420	8130	0,000	0,000
39,70	46,91	4236	5420	8130	0,000	0,000
35,53	46,91	4236	5420	8130	0,000	0,000
27,30	44,93	3548	4430	5588	0,999	0,681
25,40	45,40	3429	3570	4205	0,197	0,235
26,18	45,83	3553	3691	4050	0,018	0,040
27,17	46,36	3812	3930	3990	0,000	0,000
29,10	47,70	4257	4386	4480	0,000	0,000
45,78	42,65	3705	5420	8130	0,000	0,000
42,60	42,65	3705	5420	8130	0,000	0,000
39,75	42,65	3705	5420	8130	0,000	0,000
25,80	39,79	3490	3870	5544	0,875	0,690
24,60	40,72	3407	3558	3790	0,048	0,269
25,62	42,55	3570	3691	3834	0,000	0,133
59,54	45,05	7117	8400	10330	0,000	0,000
55,8	45,05	7117	8400	10330	0,000	0,000
52,35	45,05	7117	8400	10330	0,000	0,000
49,2	45,05	7117	8400	10330	0,000	0,000
30,82	42,31	4496	5093	5990	0,8749	0,75
28,03	43,12	3990	5049	5453	0,0405	0,2471
27,72	45,28	3990	5049	5450	0	0,0988
27,82	45,6	3990	5049	5420	0	0,016
27,98	43,7	4082	5049	5454	0	0,003696

Z3 Comfort violation	Grid imported energy [kWh]	BESS unused energy [Wh]
0,000	126,62	
0,000	126,62	
0,000	126,62	
0,000	126,62	
0,000	126,62	
0,999	121,75	
0,994	122,35	
0,917	123,80	
0,394	125,23	
0,016	126,00	
0,000	115,47	
0,000	115,47	
0,000	115,47	
0,999	108,10	0,000
0,784	109,56	0,0000
0,442	113,00	2510,0000
0,000	132,2	
0,000	132,2	
0,000	132,2	
0,000	132,1	
0,999	124,20	0
0,894	125,90	0,0000
0,405	129,50	830,5
0,4373	131,20	3657,00000
0,2166	128	

Jens Høen Hval

NTNU
Norwegian University of
Science and Technology