Home Energy Management System Under Power Pricing and Grid Tariffs

Controlling energy consumption for a household using EMS, power prices, and grid tariff.

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I Abstract

Energy costs are increased by, among others, the cost of regulation and distribution. *The Norwegian Water Resources and Energy Directorate* (NVE) proposes three new grid tariffs in a hearing document that should give consumers incentives on the low voltage grid economic incentives to reduce peek-consumption and reduce grid investment cost for the power grid [29]. The new advanced metering system (AMS) and Elhub system installed in 2019 also allows consumers on the low voltage grid to buy energy at prices based on the *Nord Pool* hourly power prices.

This master's thesis presents a unique energy management logic and discusses some aspects of using this decentralized energy managment system (EMS) to control electric water heater (EWH), house heating, and electric vehicle (EV) charger. The EMS control reference temperatures, and battery reference charge-states counter-cyclical and imposes a demand limit (DL).

The logic presented and calculations of its performance give impressive results where load peek for a residential house can be significantly reduced by 64.89%. Furthermore, the combined cost for grid tariff and power prices reduced by 23.55% using power prices for a Norwegian market area (NO2) for 2019 and 26.79% using a Danish market area (DK1), from the reference case to the case with the EMS, DL, and the cheapest grid tariff is chosen. This can have a substantial beneficial effect for the distribution system operator (DSO) and transmission system operator (TSO) by better exploiting the grid, and it can have a beneficial effect for the consumer in the form of lower energy costs.

The EMS logic is based on a reference curve normalized within each day and inverse proportional to power prices collected from the *Nord Pool* power market. It also has a DL, where the controlled loads are reduced to ensure the total load for the house does not exceed the DL.

The study also allows the comparison of grid tariffs and power costs for different control logic, with price example from a stable power market example, 2019 NO2 prices, and a more volatile power market, 2019 DK1 prices. This comparison shows how the relative to Danish, stable Norwegian power market and the proposed grid tariff will give more incentives to reduce power peeks (even the consumption out) than create counter-cyclical consumption.

The reduced load peak will give significantly lower grid investment cost for distribution system operators (DSO), and load shifting will allow for more intermittent, renewable energy sources to be included in the grid.

Key words: Energy management system, power prices, demand limit, demand side management.

II Preface

This report is written by Samuel Finsland Smeplass and Torstein Sperre Sundklakk, who both study renewable energy at the University of Agder. This project was chosen because of our interest in the power grid. We see this project as an excellent opportunity to learn how the power grid can be exploited in a better way and how the power prices and grid tariffs can be used to regulate the power market together with technical solutions, and benefit us, the consumers.

Energy production, export as well as power-intensive industries are all important to Norwegian industries. Stable power prices and low transmission costs will be positive for the Norwegian economy.

The project has been both exciting and educational to work with. We have gathered a lot of information on how the electricity grid is structured and measures that are done to stabilize the grid. We want to give a special thanks to professor Mohan Lal Kolhe for guidance during the project, and helping us with inspiration on how the project can be solved and executed in a good manner.

We also want to "thank" the COVID-19 for clearing our schedules and allowing us to work together throughout a worldwide pandemic. It also reduced our commute, and interference from fellow students, and other helpful resources at the university.

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Nomenclature

Abriviation

AMS	Advanced Metering System
BIPV	Building Integrated Photo-Voltaics
C	Celsius
CET	Central European Time
COP	Coefficient of Performance
DK1	Energy Prices for Western Danmark
DL	Demand Limit
DSM	Demand Side Management
DSO	Distribution System Operator
EMS	Energy Management System
EV	Electric Vehicle
EWH	Electric Water Heater
HAN	Home Area Network
NO2	Energy Prices for Southern Norway
NOK	Norwegian Krone
NS3031	Norwegian Standard 3031
NVE	Norwegian Water Resources and Energy Directorate
OCPP	Open Charge Point Protocol
PV	Photo-Voltaics
RME	Norwegian Energy Regulatory Authority
TEK	Technical Requirements
TSO	Transmission System Operator
U-value	Thermal Transmittance $[W/(m^2 * K)]$
UiA	University Of Agder
VAT	Value Added Tax
W	Watt. In this thesis often Wh/h
Wh/h	Watt Hour per Hour
WHO	World Health Organization
ZEB	Zero Emission Buildings

Symbol

ΔT_H	Temperature difference between indoor and outdoor
ΔT_{EWH}	Temperature difference between indoor temperature and the temperature inside the EWH.
$\Delta\ T_W$	Temperature difference in water
$\eta\%_H$	Heat recycling efficiency for ventilation
A_{EWH}	inside area for EWH
$A_{WindowsSouth}$	The area of the south-faced windows
$C_{02:00}$	Consumption at 02:00
$C_{03:00}$	Calculated consumption for 03:00
$C_{04:00}$	Consumption at 04:00
Cp_{Air}	Heat capacity for air
Cp_H	Heat capacity for furniture and building materials in house
Cp_{Water}	Heat capacity of water
H_{Solar}	Solar irradiation on a 90 degree surface turned south
$Insulationthickness_{EWH}$	Insulation thickness for EWH
$k_{MineralWool}$	Thermal conductivity for Mineral Wool
M_{Air}	Mass of air

M_{EWH}	Mass of water in EWH [kg]
$M_{Thermalmasses}$	Thermal storage in furniture and building materials
$P_{02:00}$	Price at 02:00
$P_{03:00}$	Calculated Price for 03:00
$P_{04:00}$	Price at 04:00
P_{Avg}	Average energy price for given day
P_{Max}	Highest energy price for given day
P_{Min}	Lowest energy price for given day
Q_{EWH}	Heat loss for EWH
$Q_{H_{Insulation}}$	Insulation/transmission losses for the house.
$Q_{H_{SolarGain}}$	Solar heat gain for house
$Q_{H_{Total}}$	Total heat loss/gain for house
$Q_{H_{Ventilation}}$	Heat loss due to ventilation system
$Q_{H_{Ventilation}}$	Ventilation losses for the house
$Q_{LossesEWH}$	Thermal losses for EWH.
$Q_{LossesH}$	Thermal losses for household, caused by temperature
$Q_{storedEWH}$	Stored energy in EWH
$Q_{StoredH}$	Stored energy in house
ACH	Hourly air exchange rate
SHGC	Solar Heat Gain Coefficient

1 Introduction

This chapter provides background knowledge that is necessary to understand the problem statement and how the project is solved.

With increased electrification, implementation of intermittent energy sources, and transfer cables to Europe, the Norwegian grid, and energy prices will become more unstable. This report's main contribution is to show that an energy management system (EMS) can move the load away from peak consumption, local and regional, with limited user notice due to thermal storage and electric vehicle (EV) charging.

The arrival of the advanced metering system (AMS) in 2019 allows utility companies to charge for electricity based on the hourly rate at *Nord Pool* together with new grid tariffs that make it more expensive to use more energy at once. It can be profitable to control energy usage and move the consumption away from peak-hours where the electricity prices are at the highest and even out the power consumption.

Most homes in Norway use electricity for house heating, heating water, and EVs are on the rise. These are the loads that an EMS can move to some degree without the consumer's notice.

The purpose of researching in engineering is to provide solutions to problems. The solution brought in this thesis is a household EMS that can save the consumer money, reduce peeks, and temporary cut loads if the grid is close to capacity.

Reduced peeks will also benefit society as fewer grid investments are needed. Reducing environmental impact per delivered unit of energy and allowing electricity to compete with other energy sources as it gets cheaper and cheaper.

The EMS designed for this task has two main objectives. The first objective for the system is the power price, to make the system as profitable for the customer as possible the *day-ahead* prices from *Nord Pool* is used as the base for when our system should use energy. When the power prices are low, the system is desired to use much energy, while the system is desired to use as little power as possible when the power prices are high. The second objective for the system is the grid tariffs, with the new grid tariffs proposed by Norwegian Water Resources and Energy Directorate (NVE). The objective here will be to reduce the grid tariff. Non of these objective should compromise consumer comfort.

NVE has proposed three different grid tariff models in February 2020, in this thesis, the three models have been compared with the excising grid tariff model to see how these models affect the economics for the EMS system. They are all three effect-based. Moreover, they are suited for different applications.

1.1 Problem Statement

With new upcoming tariffs and the flexibility market arriving, household customers will use equipment for controlling consumption. Control can then be automated so that the customer achieves acceptable comfort at the lowest possible price.

This master thesis develops a control mechanism, an EMS, that uses a combination of *load shifting* and *peak clipping* to reduce load peaks and reduces the expenses for both the consumer and the distribution system operator (DSO). Furthermore, the thesis analyses the control mechanism's ability to save on energy prices and the proposed tariffs.

The main tasks for this master thesis are:

- Investigate how thermal loads and batteries can be used to store energy and contribute in load shifting.
- Comparing the different suggested grid tariff models from NVE, and come with a suggestion on how further grid tariffs should be formed.

The EMS developed in this thesis should:

- Shift loads to reduce power cost for consumers.
- Shift loads to reduce grid tariff and peek-loads.
- In little or no extend change habits or demand planning from the consumer.
- In little or no extent, reduce user comfort or ability for the consumer to use electric power.

1.2 Plans that Could not be Competed

Initially, the plan was to test the EMS system at the laboratory at *University of Agder* (UiA), with a different price generated pattern and a random water consumption pattern to see if the system works in practice or if it is only working theoretically. Another purpose of the testing was to see how realistic our *Matlab* simulation models are. The outbreak of COVID-19 made the testing not possible at the time of writing. The verification of the models is encouraged.

1.3 Methodology

During this project, we used the Kanban methodology. It is a framework for projects demanding flexibility and performed by small teams. It visualizes and limits the number of tasks that we work on at a given time [5]. We performed this by writing tasks on notes and placing the task on sheets market to do, doing, and done. This methodology gave us an oversight over tasks we needed to focus on and also motivation as the list of completed tasks grew.

1.4 Mathematical Model

In order to analyze and study the effect of grid tariff and the EMS, we constructed a mathematical model of a house with electric heating, an EV charger, and an electric water heater (EWH).

The goal is to numerically calculate temperatures, the charge-state at every hour, and the control system's response. As each calculation is performed in the correct order, it mimics the system's response. For example, if the demand limit (DL) reduces power to the heating, the temperature for the next hour will be lower; therefore, the power demand that hour higher. This will give an insight into the behavior of the system.

The quality of the temperature and charge state calculation will affect the results accuracy on both total energy used, momentarily power consumption, costs, storage, and grid tariffs. It is therefore important to give accurate models for losses, uses, and thermal masses.

1.5 Buildup of the Norwegian Electricity Grid

The electricity grid is the connection between the power producers and consumers. Electricity production often takes place far away from where the consumption is. The power is transformed into high-voltage to reduce losses due to resistance in electricity lines between consumers and producers. When the power is at the consummation places, it is transformed into lower voltages again so that the power can be used where the consummation takes place.

The Norwegian electricity grid is build up by three different grid levels. It is the transmission grid that is operated by the transmission system operator (TSO) in Norway *Statnett*. The transmission grid connects the producers and consumers in a nationwide system. The transmission grid has a high voltage usually between 300 and 420 kV, but in certain parts of the country the line also carrying Voltages at 132 kV [9].

The regional grid often connects the transmission grid to the distribution grid, and may also include the production and consumption of higher voltages. The regional grid carries a voltage between 33 and 132 kV and is operated by the DSO [9].

The distribution grid consists of the local electricity grid that supplies the power to the smaller end users. The distribution grid carries voltage up to 22 kV and divides into high and low voltage segments. The dividing between the two segments is at 1 kV, and the distribution to the ordinary customer usually carries between 230 and 400 V. The distribution grid is like the regional grid operated by the DSO [9].

Larger electricity producers and consumers connect to the transmission or regional grid, typically large industries and power producers like hydropower stations and metal smelters and electrolysis plants. Small-scale consumers like households, service industries, and small-scale manufacturers usually connect to the distribution grid [9].

1.6 Power Exchange Plans for the European Network

The exchange capacity between Norway and the rest of Europe is at 6 200 MW. By the end of March 2021, a new exchange cable has been planned between Norway and Germany to be operational. This cable is called *Nordlink* and will increase the exchange capacity by 1 400 MW [20]. According to analysts, the exchange cables are going to provide higher power prices in Norway [30]. This cable is going to affect the Norwegian power prices because Norway will be able to by power when it is cheap and then sell it again when it is more expensive. This is because many of the Norwegian hydropower plants can be operated as both a generator and a pump. When the power prices are high, Norway can produce and export power, and when the power prices are low, Norway can import and use energy to pump water into higher reservoirs [14]. This connection will be beneficial for both Norway, and the rest of Europe since Norway can profit from the variation in power prices. At the same time, Germany and the other central European countries get a more stable power grid. They will be able to include more intermittent renewable energy sources in the grid.

In figure 1 obtained from *Energy Facts Norway*, it is clear that *Nordlink* labeled as "NO-DE". *Nordlink* is the first among many coming power exchange cables, by the end of 2025. It has a planned capacity of close to 14 000 MW [9]. With this in mind, an EMS will most likely have more significant economic benefits in the future. This because of the variation in electricity prices.

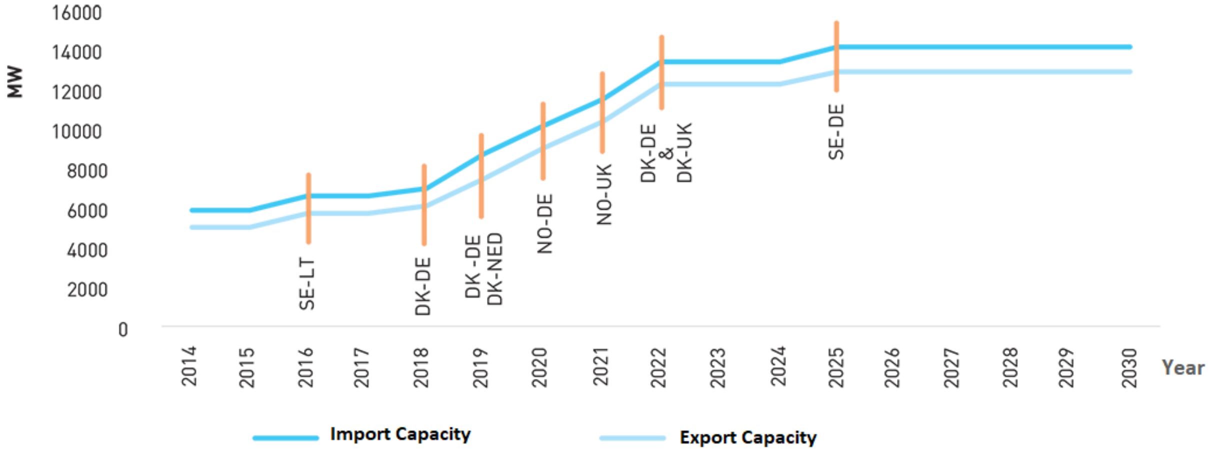

Figure 1: Planned import and export capacity for Norway [9].

1.7 Load Demand for Norway

The electric load demand is going to change in the future. More than half of the vehicles sold today are electric. The Norwegian government has a goal that by 2025 all of the vehicles sold are going to be emission-free. After that, it is just a question of time before most of the cars on the road is electric. This will lead to higher energy consumption among Norwegian consumers [7]. In figure 2, the average energy consumption for Norway in January 2020 is collected from *Statnett* and shown [36]. As the graph shows, there is low energy consumption during the night, which is stable at around 16 000 MWh/h. During the day, it is two energy peaks, one at 10:00 at around 19 000 MWh/h and one energy peak at 17:00 at 19 350 MWh/h. The highest consumption at 17:00, it can be problematic when the Norwegian car park is being electrified. With more EVs connected to the grid, the consumption-peak at 17:00 are going to be even higher if people are going to charge the EV when they come home from work [7]. This report is studying how an EMS system can avoid charging and usage of electricity during the load-peak hours, and instead use more energy during the off-peak hours.

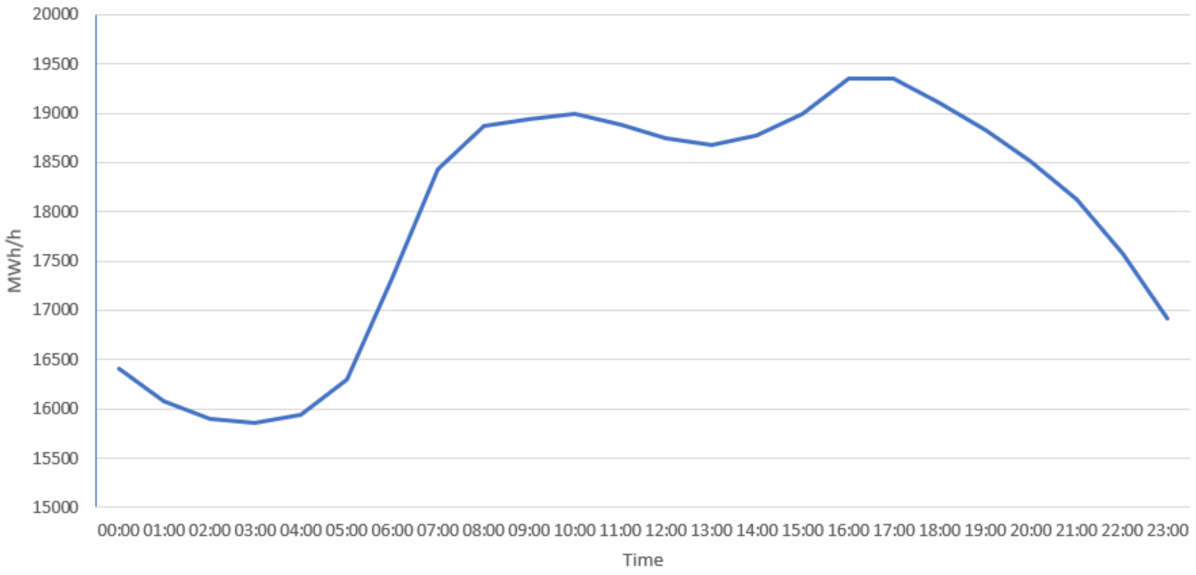

Figure 2: Average hourly power consumption for Norway in January 2020 [36].

As the grid must be built to withstand peek-consumption, it has unused potential whenever consumption is under the peek.

1.8 Demand Side Management

There is some commonly used demand side management (DSM) techniques that can lower the electricity demand during peak hours. The most relevant techniques are described below.

- **Valley filling** is one of the possible DSM methods that can be used to lower the peak consumption. By using this method, it can be achieved a greater load factor at the times when the energy demand is low. This can be achieved by encouraging the customer to use more energy during off-peak hours with cheaper energy. This way, the power suppliers can increase their profit and taking a bigger advantage of the grid. While the customer can benefit from cheaper energy prices in periods when the grid has more capacity [13].

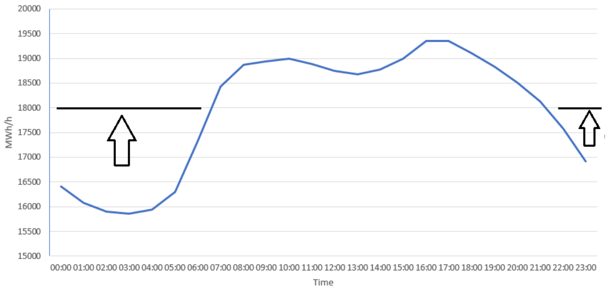

Figure 3: Valley filling

- **Peak clipping** is a measure to decrease the demand during peak hours. This is a measure more common in developing countries, and in countries where there is problems with transmission and generation capacities [13].

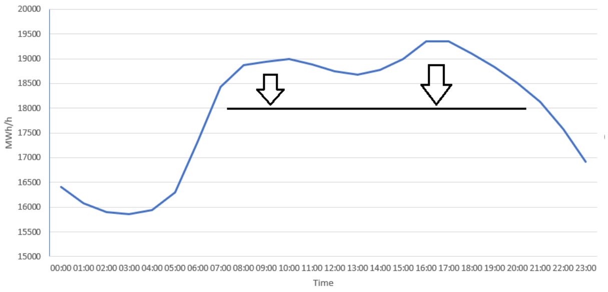

Figure 4: Peak clipping.

- **Load shifting** Is the best solution for the TSO and DSOs. This technique shifts the load from on-peak to off-peak periods without affecting the total load demand. The customers can be encouraged to use more power during off-peak hours by lower power prices. They can be compensated for having loads that can be disconnected during periods when the transmission system is close to its capacity [13].

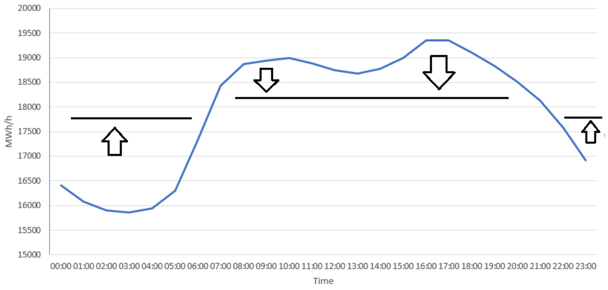

Figure 5: Load shifting.

1.9 Centralized and Decentralized Approach

There are two types of approaches that can stabilize the power grid. There is a centralized approach, and there is a decentralized approach. On the centralized approach, the TSO or DSO takes actions to adjust the power production or consumption to stabilize the grid. In the decentralized approach, the consumer stabilizes the local grid by adjusting their production or consumption. The decentralized approach can be made by using different DSM techniques for consumers.

The method described in this report is decentralized as the DL, and control systems depend on local input from HAN port (Home Area Network), and temperatures.

1.10 Nord Pool Energy Market

Nord Pool is Europe's leading power market [24]. The power market is an international market based on the requirements of the users and producers. Around 70% of the Norwegian power is traded in *Nord Pool* markets. *Nord Pool* offers trading, clearing, settlement and associated services in the *day-ahead* and *intraday* market. *Nord Pool* is established in nine European countries, and is a collaboration between Nordic and Baltic TSOs *Statnett SF*, *Svenska Kraftnät*, *Fingrid Oyj*, *Energinet.dk*, *Elering*, *Litgrid* and *Augstsprieguma tikls*. *Nord Pool* is licensed by NVE to organize and operate a market place for trading power [24]. Power suppliers buy power from the power producers at the lowest cost possible, before they sell the power to the end-user through different deals. The average purchase price on *Nord Pool* works as a reference price for the financial power trading in the Nordic region and as a reference for the other power market [39].

1.10.1 Day-ahead Market

In *Nord Pool*, the *day-ahead* market customers can sell or buy energy for the next day in a closed auction. Here the orders are matched to maximize social welfare while taking network constraints that are provided by the TSO into consideration. The *day-ahead* market has proven its efficiency by delivering a trusted market, which sets bidding zone prices for each hour the following day. Each day at 10:00 Central European Time (CET) the available capacities on interconnectors in the grid are published. After that, buyers and sellers then have until 12:00 CET to submit their final offer to *Nord Pool*, for the delivery hours the next day. The submitted orders are matched with other orders in the pan-European market coupling process, the *Single Day-Ahead* Coupling (SDAC), through an algorithm called *Euphemia*. The single price for each hour is set in the matching process, where the selling and buying price meets while taking the network constraints into account. Hourly clearing prices are typically announced at 12:42 CET or later [25]. The results from the *day-ahead* market are used as the foundation for *Statnetts* planning and maintaining of the momentary power balance for the following day [8].

1.10.2 Intraday Market

As the *day-ahead* prices are not 100% precise when it comes to the prediction of consumption and production, the *intraday* market is used to balance and trade energy even closer to the physical energy transfer point. The *intraday* market capacities are provided and updated by the TSO, based on the *day-ahead* market, volumes, and directions of trade. The *intraday* market allow trade until one hour before physical delivery [27] .

1.11 Electricity Prices and Consumption

The average power prices for the *region of Southern Norway* (NO2) was downloaded from *Nord Pool* for January 2020 [26]. The prices are collected in Norwegian Krone (NOK). As seen in figure 6 both the prices, and the consumption does have a peek at 09:00 and 17:00, while both the prices and consumption is lower during the night. The energy prices do have a peek around 09:00 at 251.31 NOK/MWh and 17:00 at 256.79 NOK/MWH. The energy prices are lower during the nights around at around 230 NOK/MWh.

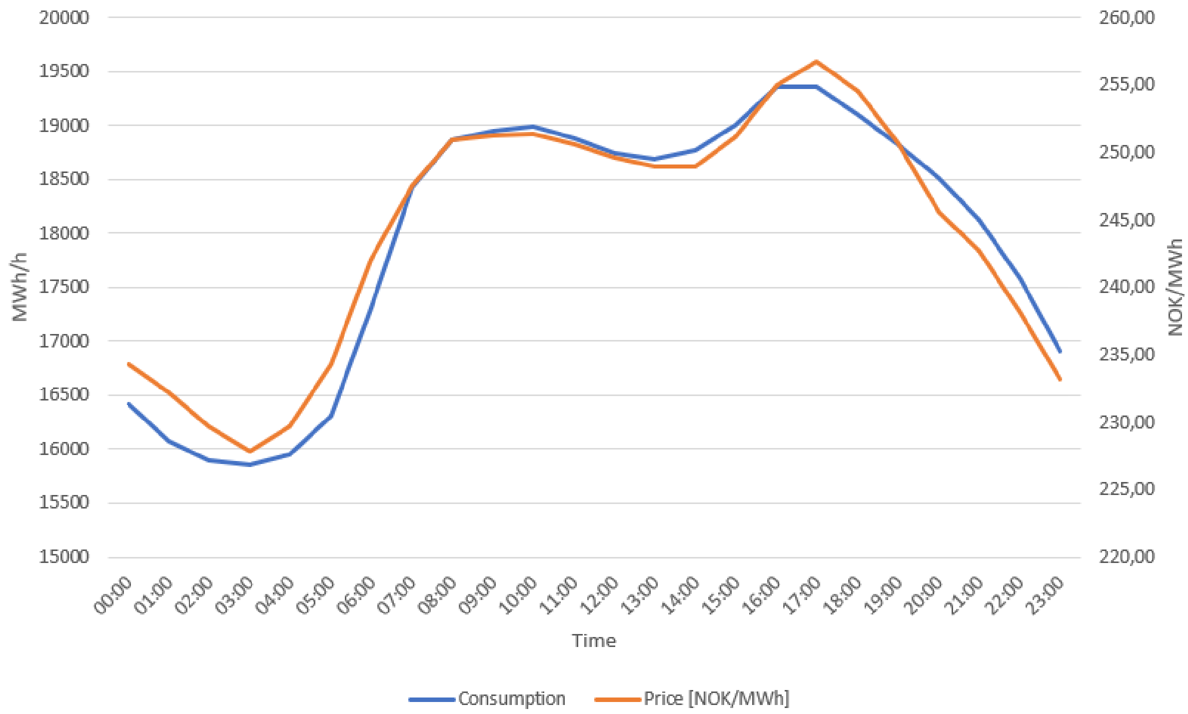

Figure 6: Consumption and power prices for Kristiansand January 2020 [36][26].

It is a strong correlation between the consumption and pricing in the energy market in Norway. Consumption during January for Norway varies with 22% between the highest and lowest consumption, while the price varies with 12.7%. In the section "*2.9 Correlation Between Consummation and Power Prices*" in this report, the correlation between the prices and consumption will be studied closer.

1.12 Communication Between EMS and Day-ahead Prices

NVE decided that before 2019 all Norwegian homes should have an AMS installed in their homes. All of these AMS power meters have an HAN-port. This port can be opened if the consumer contacts the DSO. The data collected from this port is the customer's property, and therefore the grid operator or any third party needs to make a deal with the consumer if they want to use the data [12]. In figure 7, the HAN-port is is market with a red circle on an AMS from *Kamstrup*.

Figure 7: The HAN-port market with a red circle on an AMS from *Kamstrup*.

The HAN-port makes it possible to track the consumption and other related parameters associated with the consumption. If the customer produces energy for themselves it is possible to track their energy production trough this port. For example; if the customer produces power from photovoltaic (PV) [12]. With an EMS, devises as EWH, house heating and EV-charger can be coordinated with the data from the HAN-port to reduce consumption during peak periods with high power prices.

The AMS registers time values and gives the system possibilities for both local and central load management. The local load management opens up for the customer to program and manage the electrical gadgets in their own home to turn on or off themselves. This also gives opportunities for programming and management of the consumption according to the power prices and transmission tariffs.

1.13 Grid Balancing Mechanisms

The main grid balancing mechanisms are also trading commodities that can be parted in their respective markets. The *day-ahead* market from *Nord Pool* meant to meet the supply and demand in wholesale throughout the day. The *day-ahead* market gives a good indication of energy consumption and how much energy needs to be produced throughout the day [25]. The *intraday* market adjusts for changes as close as one hour before the physical delivery of power [27].

1.13.1 Power Regulation

The primary power regulation is connected to automatic controls to ensure that grid frequency is between 49.9 Hz and 50.1 Hz [35]. When the primary power regulation has achieved the wanted frequency, it is relieved off duty by the secondary power regulation which is activated after two minutes. The secondary power regulation is meant to bring the frequency to 50 Hz [32]. The tertiary power regulation is manually reserves that have an activation time of up to 15 minutes [37]. Large scale implementation of EMS allows consumers to participate in power regulation, and power producers to free capacity for regulation.

1.14 Literature Review

There has been done much research on using EMS to manage energy consumption. Many of the relevant articles that have been read are from the UiA, but there have been lots of research from other universities as well. This is a subject where many are competing to have the best possible solution. Although most of the solutions are different from ours, it was good to get some knowledge on the research done on the subject, to understand how this article could bring new solutions to the market.

1.14.1 Home Energy Management System

In the master thesis from UiA, written by Muhandiram Arachchige Tharangi Irahika (2014), it was done work to see how much of a load of during on-peak hours that could be moved away from the on-peak hours with price as reference. The difference between that study and this one is that the prices were not based on the *day-ahead* market, but by a more general price pattern. In that study, the EMS was controlled by a DL. The DL was based on which hours during the day that the energy prices usually are higher. So that project used peak-clipping as DSM while in this project, the DSM used is a combination between valley filling and peak-clipping. Another difference between that and our project is that that project is based on average historical prices and climate in Iowa in the USA, where there are bigger price variations and a hotter climate than in Southern Norway [21]. The EMS programmed in that master thesis was based on a daily price pattern. This means that if the prices behave differently a given day, the EMS would not be able to take advantage of the electricity prices. In that thesis, it was found that the peak load demand could be reduced from 15.452 kW to 8.152 kW, and the cost savings could be 34.77% with a simple EMS system [21].

1.14.2 System design for a solar-powered thermal storage – to obtain reduction of demand-side power peaks

In the master thesis written by Anders Angeltveit Lie (2019) at UiA, a lot of testing was done to test how an EWH can be used as thermal storage for a PV system. In that project, it was developed and used a load controller to store self-produced energy. Our project has chosen to use as little energy as possible during the hours with high energy prices. In that thesis, the temperature in the EWH depends on the irradiation on the solar panel. In our project, the temperature in the EWH depends more on energy prices. Both of the thesis has taken data from *Nord Pool* to lower the consumption for an EWH during peak hours for the electricity grid. In our project, it was also wanted to do some testing on an EWH. That master thesis provided useful information on how the tests on for the EWH could be conducted. Although the master's thesis' are very different from each other, much of the same testing methods could be applied. The thesis also proposed how the testing could be done in a better way than the one used for the thesis. Unfortunately, testing and verification could not be completed for our project [18].

1.14.3 Smart Electric Vehicle System

In another master thesis from UiA, written by Gaute Ness (2017), it was implemented a local controller with Open Charge Point Protocol (OCPP) 1.6 to control Charge Points for EVs using a simple algorithm. The main goal of Gaute Ness's thesis was to protect the local grid so that the EV does not charge when the grid is being overloaded. To avoid overloading the local grid, the local controlling system sets a DL on how much energy can be used at once. The DL was decided though communication between the local transformer and the system. That thesis was written in cooperation with *Grønn Kontakt* and *Sharebox*. The prototype built in the project did work, but unfortunately, the local controller did not fulfill the requirements given by *Grønn Kontakt*. The system had a reaction time of 15 seconds, while a reaction time of 1 second was preferred. Even though the system did not fulfill the requirements, it seemed that this was a communication problem and not a problem with the implementation of the task [22]. That task was used to get inspiration about how DLs can be implemented in a power system to take better advantage of the excising power grid. Since our task has a more theoretical approach, it could not be implemented a similar system. Nevertheless, that thesis gave some interesting views on how EV charging can be implemented into the power grid [22].

1.14.4 Grid Interaction Performance Evaluation of BIPV and Analysis with Energy Storage on Distributed Network Power Management

In that doctoral dissertation written by Aimie Nazim Azim (2017) at UiA, the behavior of building integrated photovoltaic (BIPV) is analyzed in a smart grid environment. The system's application is meant to be a part of a solution for large-scale handling deployment of grid-connected distributed generators, especially PV systems. The main objective of that dissertation was to evaluate the usefulness of Zero-emission buildings (ZEBs) for load matching with BIPV generation profiles and grid interaction analysis. The real operational result of a year was analyzed for annual energy balance with on-site BIPV generation and local load [3]. Both our thesis and the doctoral dissertation focus on how a household can help stabilize the power grid when the grid gets smarter. Both of the projects uses data from Southern Norway, but the tasks focus on different ways that DSM techniques can be used.

1.14.5 Electricity price forecasting: A review of the state-of-art with a look into the future

In the report from Rafał Weron (2014), different electricity price prediction methods are explained. The work also goes through the pros and cons of the different methods. This article does not go through how an EMS should be built up, but it was beneficial to understand how the different price prediction methods work. This was especially useful for artificial intelligence models. That report brought useful information to get a general understanding of how the prices in the *Nord Pools day-ahead* market are decided [41].

1.14.6 Flexibility in the Nordic power market

Statnett wrote the report in January 2018. The report discusses the different ways the Nordic power market are going to respond when new nonadjustable renewable power sources are being connected to the Nordic grid. It is being studied how different solutions for power regulation can balance the grid towards 2040, both from the consumer and the TSO side. The report points out that there are considerable economic benefits by being able to adjust consumption. The report also points out that with the AMS power meter and smart technology, households can move parts of the consumption without affecting the user comfort. Households and commercial building together can give a significant contribution to flatten the energy prices in periods with excess or lack of production [33].

Our study aims to assess further how load-shifting can benefit the consumer and how the proposed grid tariffs affect consumers and load shifting. Therefore the report from Statnett, brought lots of useful information of how the EMS system could be implemented.

2 Power Intensive Domestic Load for Demand Side Management

An EMS is a control system that controls the power consumption. For this thesis, an EMS is used to move load from peak hours where the electric power is expensive, and the grid is close to its capacity to hours where the electric power is cheap, and the grid has more capacity available. See bullet point *load shifting* in section *"1.8 Demand Side Management"*.

This section will provide different assumptions made for the EMS system simulations in this thesis. Here we will go through how the energy prices were used as a base to control the EMS system and how the EWH, house heating, and EV charging models can store energy during periods with higher electricity prices.

2.1 Electric Water Heater

For the EWH, it is possible to control the heating element based on energy prices. It has a higher reference temperature inside the EWH when the energy prices are low, and a lower reference temperature when the prices are high. And otherwise use the same control mechanism (thermostat) as usual.

2.1.1 Stored Energy Electric Water Heater

EWHs have a high nominal rated power and large thermal storage capacity. Depending on the type of EHW and use, it is suitable to heat water and stores energy until use several hours later. This can be used to move the electricity consumption from the EWH away from peak hours. The formula for the thermal energy stored in the EWH is shown in equation 1.

$$Q_{StoredEWH} = Cp_{Water} \Delta T_W \times M_{EWH} - Q_{LossesEWH} \tag{1}$$

- $Q_{storedEWH}$: Stored energy in EWH.
- Cp_{Water} : Heat capacity of water (4.2 kJ/kg).
- $\Delta\ T_W$: Temperature difference in water °C.
- M_{EWH} : Mass of water in EWH [kg].

- $Q_{LossesEWH}$: Thermal losses for the EWH.

The thermal losses of the EWH also depend on the temperature in the EWH. During periods with higher temperatures, it is a higher thermal loss for the EWH. How the thermal losses for the EWH are calculated is shown in section *"3.8 Electric Water Heater and Losses"* of the report.

2.1.2 Hot Water Consumption

In a report written by *Energy Monitoring Company* on behalf of *the Energy Saving Trust* called *"Measurement of Domestic Hot Water Consumption in Dwelling"* in the United Kingdom [10]. It was an experiment done on 124 houses to collect the average hot water usage for a house. Of the 124 households that participated in the project, 112 of the households had analytical data. Among those 112 participants, 68 were regular boilers. The data from the regular boilers are used as a base for water usage in this project. The project shows that an average household uses 122 liters of hot water, with a 95% interval of ±18 liters each day. The average delivery temperature for the regular water heaters was found to be 52.9°C [10]. The hot water profile for one typical dwelling in the study is shown in figure 8. Here the total hot water consumption for the given household had a total hot water consumption of 202 liters each day. Even though this is high hot water consumption according to the study, this hot water usage is close to the average for a Nordic country of 190 L. [11]

Figure 8 shows that there is a peak in the hot water usage between 07:00 and 09:00, and at 17:00 when people come home from work. Both of these peak periods are when the grid is at high capacity. It is clear that if the water heater heats the water at the time of consumption, the power consumption comes at the same time as the excising peaks for the power grid. The power consumption for heating of the water can be improved. This has some similarities with the price and power consumption curves in figure 6 in section *"1.11 Electricity Prices and Consumption"*.

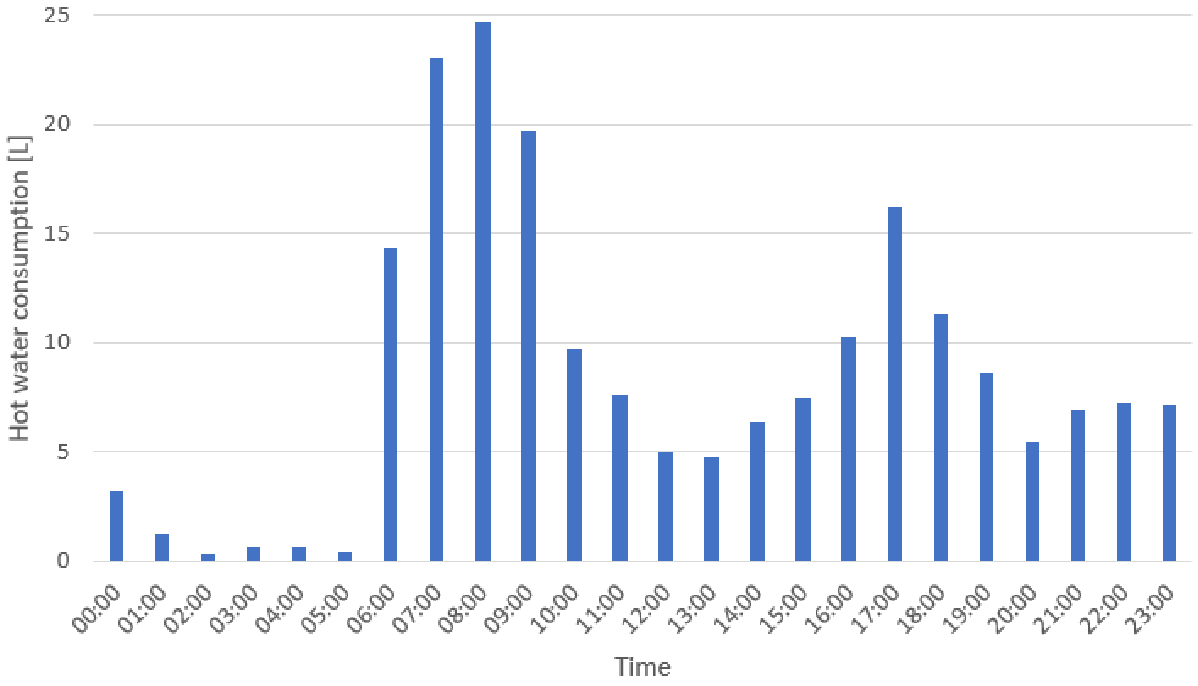

Figure 8: Hot water usage for a dwelling [10].

2.2 House Heating

For the house heating, it is also possible to control the heating based on energy prices. This is done with high reference temperature when the energy prices are low. And lower reference temperature when the energy prices are high.

2.2.1 Stored Energy House

It is possible to store thermal energy in space heating. Therefore it is also possible to store some thermal energy depending on the energy prices. Thermal energy can be stored both trough air, furniture, and building materials. The amount of possible thermal energy stored in the house is shown in equation 2.

$$Q_{StoredH} = \Delta T_H \times Cp_{Air} \times M_{Air} + \Delta T_H \times Cp_H \times M_{ThermalMasses} - Q_{LossesH} \tag{2}$$

- $Q_{StoredH}$: Stored energy in the house

- ΔT_H : Temperature difference between indoor and outdoor temperature °C.
- Cp_{Air} : Heat capacity of air (1 kj/kg)
- M_{Air} : Mass of air in kg.(1.225 kg/m^2)
- Cp_H : Heat capacity for furniture and building materials in house.
- $M_{Thermalmasses}$: Thermal storage in furniture and building materials.
- $Q_{LossesH}$: Thermal losses for the household, caused by temperature differences between indoor and outdoor temperatures.

The thermal losses for the EWH depending on the indoor and outdoor temperatures. How the thermal losses for the household are calculated is shown in section "*3.9 House Heating and Losses*" of the report.

2.3 Electric Vehicle

As the battery of an electric vehicle works as energy storage, it is possible to charge the EV as much as possible during periods when the energy prices are lower.

Another possibility is like in the thesis by Gaute Ness (2017), to restrict the EV charger when other components have high loads, and in that way limit the total loads [22]. See section *"1.14.3 Smart Electric Vehicle System"* .

2.3.1 Stored Energy Electric Vehicle

For the daily driving pattern, a modern EV exploits little of the installed battery capacity. In NVEs report on the grid tariffs, an EV is assumed to use 50 kWh of electricity each week [29]. This corresponds to 7.14 kWh each day. A new Nissan Leaf has a gross battery capacity of 62 kWh among with many other EV [23]. This means that the EV only uses 11.5% of the gross battery capacity for every day driving. If the car battery is not fully charged each day, it is not a problem during normal conditions as long as the electric car battery is over a minimum charge state each day.

2.4 Substations

When an EMS moves loads away from peek-hours, it might locally create a new and potential higher peek. If the implementation of such a system is unevenly or the control mechanism does not have any functions to prevent this, it can cause a problem locally. With proposed grid tariffs from NVE, it would be more profitable to distribute the energy usage throughout the day, as they are based on the highest power consumption. This will not remove the energy peaks altogether, but hopefully, it helps to exploit the grid in a better way, and this way saves money by not having to upgrade the grid. With an EMS system, it would be possible to even out the energy peaks without affecting the consumers by moving the load demand from devices which can store energy over time. NVE specified in the hearing document, an interest in time-of-use tariffs and if they can be used to exploit the grid in a better way. Using time-of-use tariffs makes it possible to adjust the power tariffs after how loaded the grid is at certain times—making it easier to use more power during periods when the grid has surplus capacity without making a significant impact on the grid tariffs.

2.5 Energy Pricing System

Since the peak hours can vary during the day, especially when it is being connected to new renewable energy sources to the grid, the system needs to communicate with the energy prices provided in *Nord Pools day-ahead* market, either way, which solution that is chosen. This is because energy production is going to vary during the day, and the price peaks are not necessary at the same time as the consumption peak. It is wanted that the EMS manages to use as little power as possible during the on-peak hours. For the system to use little energy during peak hours, the system needs to use more energy before and after the energy peaks. That is done by controlling different components that can be used as energy storage, to store the energy from periods with lower energy prices and then using the stored energy when the prices are higher. This thesis takes a closer look at how an EMS could affect the energy usage for the consumer without affecting the user comfort.

Electricity prices are based on many different factors; weather is one crucial factor when it comes to temperature, wind, rainfall, and solar conditions. The weather is an essential factor when it comes to both production and energy consumption. The highest energy consumption for Norway comes during the coldest days in winter; the energy prices are also higher during the winter than during the summer.

2.6 Grid Tariff

The grid tariff are approximately one-third of the electricity bill for most households, as one third is power prices, and one third is taxes and fees. When the consumer uses electricity, they pay for two different products. They pay for the power that they buy from the electricity provider, and they pay grid tariff that include taxes to the DSO. The grid tariffs go to operating and maintaining the power grid effectively and safely; mainly, the grid tariffs are used to maintain and upgrade the excising grid. The grid tariff also include Value Added Tax (VAT) and payments to the energy fond in Norway called *Enova*. The operation of the grid costs almost the same regardless if it is being transported much or little energy. It is the grid's upgrading cost when the grid is near its capacity, which is the greatest cost [1].

Today the grid tariff consist of a fixed link and an energy link. The fixed link is how much it costs to be connected to the grid, regardless of how much energy is used. The energy link is decided by how much energy that has been used during the month. This tariff do not take the maximum energy drawn from the grid at once into account. This means that the grid tariff used today do not represent the grid costs.

2.7 Grid Tariffs for EMS

In February of 2020 *Norwegian Energy Regulatory Authority* (RME), which is a subdivision of NVE, suggested three new grid tariffs models. These are formulated to represent grid maintenance, operation, and investment cost better than the model today, but still not discriminate consumers in the low voltage grid within one region.

If grid tariffs represent cost, the socioeconomically beneficial option for grid investment, or energy management, will also be the consumers' economical choice. However, if consumers are to act upon economic incentives, it needs to be comprehensive or automated.

2.7.1 New Regulation for Grid Tariffs

RME is proposing new regulations for the DSO to calculate grid tariffs on low voltage distribution. Grid maintenance and investment costs are approximately 90% due to installed capacity and 10% due to use or energy transmitted through. With the AMS meters and Elhub newly installed, a pricing model that better represents grid costs can be put in place. Not only to more accurately price the service that is provided, but also to give consumers price-signals and incentives so that the DSO can avoid and delay investments associated to capacity.

NVE states that spot-prices are not good indicators for grid use alone as they do follow not only demand but also production availability [29]. With more incentives to load-shift, new demand peeks can occur, especially in local areas. NVE further states that proposals for new grid tariffs should avoid new demand peeks, like the ones time-of-use prices may lead to. NVE propose three models for grid tariffs:

- **Subscribed-effect tariff:** The energy part of grid tariff has one value when use is below the agreed value with DSO and a higher value when the power consumption is above the agreed value. See figure 9 [29].

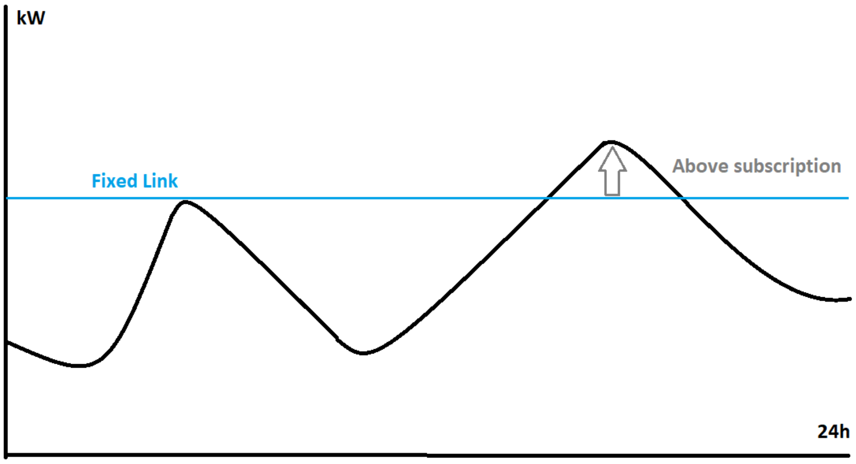

Figure 9: Subscribed-effect tariff.

- **Measured-effect:** The daily maximum measured energy consumption over one hour sets the grid tariff for that day. See figure 10 [29].

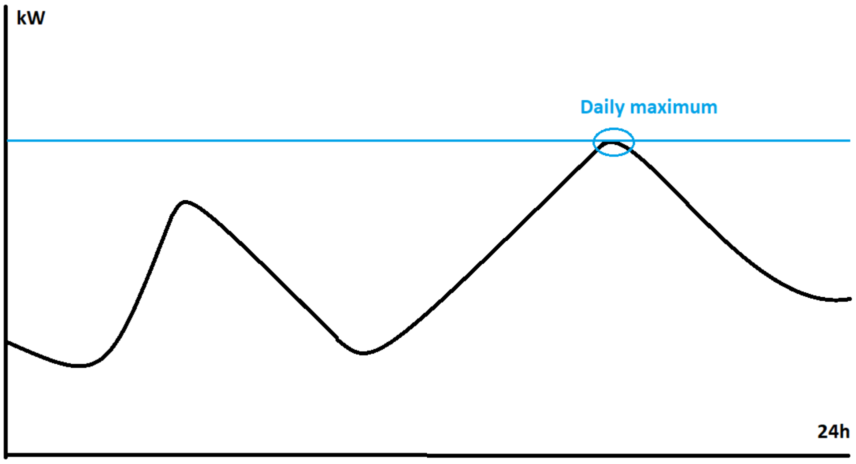

Figure 10: Measured-effect tariff.

- **Capacity-limit:** The consumer will not be able to draw more energy than the installed main fuse for the household, and pay tariff based on the installed fuse capacity for the building. See figure 11 [29].

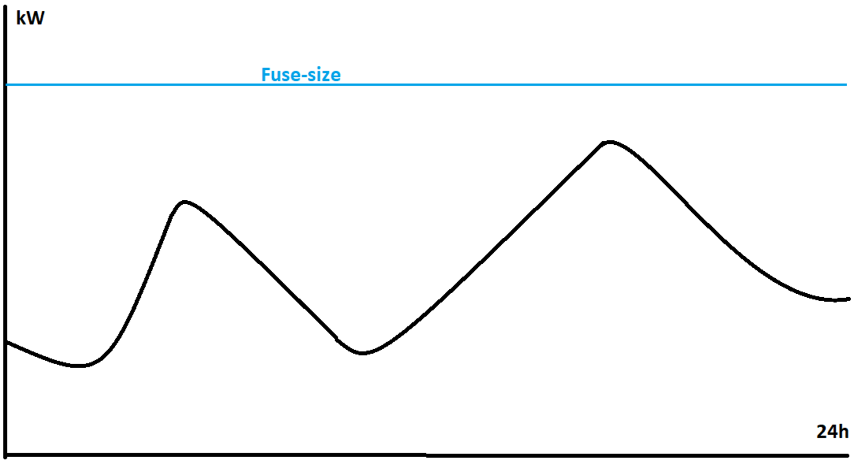

Figure 11: Capacity-limit tariff.

In table 1, the four different grid tariffs are described. For all the price calculations for in this thesis Norwegian Krones (NOK) is used as currency. In the Measured-effect tariff, the winter period is defined to be between the 1st of November to 31th March, while the rest of the year is calculated with summer tariff. It can be observed that all of the new grid tariff suggestions encourage to not use a lot of energy at the same time [29].

Table 1: Grid tariff calculations, with the different components.

	Energy price [NOK/kWh]	**Power premium [NOK/kWh/h]**	**Fixed link [NOK/year]**
Present tariff	0.1859		2046
Subscribeds-effect	0.05	1.00	1350 + 675 per kWh/h
Meassured-effect	0.05	1.49 kWh/h (summer) 2.25 kWh/h (winter)	1850
Capacity-limit	0.05		1750 + 343 per kWh/h

These different grid tariff suggestions is used for further calculations for combined energy cost of grid tariffs and power prices without taxes. These are implemented in the simulations, and in the process of choosing a DL. The value of the different components are suggested by NVE to give incentives to avoid high hourly power consumption, but also be similar in total cost for the average consumer to the grid tariff model used today.

2.7.2 No Local Price Discrimination

In their hearing-document, NVE avoided price examples that connected grid tariffs to the local sub-station/transformer. This to avoid price discrimination from prioritized neighborhoods and price models that incentives reduced capacities in certain areas.

2.8 Grid Load

NVE Ordered a study that were performed by *DNV GL* and *Pöyry Management Consulting* concerning future grid capacity requirements with EV charging [7]. They found that control systems that change charging times of EV's away from peeking consumption reduce investment and upgrading cost for grid infrastructure. They analyzed grid investment for four different EV-charging scenarios in the year 2040, assuming that almost every car is an EV.

DNV GL's study shows that national investments in new substations will be neglectable if charging mainly occurs during off-peak hours. Furthermore, that investments are directly connected to peek values for an area [7].

2.9 Correlation Between Consummation and Power Prices

Correlation between two data sets can be calculated using the data sets as arrays in Matlab. The data sets must govern the same time and number of entries. See section *"3.2 Summer and Winter Time Correlations"*.

The correlation between the consummation and the energy prices has been studied closer. The energy prices for NO2 in the entire 2019 has been downloaded from *Nord Pool* [26]. Then the energy production for NO2 for 2019 was collected from *Statnett* [34]. There was then done a correlation analysis in *Matlab* to check the correlation between these two variables. In figure 12 it can be seen that there is a high correlation between these two factors. With a correlation at 0.7443 between the consummation and prices for the NO2 market, it can be concluded that these two factors are dependent on each other.

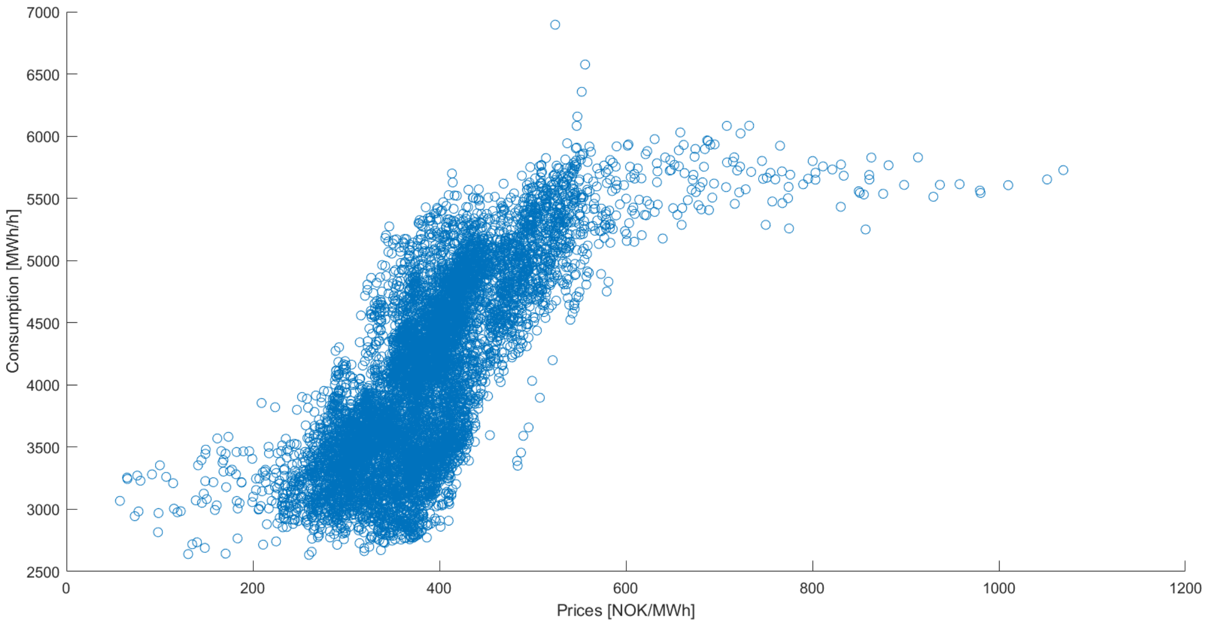

Figure 12: Correlation consummation and energy prices in Kristiansand at 0.7443.

In addition to doing a correlation study for the consumption and energy prices in NOK, it was also done a correlation study in euro/MWh. The correlation study found a correlation of 0.7235, which is lower than the correlation between NOK and consumption. The reason for a higher correlation between NOK and consumption is likely because most of the buyers in the Norwegian power market are using NOK as currency. The difference is small.

The electricity production will vary more during the day because it is being connected more unpredictable renewable energy into the grid. There has been a correlation study in a country with more wind energy in the energy mix to see how dependent price and consumption are going to be in a future scenario. In figure 13, the correlation between consumption and energy prices in the *region of Western Denmark* (DK1) is shown. In this area, the correlation is calculated to be 0.5264. This correlation is lower than the correlation in the Norwegian market, which means that the energy prices in Denmark are less dependent on the consummation.

A price dependent EMS would, therefore, in Denmark tend to use energy when the wind blows, while similar EMS in Norway would tend to level out consumption.

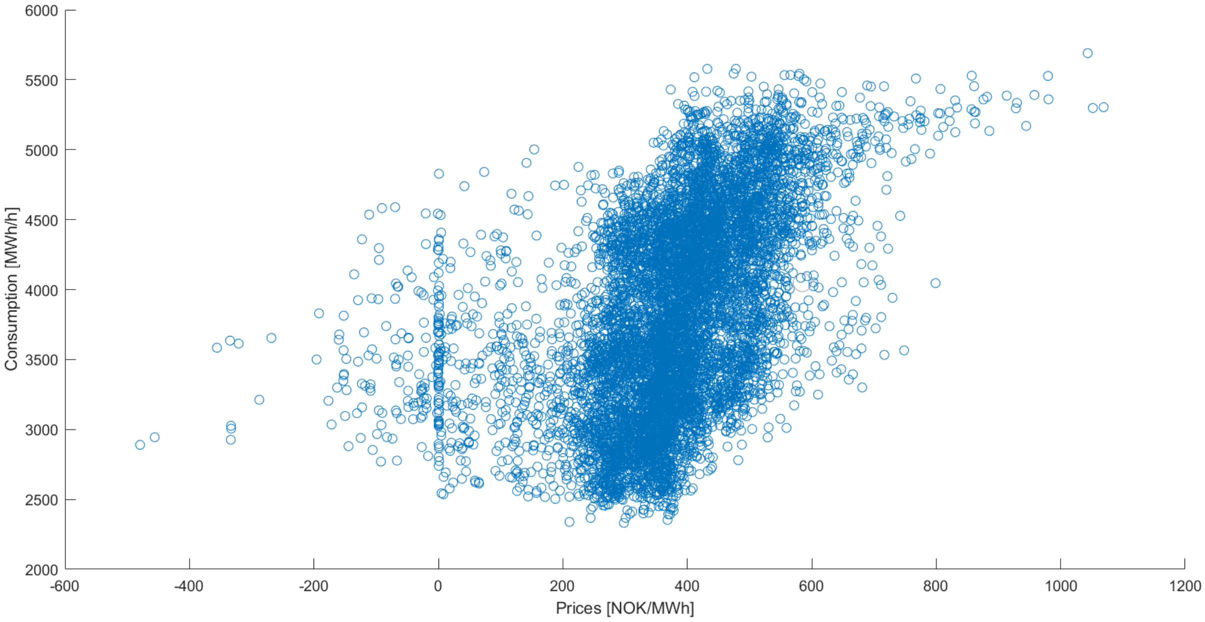

Figure 13: Correlation between consummation and energy prices in Western Denmark of 0.5264.

By comparing the prices for NO2 with the hours of the highest power consumption. It was found that between 11:00 and 12:00 at the 5th of February, energy consumption was recorded at 6896 MWh. This is the highest power consumption recorded for NO2 during the year. The power price for the given hour was at 524.14 NOK/MWh. On the 28th of July, between 05:00 and 06:00, the lowest energy consumption during the year was recorded. The electricity consumption for NO2 during this hour was recorded at 2634 MWh. The power price for this hour was recorded to be 260.09 NOK/MWh. However, the highest power price recorded during the year is at 1069.05 NOK/MWh, and the lowest electricity prices are recorded at 57.41 NOK/MWh. This tells that if many houses install EMS systems, they can help to stabilize the power prices. However, power prices depend on more than just consumption. Therefore it is hard to conclude how much the price peaks will be affected.

3 Power Intensive Domestic Loads Operation With Grid Constraints

The main objective of this thesis is not to use less energy in total, but to use less power when the energy is expensive to use and more power when the energy is cheap. This can be done by using DSM techniques. Since one of the main objectives is not to affect the consumer's user comfort, it is chosen to use a combination between *load-shifting* and *peak-clipping*. By using *load-shifting* and *peak-clipping*, electric components that store energy can be used as energy storage. So that they only use a minimum amount of energy when the electric prices are higher without creating new consumption peaks.

Using *MatLab* to build up a simulation model enables fast calculations at low cost of many scenarios with different control-parameters and price scenarios. The control system itself is not analyzed, only the behavior, as each calculation is based on the amount of energy consumed for one hour. This will give accurate grid tariff calculation as Elhub, and cost calculation is based on effect as energy per hour.

3.1 Simulation

To estimate how much load can be shifted by using economic parameters and not restraining consumer energy use, a *MatLab* model was used. The *MatLab* simulation uses price data from the NO2 zone in the *Nord Pool day-ahead* market, to calculate willingness and further on minimum temperature profiles for Southern Norway. Willingness and the process of calculating willingness are described later, in section *"3.5 Willingness"*.

The model uses matrix/arrays to match the energy, cost, heat, use, and other datasets, to the respected hour throughout the year. Simulations can be run for different periods within the year. In this study, every data set is based on arrays of 8760 hourly values. Each value's index is the specific hour where the data takes place. There is 8760 hours in a year.

Denmark is a country with a higher implementation of intermittent renewable energy sources, particularly wind energy. The European and the Norwegian energy mix, will begin to include more wind energy and connections to wind energy heavy grids. DK1 power market are used as a scenario for the direction of price behavior that the Norwegian power market might develop towards. Not saying Norwegian market prices in the near future will be like danish market prices. But they will most likely approach the danish market price pattern. Therefor both N02 and DK1 price markets for 2019 is used.

3.2 Summer and Winter Time Corrections

To make prices and consumption add up with the parameters decided in the simulation model, summer and winter time differences had to be considered. The way this was taken care of was that it was added a new value in the price and consumption script between 02:00 and 03:00 at 31 Mars, to make up for the hour that did not exist. This value was calculated as shown in equation 3 and 4.

$$C_{03:00} = \frac{C_{02:00} + C_{04:00}}{2} \tag{3}$$

$$P_{03:00} = \frac{P_{02:00} + P_{04:00}}{2} \tag{4}$$

- $C_{03:00}$: Calculated consumption for 03:00
- $C_{02:00}$: Consumption at 02:00
- $C_{04:00}$: Consumption at 04:00
- $P_{03:00}$: Calculated Price for 03:00
- $P_{02:00}$: Price at 02:00
- $P_{04:00}$: Price at 04:00

When the consumption and the price was calculated, as shown in equation 3 and 4, the price and consumption for 03:00 becomes an average between the values for 02:00 and 04:00.

Between 02:00 and 03:00 on the 27th of October, one hour has been recorded twice because of the transition between summer and winter time. The way this was taken care of was by deleting one of the hours that had been recorded twice. These measures were also done for the correlation study between consumption and price, because these scripts were built up the same way.

3.3 Design Parameters

The EMS system has different priorities that must be taken into account to preserve the consumers, DSO, and TSO interests. These criteria are essential to ensure the implementations and use of an EMS. Priorities are listed bellow as essential tasks for the EMS:

- Preserve user comfort.
- Reducing power consumption peaks.
- Avoid making new and higher consumption peaks.
- Have an economic benefit on the electricity bill. Both when it comes to electricity prices and the grid tariffs.
- Allow the energy to be stored from periods with lower electricity prices to use when the electricity prices are higher.

3.4 Control Systems

The EMS has two main tasks for this project. The first task is to have an overall smaller electricity cost. The second task is to reduce the costs for the upcoming grid tariffs, by reducing the consumption peaks. Because of these two different tasks for the EMS system, two different control system is used:

- **Price incentives control:** To reduce regional/national power peeks.
- **Power reduction:** To reduce grid capacity use.

These two control systems run on top of each other, connected in series. These control systems makes the EMS controlled devices receive energy only if both of the control systems allow it.

3.5 Willingness

As the EMS aims to save money for the consumer in terms of lower energy costs. This is done by shifting the loads away from the peak prices and shifting them towards cheaper periods without affecting the user comfort. This EMS defines reference values and allow the connected components to store thermal or other storable values. Furthermore, use less electric energy to the same sources when the cost is high.

The willingness to use energy depends on energy prices. Assuming the energy demand for a given period, one day, it is wanted to use the same amount of energy in total over that day. While within that day, when the energy prices are low, it is desired to use as much energy as possible. When the energy prices are higher, it is wanted to use as little energy as possible, without affecting the user comfort.

To calculate the willingness for a given day, the energy prices for a given day are downloaded from *Nord Pool*. Equation 5 and 6 shows how the willingness is calculated for our system with a maximum willingness of 1 and a minimum willingness of -1.

$$Willingness = \overset{if P \geq P_{Avg}}{\frac{-(P - P_{Avg})}{P_{Max} - P_{Avg}}} \tag{5}$$

$$Willingness = \overset{if P \leq P_{Avg}}{\frac{P - P_{Avg}}{P_{Min} - P_{Avg}}} \tag{6}$$

- P : Electricity price for the given hour.
- P_{Avg} : Average electricity price for the given day.
- P_{Max} : Highest electricity price for the given day.
- P_{Min} : Lowest electricity price for the given day.

Figure 14 shows how the willingness and the electricity prices for Monday the 4th of February to Sunday the 10th of February 2019. Where the willingness is market in red, and the price is blue. The figure shows that the willingness varies from -1 when the power prices are at the highest for the given day, to 1 when the power prices are at the cheapest for the given day. The prices vary between 450 NOK/MWh, and 590 NOK/MWh, where the lowest power prices usually come after midnight.

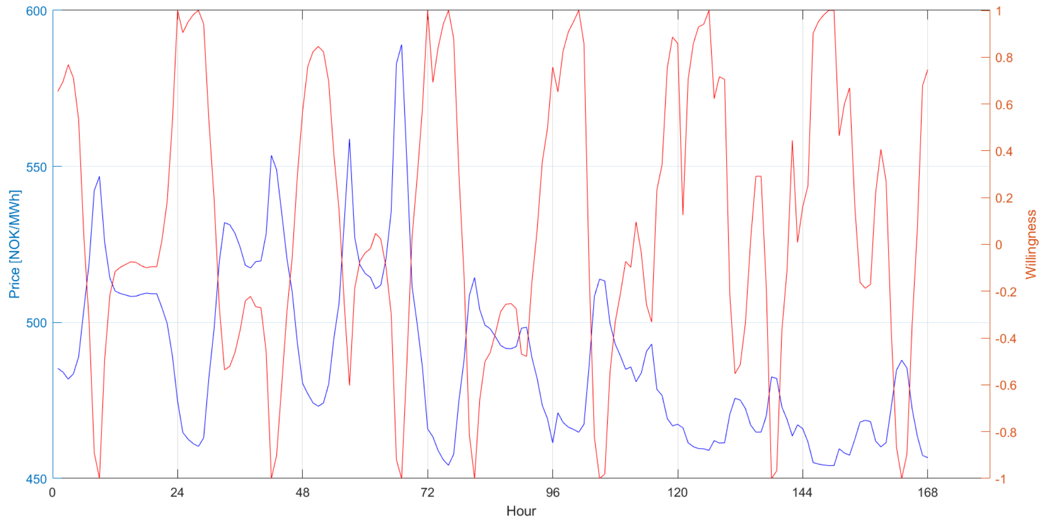

Figure 14: Willingness and the price for first week of February 2019 in Southern Norway.

To be able to calculate willingness, the prices must be known in advance. In this case, the willingness is calculated on 24h calendar days. The hourly price for electricity is published on *NordPool day-ahead* market, the day ahead. So willingness can in a real-life test scenario be calculated before the willingness is used.

As the new tariff models do not allow for calculation before after energy use is calculated, they are not implemented to the willingness curves. NVE also mentions time-of-use tariffs as possible ad-on to grid tariff prices. If this was used instead of effect based tariffs, willingness could have included grid tariff in the price data input.

3.6 Demand Limit

The other main task for the EMS is to reduce the grid load, to avoid high grid tariffs for the EMS system, it is also implemented a DL that sets a maximum value for how much power the house is allowed to draw during an hour. Setting a maximum value that the EMS can draw per hour can avoid the creation of new and higher demand peaks during periods with lower energy prices.

A low DL will trade-off savings from energy price saving for grid tariffs savings. The DL will also restrict access to energy and might for example restrict heating and might lower the top, average, and low temperatures. A high DL will allow for higher energy price savings but generally make the grid tariffs more expensive.

Since the grid tariffs are not included in the willingness, some experiments are done by applying a DL. It is aimed to see if it is possible to increase the savings by adjusting the maximum allowed consumption for the household. This can be beneficial for the consumer in the form of a lower grid tariff and the DSO by not creating a new consumption peak in hours when electricity is cheap.

3.7 Critical Loads

A typical user pattern for a house in Norway is collected from *Akershus Enøk og Inneklima*. In table 2, the electricity use for different equipment, and the usage time per week is listed [2]. These data are used for the essential electric consumption whom the EMS can not control. Even if the power prices are high and the consumption is near the DL, the customer still needs to be able to cook or watch TV.

Table 2: The electricity usage for different electric components and use per week [2].

Equipment	**Power[W]**	**Use per week [H]**
Stove	2 200	7
Kitchen extractor	75	2
Coffee maker	1 500	3.5
Dishwasher	2 000	7
Fridge	160	56
Freezer	175	70
Toaster	1 000	0.2
Clothes washer	2 500	4
Clothes Dryer	3 000	3
Hair dryer	750	1
Electric shaver	10	0.5
TV	100	21
Stereo	25	28
Vacuum cleaner	1 000	1
Light	1 080	49

Based on the loads given in table 2, a critical load profile for a typical workday was created, seen in figure 15. In the figure, it is a base usage of 441.25 W, and the highest load is at 17:00 at 2662.68 W. In the critical load profile, electric devices as EWH, house heating, and EV is excluded since these loads can be controlled through an EMS. This critical load profile was used for every day during a year for the simulations.

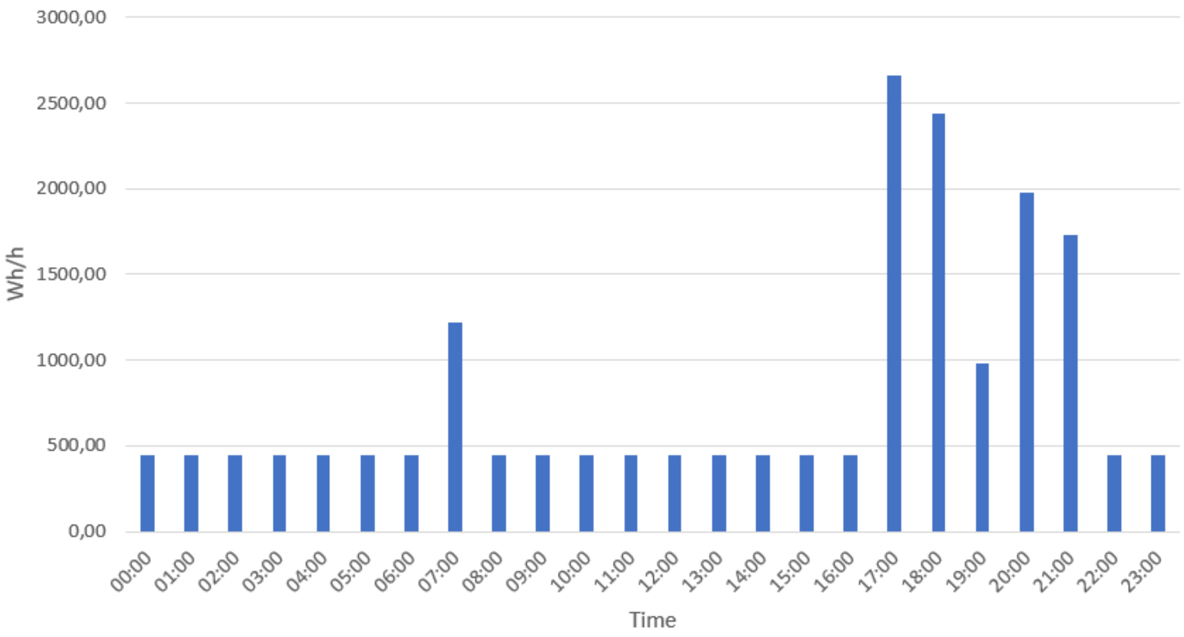

Figure 15: Critical load profile for a household.

Since these loads could not be moved, the EMS needs to consume less power during these periods when critical loads consume much power. The reason to avoid using power during these periods is that that could lead to high consumption peaks.

3.8 Electric Water Heater and Losses

Losses and volumes are based on volumes for an actual EWH at UiA [4]. The user pattern is based on the study about hot water consumption study from British dwelling mentioned in section *"2.1.2 Hot water consumption"* earlier in the report. The heat loss for the EWH is calculated, as shown in equation 7.

$$Q_{EWH} = \frac{k_{MineralWool}}{Insulationthickness_{EWH}} * A_{EWH} * \Delta T_{EWH} \tag{7}$$

- Q_{EWH} : Heat loss for the EWH
- $k_{MineralWool}$: Thermal conductivity for Mineral Wool (0.035 $w/m * k$)
- $Insulationthickness_{EWH}$: Insulation thickness for the EWH (0.038 m)
- A_{EWH} : Inside area for EWH. (2.1679m^2)

- ΔT_{EWH} : Temperature difference between the indoor temperature and the temperature inside the EWH.

The calculations showed that the heat loss was 1.9964 W per C°difference between the temperature inside the EWH and the indoor temperature. Stratification is not taken into account. The energy lost from the EWH is not added to house heating.

3.9 House Heating and Losses

House heating is a complex topic with many variables and preferences. We have built the model described in this chapter to give the general behavior of energy storage in a modern Norwegian dwelling. The model is sensitive to variations in building material, building age, temperature preferences and heat sources, human activity, and more.

For the heating, it is considered air to air heating pump, which covers 50% of the heating required during the winter (December to February) and covers 75% of the heating required during the rest of the year. Further, it is considered that the coefficient of performance (COP) factor for the heat pump is 1.8 during the winter and 3.0 for the rest of the year since the heat pumps have higher efficiency with higher outdoor temperatures. These numbers are based on the consultative document from RME [29].

The total heat loss/gain for the household can be expressed as in equation 8.

$$Q_{H_{Total}} = -Q_{H_{Insulation}} - Q_{H_{Ventilation}} + Q_{H_{SolarGain}} \tag{8}$$

- $Q_{H_{Total}}$: Total heat loss/gain for the house.
- $Q_{H_{Insulation}}$: Insulation losses for the house.
- $Q_{H_{Ventilation}}$: Ventilation losses for the house.
- $Q_{H_{SolarGain}}$: Solar heat gain for the house.

3.9.1 House Data

The study considers a new building with a length of 10 m, a width of 9 m, and two floors. The different household data in m^2 chosen for the project is shown in table 3.

Table 3: Measurements for house.

Building data	m^2
Walls	166.86
Ceiling	90.68
Floor towards ground	90.00
Windows	11.00
Windows faced South	2.75
Doors	3.78

3.9.2 Transmission Losses

A number for thermal transmittance in $[W/(m^2 * K)]$ is known as a U-value. The better the insulation is, the lower the U-values are. The different U-values for the different technical requirements (TEK) standards for the household is given in table 4. For the house in this thesis is has been taking base in a TEK17 standard, but it can be observed that it is less optimal to store energy for a house with an older TEK standard.

Table 4: Different TEK standards and U-values $[W/(m^2 * K)]$ [6][15][16][17][19][31].

	Building regulations 1949	**Building regulations 1969**	**Building regulations 1987**	**TEK 97**	**TEK 10**	**TEK 17**
Roof	0.6-1.0	0.41-0,58	0.20	0.15	0.13	0.13
Floor	0,8	0.41-0.70	0.30	0.15	0.15	0.10
Walls	0.6-1.1	0,46-1.28*	0.30	0.22	1,18	0.18
Doors & Windows	2.91–3.48 (8.14 if window area is less than 1/8 of floor area)	*Included in walls calculations	2.4	1.6	1.2	0.8

To calculate the losses for the household during the month the average temperature for each month was downloaded from *timeanddate.no* [40]. In table 5, the average temperature for Kristiansand for each month from 1985 to 2015 can be observed. These values are used to calculate the house heat loss during the different months of the year.

Table 5: The average monthly outdoor temperature for Kristiansand from 1985 to 2015 [40].

Month	**Temperature [C°]**
January	1
February	1
March	3
April	6
May	10
June	14
July	16
August	16
September	13
October	9
November	5
December	2

With these data, it was possible to calculate the total heat loss due to the house transmission. These calculations is shown in equation 9.

$$Q_{H_{Insulation}} = \sum (U_{values} * A_{values}) * \Delta T_H \tag{9}$$

- $Q_{H_{Insulation}}$: The heat loss for the house.
- U_{values} : The different U-values for the household.
- A_{values} : The different areal for connected to the U-values.
- ΔT_H : The temperature difference between the indoor and outdoor temperature

From these calculations, it was found that heat loss due to transmission was 64.1467 W per °C difference between the indoor and outdoor temperatures for the house.

3.9.3 Ventilation Losses

In addition to the heat losses due to the house insulation, the house has some loss due to the building ventilation. For the ventilation, it is considered that it is 0.5 air exchanges for the household each hour. The heat regeneration for the ventilation is 80%. The heat loss due to the ventilation could then be expressed as:

$$Q_{H_{Ventilation}} = ACH * (1 - \eta\%_H) * Cp_{Air} * \Delta T_H \tag{10}$$

- $Q_{H_{Ventilation}}$: Heat loss due to ventilation system.
- ACH : Hourly air exchange rate for the ventilation(0.5).
- $\eta\%_H$: Heat recycling efficiency for the ventilation (80%).
- Cp_{Air} : Heat capacity for air (1005 j/kg)
- ΔT_H : Temperature difference between the indoor and outdoor temperature.

With these values, it was possible to find a heat loss due to ventilation of 14.7732 W per ΔT. In older houses without heat recycling trough the ventilation, the heat losses due to the ventilation is much higher.

3.9.4 Solar Irradiation Gain for House

There are not only heat losses for a building due to climate, but the house also has a heat gain due to solar irradiation. The south-facing windows do receive a varying degree of solar irradiation during the year. To find out how much heat is received through these windows, irradiation for a 90°south-facing square meter for Kristiansand was downloaded from *PVGIS* [28]. The average solar irradiation through the year collected from *PVGIS* is visible in table 6.

Table 6: The solar irradiation for Kristiansand on a 90°surface turned south. $[W/m^2]$[28]

	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
00:00	0	0	0	0	0	0	0	0	0	0	0	0
01:00	0	0	0	0	0	0	0	0	0	0	0	0
02:00	0	0	0	0	0	0	0	0	0	0	0	0
03:00	0	0	0	0	0	0	0	0	0	0	0	0
04:00	0	0	0	0	0	0	0	0	0	0	0	0
05:00	0	0	0	0	0	3	0	0	0	0	0	0
06:00	0	0	0	0	10	17	12	1	0	0	0	0
07:00	0	0	0	11	28	35	31	18	2	0	0	0
08:00	0	0	18	61	58	54	51	54	50	2	0	0
09:00	0	5	108	173	176	170	156	160	143	88	0	0
10:00	1	92	227	297	284	288	267	271	244	177	76	0
11:00	99	192	319	408	386	391	362	367	316	242	168	90
12:00	152	246	392	472	443	455	412	422	392	304	216	174
13:00	194	254	440	501	488	490	456	481	413	314	218	189
14:00	186	240	426	500	471	478	470	472	406	304	216	174
15:00	158	165	405	447	434	427	423	428	359	261	172	136
16:00	79	91	342	365	348	351	346	352	296	191	96	2
17:00	0	5	225	265	241	244	252	256	195	110	0	0
18:00	0	0	111	139	122	124	137	138	98	12	0	0
19:00	0	0	11	29	41	49	49	35	11	0	0	0
20:00	0	0	0	5	22	32	31	15	0	0	0	0
21:00	0	0	0	0	4	15	12	1	0	0	0	0
22:00	0	0	0	0	0	0	0	0	0	0	0	0
23:00	0	0	0	0	0	0	0	0	0	0	0	0

When the data was downloaded from *PVGIS* it was used to calculate the total heat gain for the house due to the solar conditions shown in equation 11.

$$Q_{H_{SolarGain}} = H_{Solar} * SHGC * A_{WindowsSouth} \tag{11}$$

- $Q_{H_{SolarGain}}$: Heat gain for house due to solar conditions.
- H_{Solar} : Solar irradiation on a 90 degree surface turned south.
- SHGC : Solar Heat Gain Coefficient for windows (0.65).
- $A_{WindowsSouth}$: The area of the south-faced windows ($2.75m^2$).

3.9.5 Thermal Mass of a House

To estimate the thermal mass of the house, values collected from *SIMIEN* was used. *SIMIEN* is an energy calculation tool to simulate variation in indoor climate, energy needs, a dimension of heating, ventilation, and room cooling [38]. *SIMIEN* is a building energy calculation program used to calculate the building's energy needs after Norwegian Standard 3031 (NS3031).

Even if energy calculation uses some input from *SIMIEN* the total energy calculation is probably less accurate than calculations made in *SIMIEN*. The main objective for the model developed through this thesis allows analyzing energy storage and load shifting, setting upper and lower temperature, and effect limit.

SIMIEN is evaluated to be within an accuracy class B for the calculation standard. The information used from *SIMIEN*, is what the standard program calculation basis. Table 7 shows what data was used, and other data for thermal masses for households.

Table 7: Thermal masses for a building with different specifications.

	Light value $[W/(m^2 * K)]$	**Used values** $[W/(m^2 * K)]$	**High values** $[W/(m^2 * K)]$
Furniture	2.0 Light furnished home	4.0 Medium furnished home	6.0 Heavy furnished home
Roof	2.4 Plaster ceiling	2.4 Plaster ceiling	63.0 >100 mm concrete
Floor	3.0 Light floor	13.0 Medium value	63.0 >100 mm concrete
Walls	2.4 Plaster wall	3.0 Light wall	63.0 >100 mm concrete

3.10 Electric Vehicle and Losses

The EV is modeled to use a specific amount of energy every day to represent the daily commute and any losses. The power consumption is the same every day, weekdays and weekends, throughout the year.

From the NVE report on grid tariffs, an estimate of 50 kWh is used each week for the EV. From these numbers, it was calculated that the average energy consumption for 7.14 kWh each day [29]. In this thesis, this is modeled as a total energy drain from the battery. Furthermore, the EMS can recharge the battery based on the reference curve for the battery and restricted by DL and restricted to only charge between 18:00 to 08:00. The daily power consumption is drawn between 08:00 and 18:00. The car is not connected to the charger in this time, and all losses are considered in the power consumption, the power is drawn from the battery momentously. Figure 16 illustrates when the EV can charge and when the energy is drawn in the simulation model. The model uses a battery capacity of 62 kWh. More about the numbers used, see chapter *"2.3 Electric Vehicle"*.

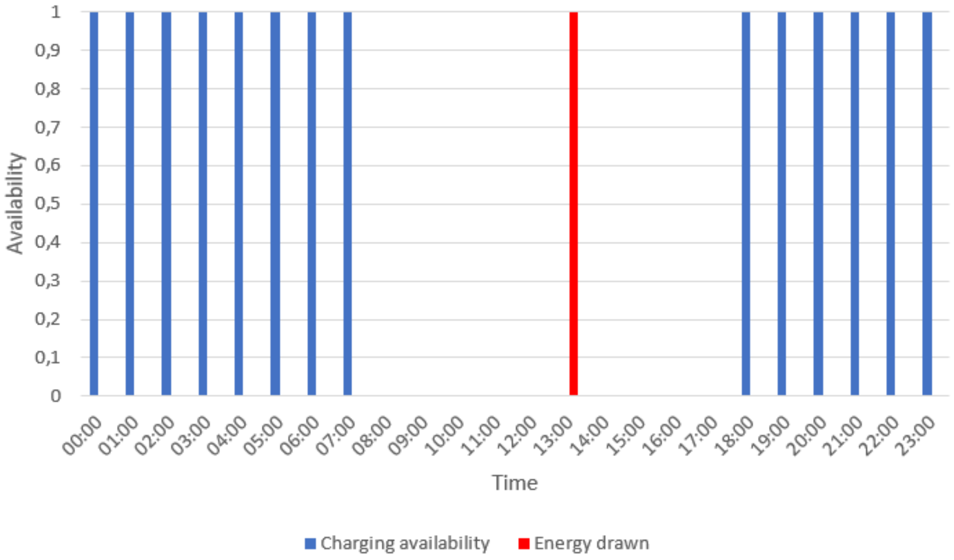

Figure 16: Electric Charging Availability.

3.11 Grid Tariff Calculations

Based on the models described in table 1 in section *"2.7.1 New regulation for grid tariffs"*, the three new grid tariffs and the reference model used today, is simulated to see how the system behaves for different grid tariffs. These simulations helped to conclude which grid tariff that will benefit the EMS user the most.

4 Operational Strategies of Power Intensive Domestic Loads

This chapter provides information on how the simulation script is built up, and which parameters and assumptions that are used in the simulations. As the calculations are based on many parameters that affect the results, it is important to understand in what way the calculations build on each other and to understand how they work together. Particularly when the DL is included, the system can then restrict one load based on the demand from other loads.

4.1 Simulation Buildup

The strategy is to run simulations in three main steps. The first is calculating fundamental values, making the willingness, and setting the initial values. The second is the loop that calculates energy state, losses, and electric load for every component, for every hour. The final step is presenting these large matrices in temperatures, cost, and calculating grid tariffs.

The reason for this construction is that every calculation is done using measurable data such as temperature, except willingness and the reference matrices, which would all be accessible at the time of calculation if implemented in a real-life scenario.

4.1.1 Willingness, Losses, and Initial Values

The willingness was calculated in *Matlab* as shown in section *"3.5 Willingness"*. For the *Matlab* simulations, the willingness had to be calculated for each day during the year. This was done by using the hourly day-ahead price data collected from *Nord Pool*, and then make *Matlab* calculate a new minimum, average, and maximum values for each 24-hours during the year. This willingness calculate the reference curves for the EWH, house heating, and EV charging.

The thermal losses for the EWH and the house heating varied with the outdoor temperature, indoor temperature, and the temperature in the EWH. Therefore each hour during the year, the thermal losses in both the EWH and the house were calculated using the simulated temperatures in the script. When the loss was calculated, it was subtracted for the stored energy that was calculated for the house heat and EWH.

Most of the calculations in the script are calculated in Wh, or Wh/h. Therefore the initial values and temperatures were calculated from °C to Wh. By using Wh as the base for the calculations, it was much simpler to calculate the heat gain and losses. For the house heating, the initial values are set to be at the reference curve deiced by the willingness. To get the results back from Wh to °C, they are calculated back for each hour to see how the temperature changes. To calculate from temperature to energy, the respective thermal masses are used. See section *"3.9.5 Thermal Mass of a House"* and *"3.8 Electric Water Heater and Losses"* for calculations.

4.1.2 The Simulation Loop

The loop is build up by two nested for-loops. The first loop counts days with the index D, and the second loop counts hours using a pre-defined matrix that allows it to count from 1 to 24 the first day, from 25 to 48 the second day, all the way up to 8760. The index for the second loop is N. N is used as an index when creating arrays with one value for the calculated period every hour. In this study, it is calculated for one year, 8760 values.

The Day-matrix is a matrix where the row's index represents the day through the calculation period, the first column the first hour that day, and the second column for the last hour.

Within the nested loops, N can be used to index the hour in question. D to index the day in question.

The first task within each loop is to know how much energy is stored in each component. If it is the first hour, the reference matrix value is used, assuming that the reference system would have been close to its reference value.

After stored energy is found, the difference between stored energy and the reference value for each component is calculated. These values are added together from each component and the critical load for that hour. This total power consumption is controlled against the DL. If the need for energy is higher than the available energy, an availability-number between 0 and 1 is created and later multiplied with the electric load.

The last calculations in the loop calculate power drawn from the grid, electric load. One using reference curves based on a constant temperature or battery state of charge, the reference case. The other with the willingness-based reference and availability number.

The loop is illustrated in figure 17.

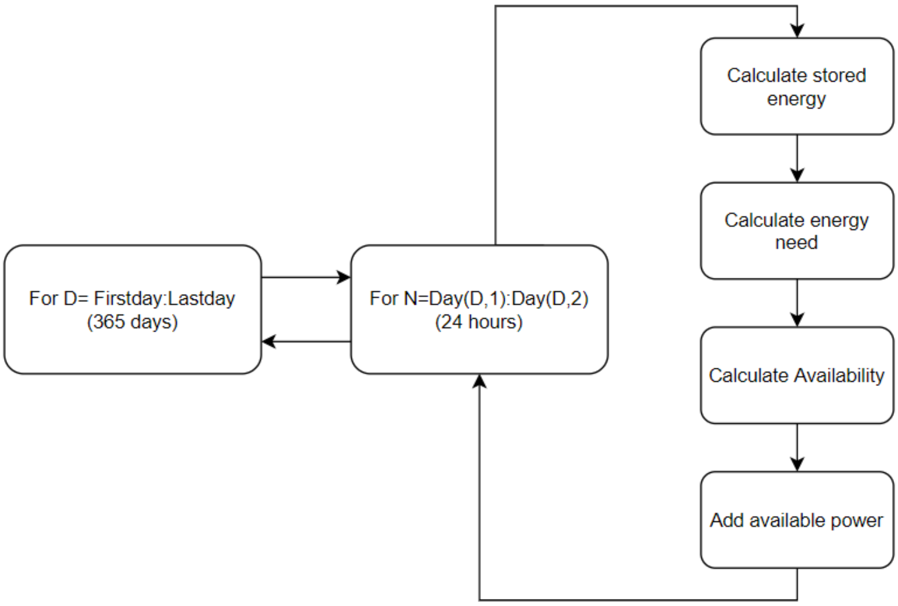

Figure 17: Loop for the *Matlab* simulations.

A single loop with all these calculations is needed as availability makes each load effect each other.

4.1.3 Grid Tariffs and Presentable Values

The model for calculation of the grid tariffs is shown in table 1 in section *"2.7.1 New Regulation for Grid Tariffs"*. To include these values in the simulations the different grid tariffs had to be calculated in different ways based on the consumption. The four tariffs are described below:

- **Present grid tariff:** For the reference grid tariff, also known as the grid tariff in Norway today. The grid tariff is based on the total energy consumption and a fixed amount. The reference grid tariff consist of a fixed link, which is the price for being connected to the grid, and a tariff for each kWh used. Therefore the energy consumption for each day was multiplied with the tariff for each kWh consumed and then added together with the fixed yearly amount to calculate the total grid tariff for this case.
- **Subscribed-effect:** For the Subscribed-effect, the grid tariff depends on the subscription size for the grid tariff. The grid tariff consist of a fixed amount, independent of the subscribed effect. The amount that varies with the size of the subscribed effect, a higher price per kWh/h above the subscribed effect, and a smaller amount is decided by how much power that is used. It is important to investigate the optimal subscription and DL

for each of the cases. The fixed joint was added with the subscription cost, the grid tariff per kWh used, and the power used above the subscribed effect to calculate the total costs for the Subscribed-effect tariff.

- **Measured-effect:** The Measured-effect consists of a fixed joint, a small amount for each kWh used, and an amount that is decided by the highest power usage for every day. For calculation of the Measured-effect, the highest hourly energy consumption for each day was found using a function that measured the highest power consumption for every 24 hours. The effect was then multiplied with the price rate for the maximum daily effect, depending on if it is summer or wintertime. All of these effects were summarized for a year. Afterward, it was added together with a fixed link. The grid tariff, and a small amount for each kWh used during the year.

- **Capacity-limit:** For the grid tariff that are based on the capacity limit. The grid tariff are calculated by a fixed link for the costs of being connected to the grid. A link that varies in price according to the installed main fuse for the house. Together with a low grid tariff for each kWh used during the year. For these simulations, the Capacity-limit is decided to be equal to the highest energy consumption during the year. Therefore, many of the Capacity-limit simulations have a lower value than they would in a real situation.

4.2 Demand Limit Model

The DL model is built up to restrict if the system wants to draw more power than what is available. The system adjusts the power consumption to the wanted level. As seen in figure 18, if the EMS wants to use more power than the available power. A new availability is calculated in *Matlab*. This availability is used to reduce the load's currents as close as possible to the DL without exceeding it for all the controlled EMS units. If the EMS wants to use less power than the DL, the availability is at 1, and the units can use electricity as planned.

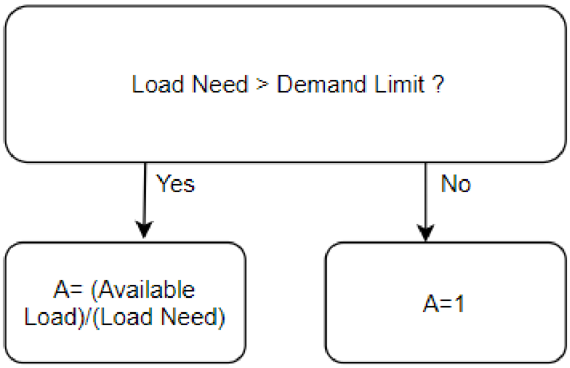

Figure 18: Working of the demand limit.

4.2.1 Iterative Method of Finding the Demand Limit and Subscribed Effect

As the DL affects all the power consumption-based grid tariffs and temperatures as it delays heating, the most beneficial DL was decided by an iterative process. We call the process iterative as we repeat the simulation, getting closer and closer till we find the cheapest option.

The purpose of the DL is to reduce the max power drawn. By lowering the power consumption from each household, grid investments can be reduced, and grid tariffs after all the effect based tariff models can be reduced. The energy is dispersed over a more extended period.

A low DL will affect energy cost and comfort. A low DL will also reduce the power consumption tops and spread consumption out in time. This will again reduce savings on energy, as it can no longer be bought while on it is cheapest. If the DL is too low, the system cannot deliver the amount of energy required. This will negatively affect comfort.

If the DL is adjusted bellow the critical load level for the household in the simulations. It has to be implemented a barrier that does not allow energy to be drawn from EWH, house heating and EV to supply the critical loads with energy.

The DL will be the empirical result of running simulations with 100 Wh/h intervals until a low point in combined cost with energy price and grid tariff. The empirical method of finding the optimal DL is shown in figure 19. The same method is used to find the cheapest subscribed effect for every DL tested in this process.

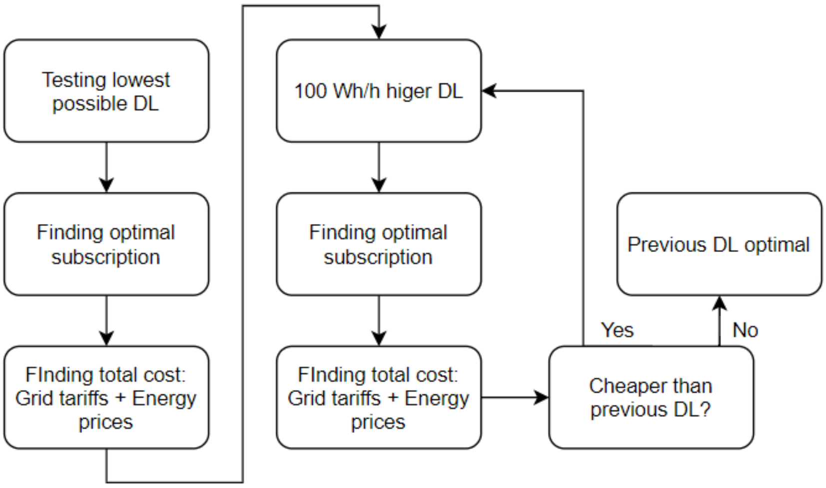

Figure 19: Method for finding demand limit.

4.3 Electric Water Heater Model

The simulated EWH model is based on the testing equipment at UiA. This tank has a volume of 190 L, and the effect of 1.95 kW [4]. The temperature in the EWH should neither go higher than a maximum safe temperature nor bellow the temperature where Legionella starts to grow. For EWHs, a safety relief valve is installed to ensure that the water does not start to boil and build up pressure inside the EWH. The safety switch is typically activated at 95°C to have some margin for safety before the water starts to boil at 100°C. According to *World Health Organization* (WHO), to avoid the legionella batteries to grow in the water, the water needs to have a stable temperature above 52°C, or the water needs to be heated up to 70°C for some seconds form time to time [43]. To avoid heating the water to where the safety switch is activated, the maximum heating point for the EWH is set at 90°C. To avoid growing Legionella in the water. The minimum reference temperature is set to be 60°C for the EWH.

As can be seen in figure 20, the EWH turns on if the temperature is lower, the reference temperature. If the water temperature is above the reference temperature, the EWH turns off.

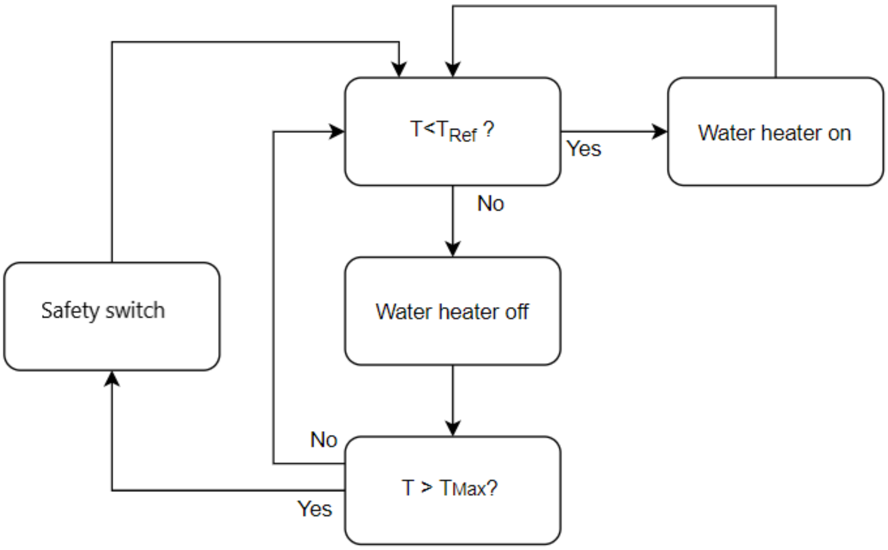

Figure 20: Flowchart electric water heater.

4.3.1 Stored Energy in Electric Water Heater

In figure 21, the total stored energy for the EWH, is shown. The figure shows that the amount of stored energy increases when is it been applied heat in the form of power. The stored energy decreases trough thermal losses in the EWH and when hot water is used, and the tank is refilled with cold water. For the task, it is wanted to see if it is profitable to store energy from periods when the energy prices are low to periods with higher energy prices when heat losses are being included.

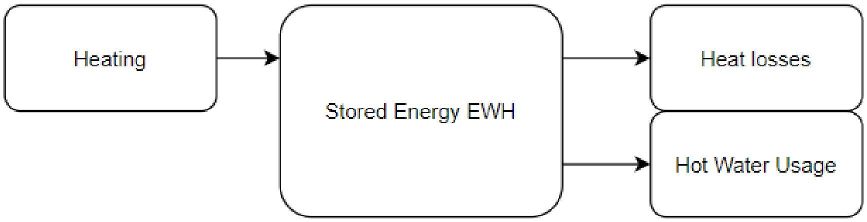

Figure 21: The stored energy of the electric water heater.

4.4 House Heating Model

It is simulated with a heat pump that has a effect of 3.3 kW and that there is 2 kW that is covered by floor heating and heating ovens. Combined these gave a total heating capacity of 5.3 kW and a combined COP at 2.5 during the summer and 1.4 during the winter. The temperature for the household should stay between temperatures where the user's comfort is not compromised. Therefor to stay between comfortable limits, the temperature should be between 19°C and 21°C.

As seen in figure 22, the heating turns on if the temperature is lower than the reference temperature and turns off if the temperature goes above the reference temperature.

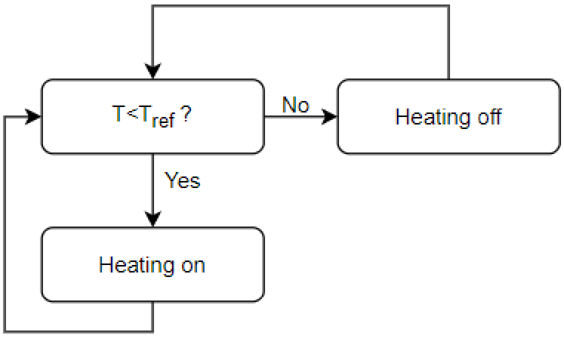

Figure 22: Flow chart for house heating.

4.4.1 Stored Energy in House

The total stored energy for the building can be expressed, as shown in figure 23. In the figure, it can be seen that the stored energy trough heat in the house, increases with the solar irradiation and heating in the form of power consumption. It can be seen that factors that negatively impact the household's stored energy include heat losses through transmission and ventilation losses.

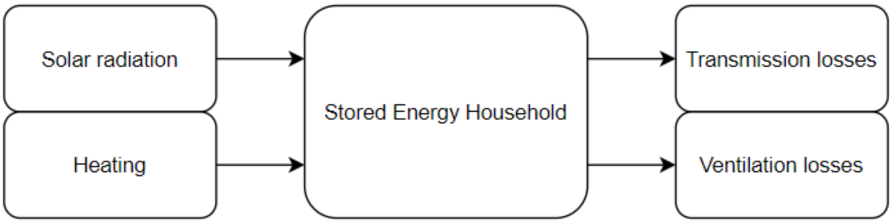

Figure 23: Stored energy for the household.

4.5 Electric Vehicle Charging model

Today an EV is usually sett to charging when people come home from work around 17:00. This is during peek hours both for the grid, and the energy prices. The EV does not use much of its rated battery capacity during regular use. It is, therefore, possible to charge the EV when the power is cheap during regular use, without the consumer needs to change the charging routine for the EV. Since EVs today have such big battery capacities, the EV does not need to be fully charged every day. As long as the battery stays above a certain level. There are already different technologies integrated into the EV that allows the cars to charge more smartly. This includes when the EV should be charged up and at which energy prices it is wanted to charge the vehicle. Nevertheless, the EV is included into the system because it is possible to implement it in a overall system.

Assessment of EV charging is an opportunity to learn how EVs will affect the grid, and power markets as this is relatively new, and increasing in scope.

The EV charger uses willingness to sett the reference battery charging level. When the electricity prices are at the highest for the given day the reference EV charging is at 50%. When the electricity prices is at the lowest point during the day the reference charging level is at 100%. As seen in figure 24, the EV charges only when the battery is not full, and the willingness is higher than the reference willingness. Since a charger for an EV is typically between 3.3 kW and 7.4 kW, the electric car charger for this task is set to have a power usage of 3.7 kW.

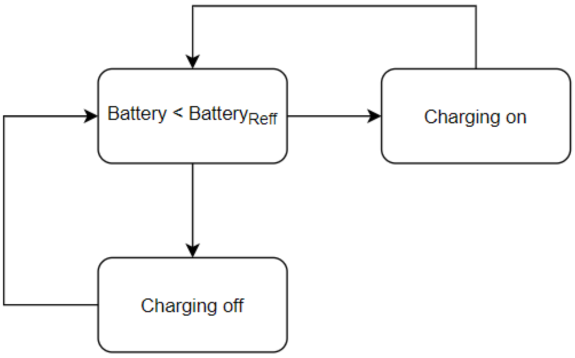

Figure 24: Electric vehicle flowchart.

4.5.1 Stored Energy in Electric Vehicle

For the EV, it is not any thermal losses. When the battery is charged, the state of the battery stays at the same level until the EV is used next time. The stored energy for the EV is shown in figure 25. The figure shows that the only two factors that affect the EV's stored energy are whether the vehicle is charging or using energy.

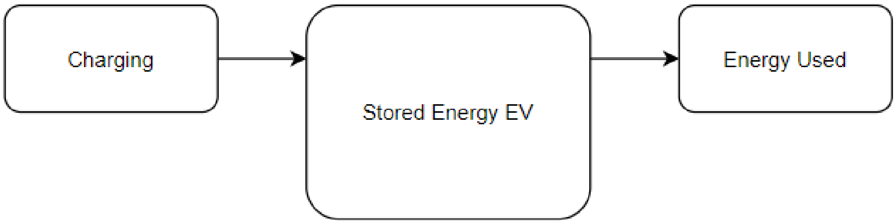

Figure 25: Stored energy for the electric vehicle.

4.6 System Buildup

The system needs to stand between the main fuse and the components themself. As this EMS works based on reference temperatures, it needs to replace the components' original control systems.

4.7 Summary of *Matlab* Script

This chapter describes the strategy of calculations done in this thesis, and it can be described in three phases.

- **First phase:** Initial values, such as house transmission losses, ventilation losses, irradiation, EV-power consumption are calculated, downloaded, and made available for further calculations. Here willingness, temperature, and battery charge state reference-values are also calculated based on the willingness, which is based on energy prices.
- **Second phase:** Initial values, and what can be calculated without affecting other components are already calculated. In this phase, hourly calculations, where every calculation is based on last hour's calculation, are done. Starting at initial values and giving values such as power consumption and energy state for every hour of the calculation period (the year of 2019.). These values are stored in 1 by 8760 arrays.
- **Third phase:** The long arrays from the second phase are used to calculate grid tariffs, energy prices, and plotted as graphs to see developments and trends.

5 Planned Experimental Work At UiA Laboratory

This chapter provides a brief introduction to experimental testing to verify the simulations and some ideas for implementing the EMS system. The testing and setup of the test equipment were meant to be provided in this section. Due to the current situation with the lock-down of the university due to COVID-19, these tests could not be completed in a safe manner.

Testing and small scale implementation of the EMS system is essential to learn how smart houses and EMS work in a real-life scenario. Experiences from testing of varying water temperatures, hot water usage, indoor temperatures, and different power restrictions are useful for learning how an EMS system could be implemented.

This thesis discuss load shifting concerning grid tariffs, *day-ahead* market prices, consumer needs, and grid investments hourly calculations are used. It is envisioned a control system based on current control or turning equipment on and off to enforce DL installed in series with thermostat control. All grid tariffs except the Capacity-limit are based on hourly calculations, not maximum power. These will give the same results in grid tariff calculations and energy cost calculation.

5.1 Potential tests

To improve and evaluate calculations done in this thesis, several tests can be performed. These tests are presented below. The primary purpose of these tests is to evaluate simulation behavior and be connected to thermal mass.

- **Floor heating:** The EMS system could be connected to heating cables that set different reference temperatures for the heating cables. This could provide information on a more accurate model of heating cables used as thermal storage. These results could help describe a delay in heating.
- **Room heating:** The EMS system could have been connected to heat ovens or a heat pump with different reference temperatures. This would have helped to verify if the simulation model is accurate. Moreover, it would have helped to optimize the system further.
- **EWH optimization:** With some test on an EWH, it could be verified if the system worked or not and if the simulations model is accurate. The test result from the EWH could have been used to optimize the EMS system further. At UiA a test tank is equipped with both temperature sensors, valve controller, and can be controlled by a computer that has software to control the reference temperature for the EWH. With all of these

control parameters already installed, testing and verification on the EWH could have been completed at the university.

5.2 Verification

The calculations made in this thesis are based on theoretical values and behaviors. Carefully designed experiments would verify or give reason to adjust these numbers.

Among sources for errors are building standards, human behavior, and simplifications in the calculation. Some of the most critical numbers to verify is, thermal mass in buildings, heat losses related to different buildings and air infiltration, if critical loads can be considered as room heating, and whether data.

To verify the EWH, it would be interesting to see if the EWH simulations are accurate. It could be possible to measure if the simulation model is accurate or inaccurate when it comes to heat loss, heat gain, and power consumption for the EWH. With physical tests to verify the simulations, it could be found that it is economical to store energy in the EWH.

For verification of the floor heating and room heating, it is not any equipment at the university to verify the simulations. These simulations could, however, be verified by collecting data for smart houses projects. The university has access to different data from a smart house project. From these smart houses, it could have been collected data about the electricity consumption used for floor and room heating, and how these data changed with the outdoor temperatures.

5.3 Implementation

The EMS is visioned to be the control system of the different components, and replace the control system used today, such as thermostat and charger control.

For controlling the EWH, it is necessary with some temperature measurements and controls. The testing EWH at the university, has already installed equipment that allows the EMS system to be tested. It is possible to include two control signals for the EWH. One signal is for the control valve. With a control signal for the control valve, it is possible to estimate different usage patterns for the EWH. The other control signal for the EWH is the thyristor regulator. The thyristor regulator makes it possible to control the power input for the EWH [18].

By using the two control systems, it is possible to simulate different user patterns with different price patterns and DLs. This way, the test would have helped to optimize the Matlab simulations.

5.3.1 Demand limit

The EMS control system can use two technical solutions to Implement the DL. The AMS system allows for charging consumers based on hourly average consumption, and information from HAN-port arrives every 15 seconds. Note that the DL does not include the control system to the component. The two solutions:

- **Current control:** By extrapolating the power consumption through the hour, and adjusting the current and thereby the power consumption to not exceed the DL.
- **Discontinuous operation:** When power consumption extrapolated through the hour reaches the DL, the EWH, house heating, and EV charger get disconnected, and eventually connected back on again if new estimate shows use below the DL.

6 Results

In this chapter, the results from the *Matlab* simulations are presented. The simulation graphs shown in this chapter are for Monday the 4 of February to Sunday the 10 of February (week 6) for the year 2019. During February, the solar irradiation is low at the same time as the temperature is low. For February, the average outdoor temperature in Kristiansand is 1°C. So this gives a good indicator of how god the EMS system works. If the simulation results from a summer month were presented, the simulation results would be less relevant due to lower energy consumption needed to heat the building.

6.1 Reference case- no Load Shifting

These simulations are without load shifting and based on the assumed user pattern from chapter *"2.1.2 Hot Water Consumption"* and *"3.7 Critical loads"* but without an EMS to control the consumption. The reference case represents how energy consumption would be with normal energy consumption for a house. These data give a good indicator if the EMS system has a positive or negative impact.

6.1.1 Electric Water Heater

Figure 26 shows the simulated results for the reference case. As seen in the figure, the temperature in the EWH is stable at 75°C; that is because, in the hot water consumption profile, the usage is never higher than the EWH manages to heat up again during an hour. Another thing worth noticing is that the EWH uses much power during the midday and afternoon. During these periods, the electricity prices are higher, and the electricity grid is closer to its capacity limit, while the EWH uses less power when the electricity prices are lower, see section *"2.1.2 Hot water consumption"*.

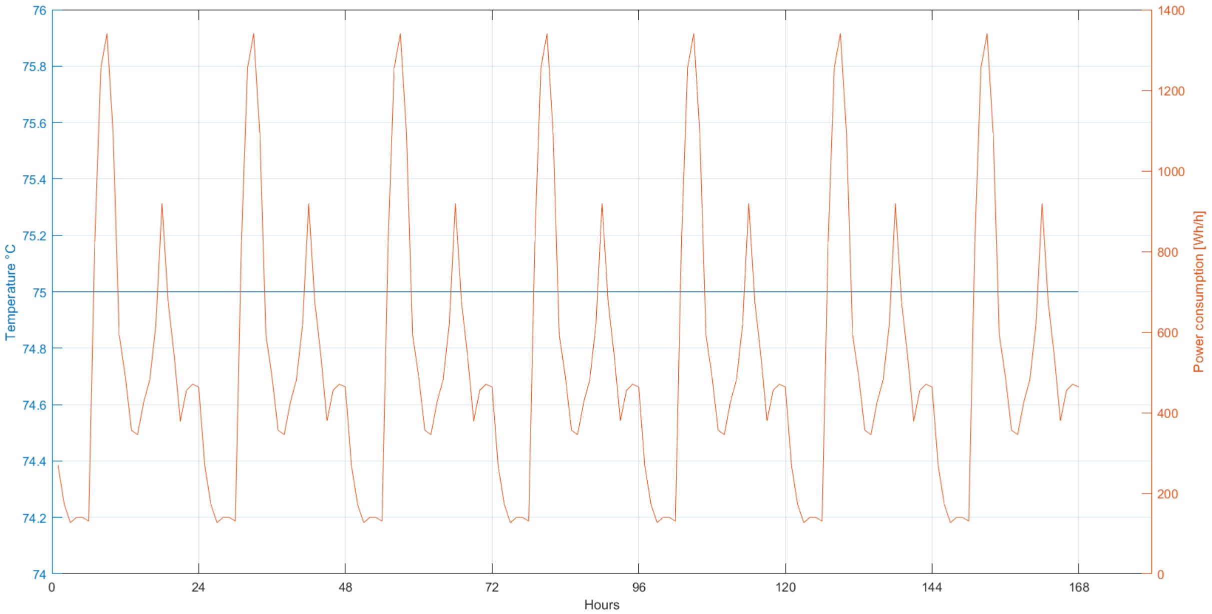

Figure 26: Reference case for the electric water heater.

The simulated energy cost per year for the EWH in the reference case for 2019 is at 1830.3 NOK, and the consumption is at 4636.9 kWh.

6.1.2 House Heating

In figure 27, the simulated results for the case for house heating are shown. As seen in the figure, the temperature is stable at 20°C. It can also be observed that the heating need is lower in the middle of the day when the solar irradiation is at its highest, see section *"3.9.4 Solar Irradiation Gain for House"*. The electric load on heating for week 6 is typically at 600 Wh/h.

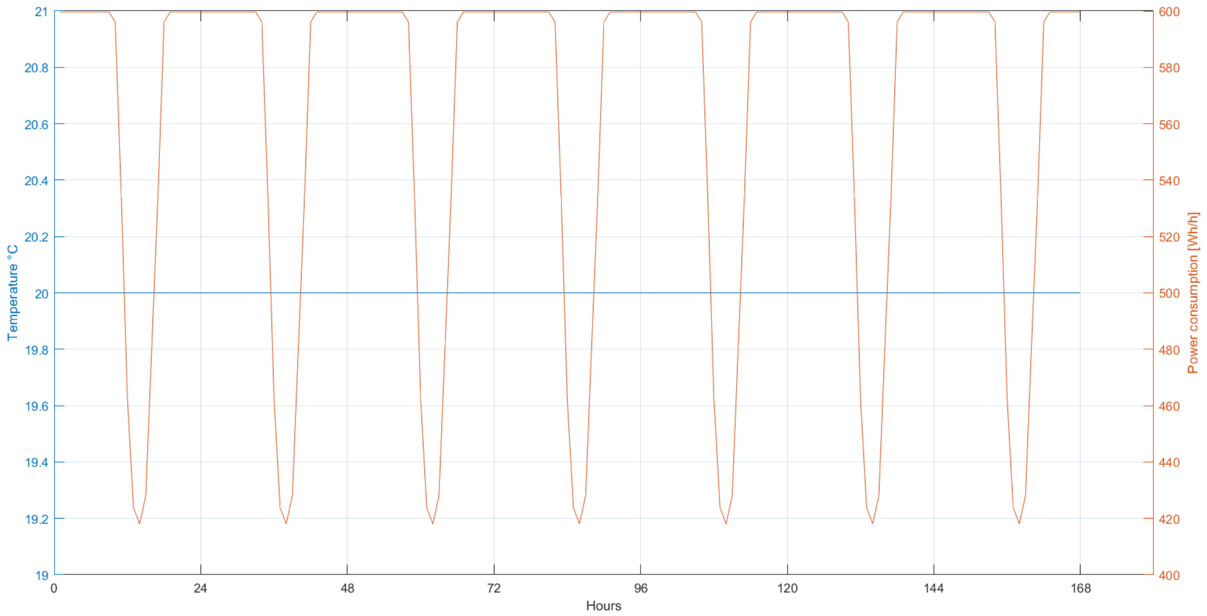

Figure 27: Reference case for house heating.

The simulated energy cost per year for the house heating in the reference case for 2019 is at 1112.9 NOK, and the consumption is at 2653.0 kWh.

6.1.3 Electric Vehicle Charger

Figure 28 shows the reference curve for EV charging. As can be observed in the figure, the reference curve for EV charging, the battery charges to 75% every day when the EV is plugged into charging. That leads to the EV charger using electricity when the power prices are at the highest, and the grid is nearer to the capacity limit. The power consumed is drawn from the battery as one operation which leads to the instant drop in battery charge. See chapter *"3.10 Electric Vehicle and Losses"* for EV power consumption.

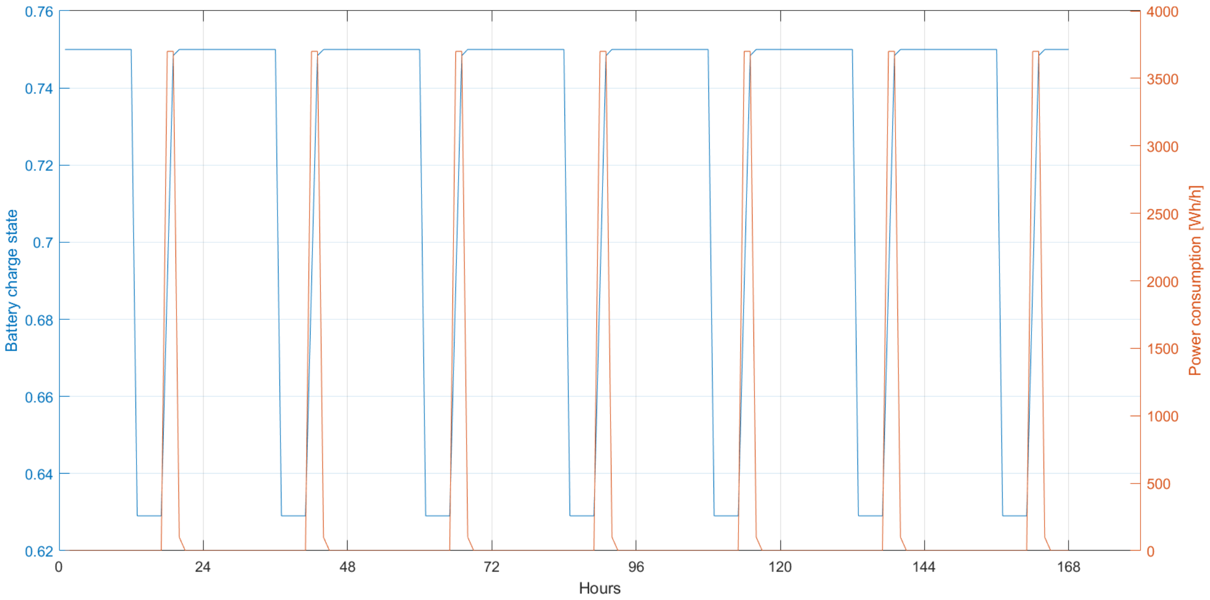

Figure 28: Reference case for electric vehicle charging.

The simulated energy cost per year for the EV charger in the reference case for 2019 is at 1107.3 NOK, and the consumption is at 2737.5 kWh.

6.1.4 Total Load

In figure 29, the reference curve for the total load for the household is shown. In the figure, it is possible to observe that almost every day, the total load is close to 7600 W in the afternoon. The reason for the high energy peak during the afternoon is that the EV charges at 3.7 kWh/h and the critical load profile, as seen in section *"3.7 Critical Loads"* has a consumption peak at this point.

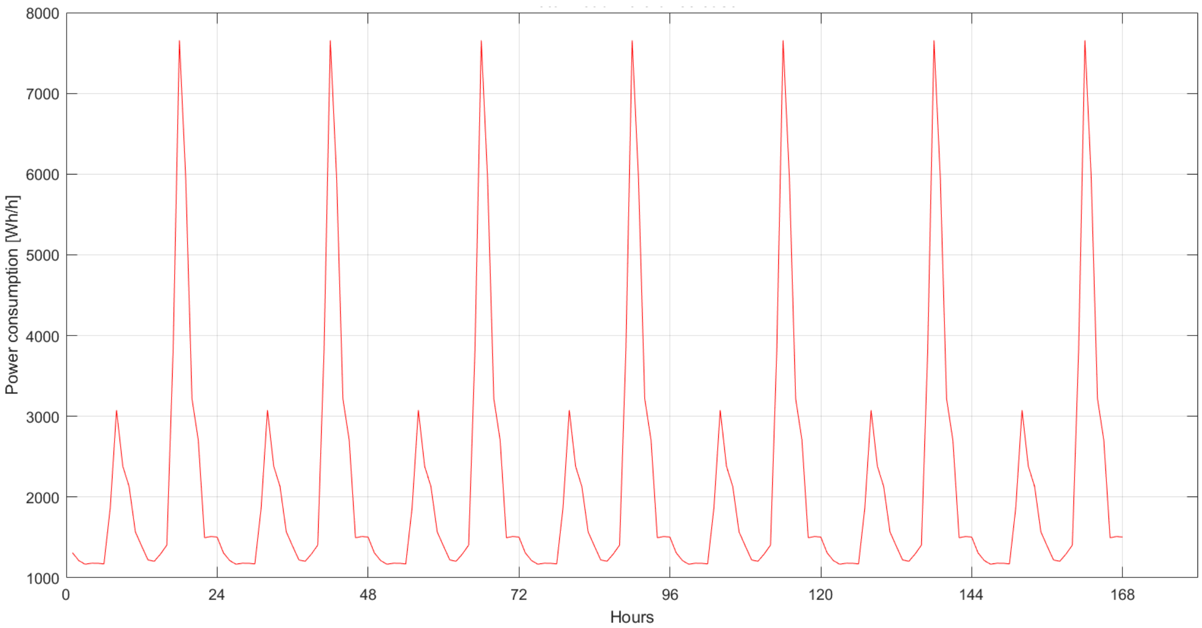

Figure 29: Reference case for the total load of the household.

6.1.5 Consumption Peak

The highest consumption peak for the reference case is recorded on the 28 of February at 18:00 with a value of 7687.2 Wh/h. This value is used for comparison for the other simulations to see how much it is possible to reduce the consumption peak.

6.1.6 Energy prices

The calculated energy prices for an entire year, with the reference user profile and the electricity prices for the hours of consumption, are 6762.6 NOK for 2019. This value is used for comparison for the other results to see how much the energy prices are reduced if an EMS system is implemented. This value is also used to calculate the combined costs with grid tariffs included.

6.1.7 Grid Tariffs

The different grid tariffs calculated for the different grid tariff models are shown in table 8. These numbers are calculated with an optimal subscribed effect of 5.4 kWh/h for the Subscribed-effect tariff and a Capacity-limit of 7687.2 Wh/h for the Capacity-limit tariff. All cost are for the duration of a year. From these calculations, it can be observed that the cheapest option for the reference case in terms of grid tariffs is the grid tariffs that we have today. The other grid tariffs react more to higher consumption peaks is stead of the how much energy that is used, see section *"2.7 Grid Tariffs for EMS"*.

Table 8: The different grid tariffs in the reference case [NOK].

Subscriptionvalue: 5400 W Max Load: 7687.2 W	**Present tariff**	**Subscribed-effect**	**Measured-effect**	**Capacity-limit**
NOR - Reference Case	5196.3	5294.9	8712.1	5234.0

6.1.8 Total Price

The combined yearly cost for the different grid tariff models are given in table 9. The present tariff calculation gives the cheapest grid tariff at 5196.3, Capacity-limit, and Subscribed-effect tariff are slightly higher, respectively, at 5234.0 NOK and 5294.9 NOK. Measured-effect is most expensive at 8712.1 NOK. This is also represented in the combined cost as energy prices are the same in every case. The energy prices are the same in the table due to identical user pattern, independent of the grid tariffs.

Table 9: The total energy cost for Norway for the reference case.

NO - Reference case [NOK]	**Present tariff**	**Subscribed-effect**	**Measured-effect**	**Capacity-limit**
Grid tariff	5196.3	5294.9	8712.1	5234.0
Energy price	6762.6	6762.6	6762.6	6762.6
Combined cost	11958.9	12057.5	15474.7	11996.6

6.2 Results With EMS Without Demand Limit

In these results, the case is simulated without an upper limit for electricity consumption. This is an optimal case when it comes to savings in electricity prices alone, but it is not necessary the best option with the new grid tariff regulations and the DSO operator in mind.

6.2.1 Electric Water Heater

Figure 30 shows the temperature for the EWH with the EMS without a DL. The figure shows that the EWH both have periods when the heating is off, and more extended periods where the heating is on, compared to the reference case. It can be seen that there is usually a higher power consumption during the night when the power prices are at a lower level. And a lower power consumption during the day. It is also worth noticing that when much water is being used in the morning, the EWH does not necessarily heat the water again. However, it lets the hot water have a lower temperature until the electricity prices allow for more power usage.

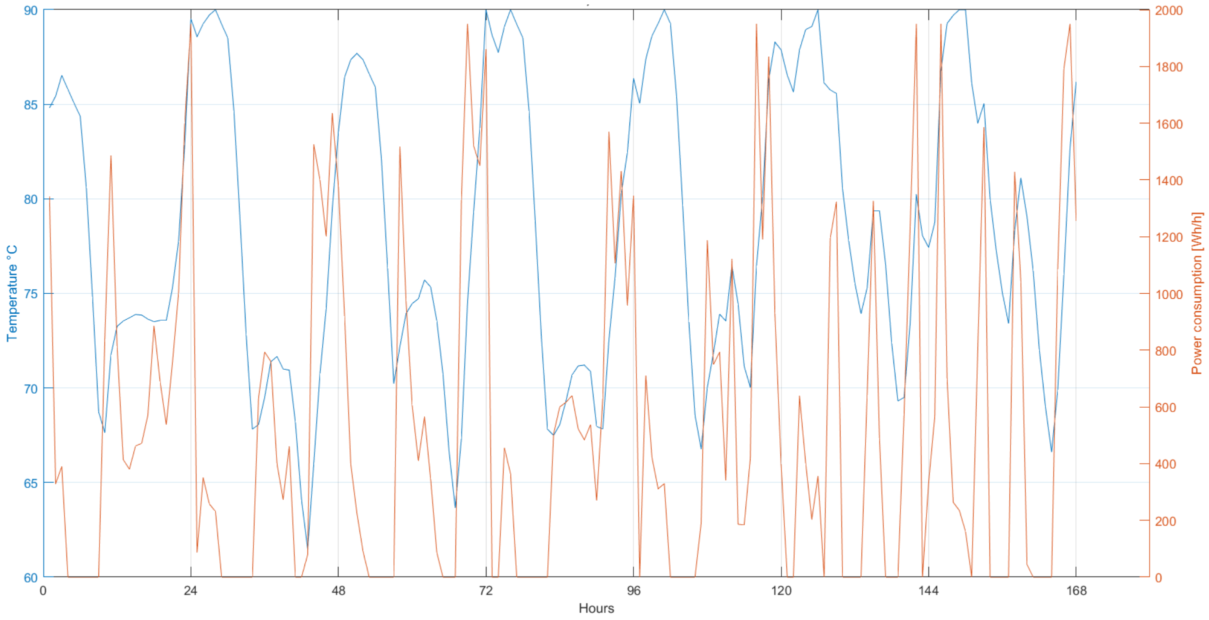

Figure 30: Water heating with EMS.

The simulated yearly energy cost for the EWH with EMS for 2019 is at 1774.3 NOK, and the consumption is at 4672.3 kWh.

6.2.2 House Heating

In figure 31 the inside temperature for the house is shown, with EMS and without DL. The figure shows the house is usually heated to 21°C during the night and cooled down to slightly above 19°C. This leads to that the heating is both turned on and of for more extended periods.

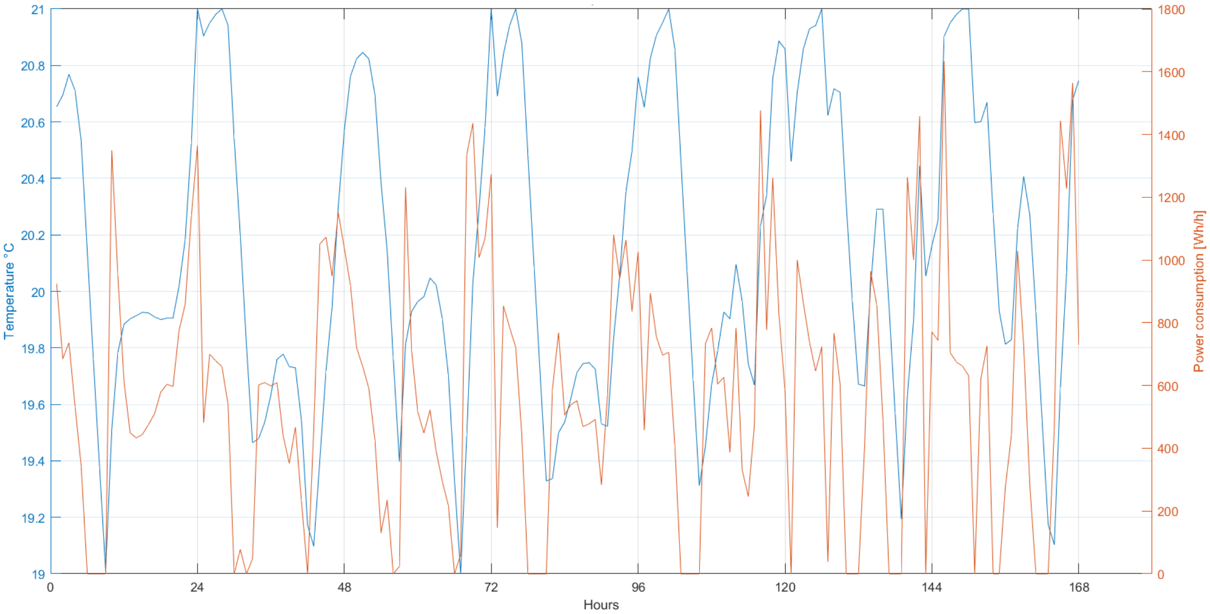

Figure 31: House heating with EMS.

The simulated yearly energy cost for the house heating with EMS for 2019 is at 1113.9 NOK, and the consumption is at 2727.7 kWh.

6.2.3 Electric Vehicle Charger

In figure 32, the EV charging is shown with EMS without a DL. Here, the car battery is charged up to 100 % almost every night when the electricity prices are low. In the reference case, the car battery is charged up to 75% every afternoon with higher energy prices. In the figure, it can be seen that the EV charging stops it charging when the battery capacity is above the reference level as shown in section *"4.5 Electric Vehicle Charging Model"*

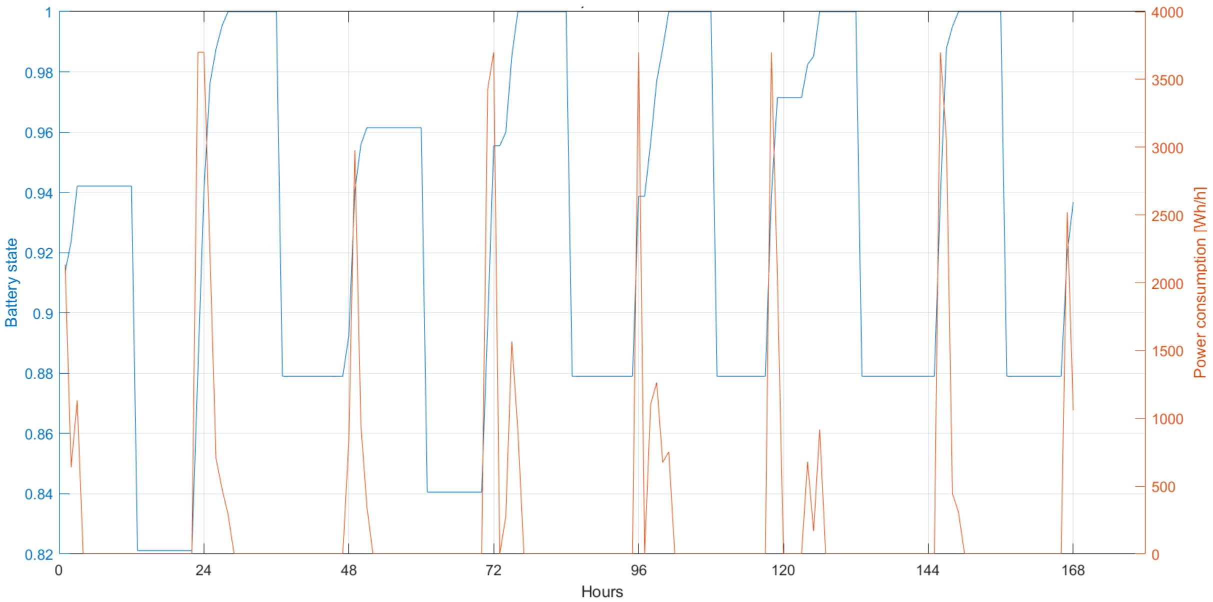

Figure 32: Electric vehicle charging with EMS.

The simulated yearly energy cost for the EV with EMS for 2019 is at 982.1 NOK, and the consumption is at 2745.5 kWh.

6.2.4 Total Load

Figure 33 shows the total load for the dwelling with both the reference case and the EMS without a DL. The reference case market in red and the case with EMS without a DL is market in blue. The load peaks with the EMS without the DL is higher than the load in the reference curve. Where the reference curve has energy peaks (at approximately 7.6 kWh/h during week 6) in the early evening hours around 17:00, the blue curve with the EMS has similar consumption peaks around midnight.

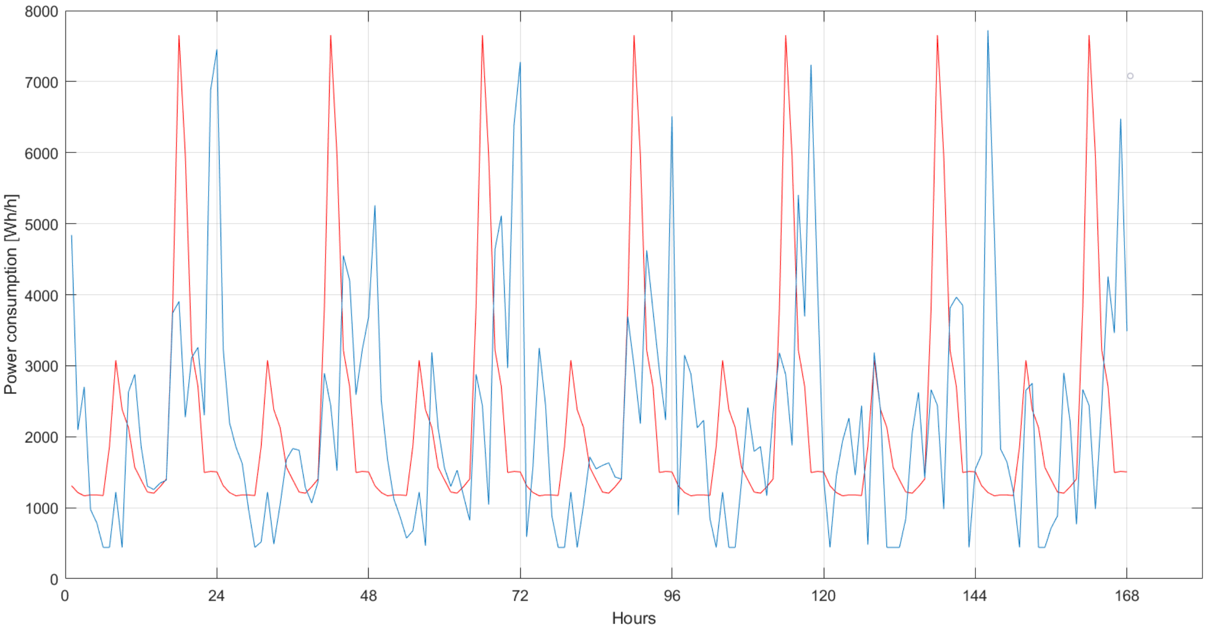

Figure 33: Total Load with EMS compared to the reference case.

6.2.5 Peak Reduction

When simulating an entire year in the simulations, it's found that the highest consumption in the reference case is at 7687.2 Wh/h on the 28 of February at 18:00, while the highest consumption with the EMS is at 8958.3 Wh/h on the 18 of October at 21:00. This means that the highest consumption peak has not been decreased, but increased by 16.53%. With an increasing consumption peak, the EMS system that has been designed does have an potential economic downside for the DSO or TSO.

6.2.6 Energy Prices

The energy price for the reference case is calculated to be 6762.6 NOK. For the case with an EMS system, the calculated energy price is 6579.3 NOK, compared to the reference case, it is a price reduction of 2.78%. These numbers show little savings for the EMS system with Norwegian prices, in the terms of power prices.

6.2.7 Grid Tariffs

Table 10 shows the calculated values for the different grid tariffs. Max load was at 8958.3 Wh/h and set the basis for the capacity limit. The best outcome was given with a subscription value of 4600 Wh/h.

Table 10: Grid tariffs with EMS [NOK].

Subscription: 4600 W Max Load: 8958.3 W	**Present tariff**	**Subscribed-effect**	**Measured-effect**	**Capacity-limit**
NOR - EMS	5218.3	4929.8	7850.0	5675.9

6.2.8 Total Price

For the case with EMS without DL for the combined cost with the different grid tariff models are shown in table 11. The cheapest alternative is the Subscribed-effect grid tariff at a combined cost at 11509.1 NOK.

Table 11: Total energy cost with EMS [NOK].

NO - EMS without DL	**Present tariff**	**Subscribed-effect**	**Measured-effect**	**Capacity-limit**
Grid tariff	5218.3	4929.8	7850.0	5675.9
Energy price	6579.3	6579.3	6579.3	6579.3
Combined cost	11797.6	11509.1	14429.3	12255.2

6.3 Results With EMS and Demand Limit

These simulations have been tested to find the most price-efficient DL. The most economical DL is found at 2.7 kWh/h. The critical load peak surpasses 2.6 kWh/h, and DL lower than 2.7 kWh/h was therefore not considered. The low DL might compromise user comfort in a real case where temperature data are used instead of monthly averages, and the electricity consumption for the EV varies. This brings the indoor temperature below comfortable levels and the EV with an empty battery. It is, therefore advised to have a higher capacity limit to avoid such scenarios.

6.3.1 Electric Water Heater

In figure 34 the temperature for the hot water and the effect for the EWH with the EMS and a DL of 2.7 kWh/h is shown. The red line shows power consumption, and the blue line shows water temperature. Power consumption lays at or close to 0 Wh/h, typically around 17:00 but reaches 1200 Wh/h and 1300 Wh/h about once or twice a day, around mid-day. The water temperature is between 60°C and 83°C this week.

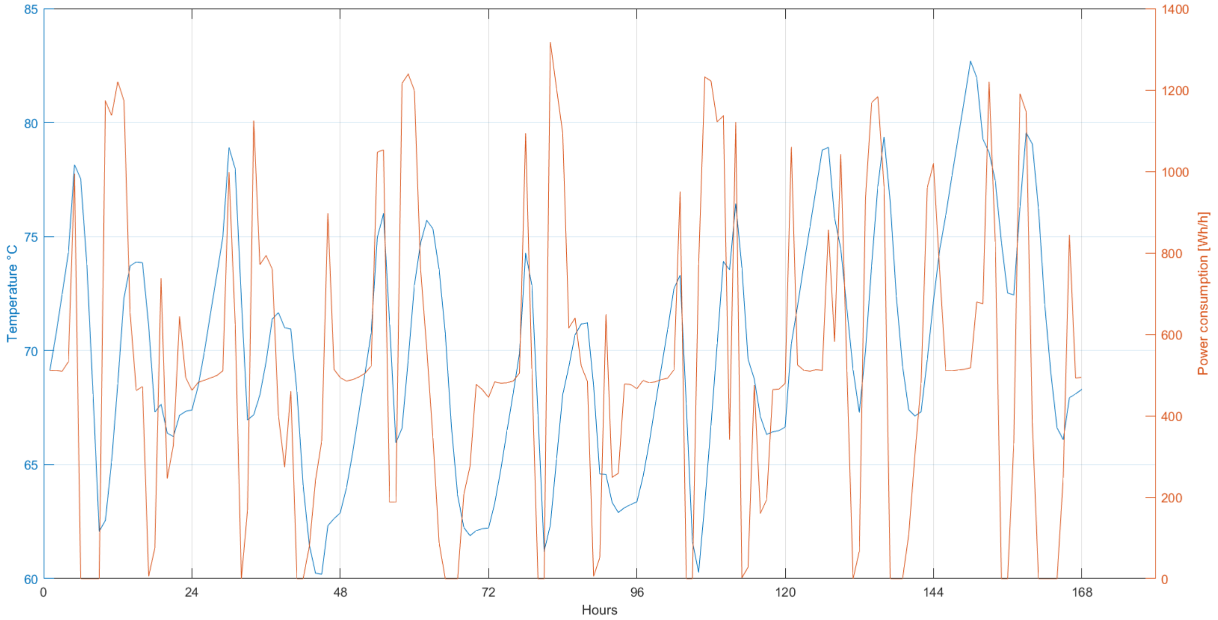

Figure 34: Water heating with EMS and a demand limit.

The simulated energy cost for the EWH with EMS and DL for 2019 is at 1740.4 NOK, and the consumption is at 4561.7 kWh. The lowest recorded temperature in the EWH during the year is at 53.71°C. This is well above the temperatures where legionella starts to grow in the water seen in section *"4.3 Electric Water Heater Model"*

6.3.2 House Heating

Figure 35 shows building temperature and power consumption. Temperature reference varies between 19°C and 21°C, and the temperature reaches almost as low as 18.6°C. During week 6, in 2019, data. The highest reach this week was approximately 20.5°C. Electric load never surpassed 1500 Wh/h. This is low compared to the installed effect, but the electric heating is completely off during short periods compared to the reference case.

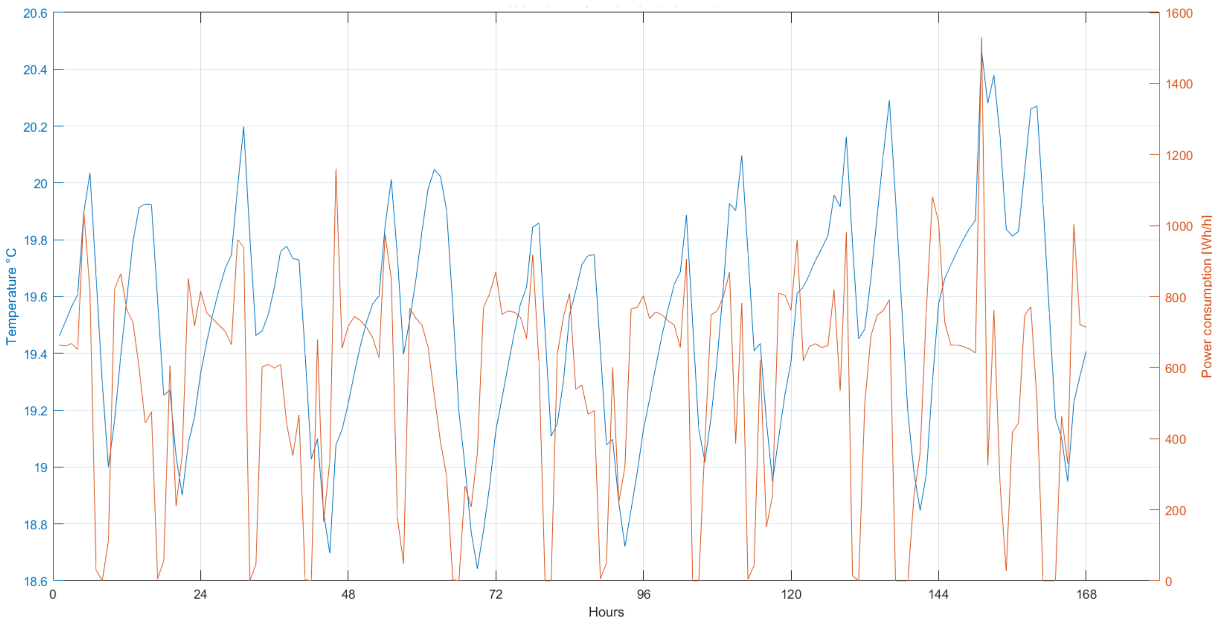

Figure 35: House heating with EMS and a demand limit of 2.7 kWh/h.

The simulated energy cost for the house heating with EMS and DL for 2019 is at 1067.2 NOK, and the consumption is at 2614.6 kWh. The lowest recorded indoor temperate recorded during a year is at 18.24°C. Even with these low, stable effects, the user comfort is preserved.

6.3.3 Electric Vehicle Charger

Figure 36 shows EV rate of charge and electric load. The blue line is the battery charge. The battery charge increases while charging occurs, and decrease only once a day as daily driving is modeled as an instant energy loss. It is only able to charge in the evenings and nights. In the case with EMS and DL, the battery level is stable lower than the case without the DL. Even if the battery level for the EV is lower than for the case without the DL, there are still plenty of battery capacity left for the vehicle.

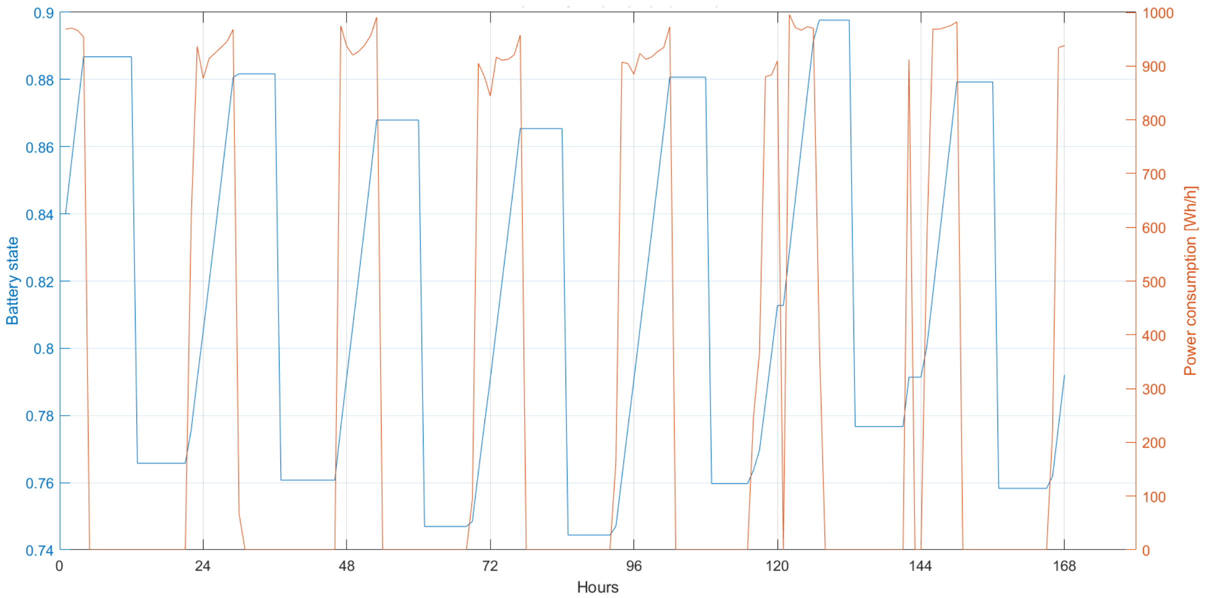

Figure 36: Electric vehicle charging with EMS and demand limit of 2.7 kWh/h.

The simulated energy cost for the EV with EMS and demand limit for 2019 is at 993.2 NOK, and the consumption is at 2737.5 kWh. The lowest recorded battery level during the year is at 60.50%, which means that the user comfort is preserved.

6.3.4 Total Load

Figure 37 shows total electric load with EMS, with and without DL. The red line shows without DL and the blue line shows with DL at 2.7 kWh/h. The power demand without DL, red line, spikes at approximately 7.6 kWh/h every day, while the power demand with DL, blue line never passes the DL at 2.7 kWh/h.

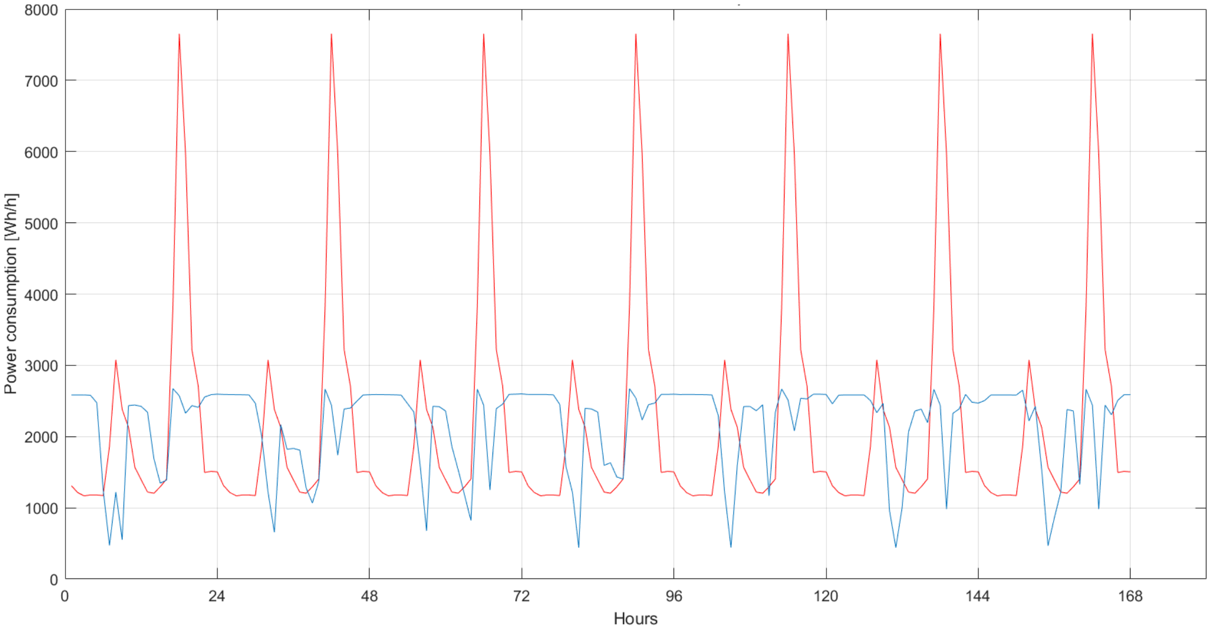

Figure 37: Total load with EMS and a demand limit of 2.7 kWh/h.

6.3.5 Peak Reduction

With the DL, the highest energy peak for an hour is 2699.0 Wh/h, while in the reference case, the highest energy peak is at 7687.2 Wh/h. This is a peak reduction of 64.89%. This is a high peak consumption reduction, and the user comfort almost is not affected at all. This is a good indicator of that the DL for the system works as desired, and that it is possible to flatten the consumption peaks without affecting the user comfort.

6.3.6 Energy Prices

Where the power prices for the reference case is at 6762.6 NOK (shown in section *"6.2.6 Energy prices"*), the power prices for the case with EMS and DL is 6515.1 NOK. This is a reduction of 247.5 NOK or 3.66%. This shows that even with the small variations in the Norwegian power prices, the EMS system with the DL manages to shift the loads towards lower power prices.

6.3.7 Grid Tariffs

The grid tariffs for the EMS with a DL of 2.7 kWh/h is shown in table 12. For these calculations, it was used 2.6 kWh/h as the subscribed effect, and 2.7 kWh/h as the capacity limit.

Table 12: Grid tariffs with EMS and a demand limit of 2.7 kWh/h [NOK].

Subscription: 2600 W Max Load: 2699.0 W	**Present tariff**	**Subscribed-effect**	**Measured-effect**	**Capacity-limit**
NOR - EMS and DL	5175.2	2627.6	4883.7	3517.4

6.3.8 Total Price

Table 13 includes grid tariffs, energy prices, and the combined cost for each case under Norwegian prices with EMS and DL. The DL is at 2.7 kWh/h, and the subscription at its cheapest, 2.6 kWh/h. The cheapest alternative is using the Subscribed-effect grid tariff. The most expensive is the present tariff.

Table 13: Total energy costs with EMS and a demand limit of 2.7 kWh/h [NOK].

NO - EMS & DL [NOK]	**Present tariff**	**Subscribed-effect**	**Measured-effect**	**Capacity-limit**
Grid tariff	5175.2	2627.6	4883.7	3517.4
Energy price	6515.1	6515.1	6515.1	6515.1
Combined cost	11690.3	9142.7	11398.8	10032.5

Different prices with other DLs and subscription values were also calculated. This was to demonstrate how the combined cost changes with a changing DL. The results for these calculations is shown in table 14.

Table 14: Combined costs for the different grid tariffs with EMS and demand limits [NOK].

DL/ Capacity [Wh/h]	**Subscription Value [Wh/h]**	**Present tariff**	**Subscribed-effect**	**Measured-effect**	**Capacity-limit**	**Energy cost**
2700	**2600**	11690	9142.6	11399	10032	6515.1
2800	**2700**	11699	9192.5	11434	10072	6518.9
2900	**2800**	11707	9262.6	11504	10110	6522.2
3000	**2900**	11714	9334.1	11585	10150	6525.8
3100	**3000**	11721	9406.2	11668	10189	6529.4
3200	**3000**	11727	9475.0	11746	10226	6532.3
3300	**3100**	11734	9531.5	11828	10265	6536.2

6.4 Reference Case - no Load Shifting, Danish Price Market

Danish electricity prices are used to represent more volatile energy prices for markets with more intermittent renewable energy. The Danish power grid has a lot of wind energy, a form of energy that will impact the Norwegian power grid in the future. The Danish power price market are therefor used to simulate a potential future price market for Norway, more affected by intermittent energy sources.

Since the user pattern for the reference case is more or less the same and does not regard the electricity prices, the electricity usage pattern is identical to the reference cases with Norwegian prices. See section*"6.1 Reference Case- no Load Shifting"* for EWH, house heating, and EV. Therefore only the price results from the simulations are presented for the danish reference case. The simulated energy cost for the EWH is at 1874.1 NOK, house heating at 1034.8 NOK, and EV charging is at 1204.8 NOK, for the reference case with Danish prices during a 2019.

6.4.1 Energy Prices

In the reference case with Danish market prices, the energy cost was at 6881.0 NOK for the household in 2019. This is some higher than the power prices for the reference case with the Norwegian price market shown in section *"6.1.6 Energy Prices"*

6.4.2 Grid Tariffs

After a lot of calculation and testing, the optimal prices for the Subscribed-effect grid tariff and Capacity-limit grid tariff where found, these prices can be seen in table 15 among with the other grid tariff costs. In this case, the optimal subscription was found to be at 5.4 kWh/h for the reference case. The Capacity-limit grid tariff are equal to the highest consumption for an hour during the year at 7687.2 Wh/h.

Table 15: Reference grid tariffs with EMS, a demand limit of 2.7 kWh/h, and Danish prices [NOK].

Subscription: 5400 W Max Load: 7687.2 W	**Present tariff**	**Subscribed-effect**	**Measured-effect**	**Capacity-limit**
DK - Reference Case	5196.3	5294.9	8712.1	5234.0

6.4.3 Total Prices

Table 16 includes grid tariffs, energy prices, and combined cost with danish power prices, no EMS, and no DL. The cheapest alternative is the Present tariff. It is worth noticing that all the tariff models are quite similar except for the Measured-effect, which is more expensive.

Table 16: Total energy cost with EMS,a demand limit of 2.7 kWh/h, and Danish prices.

DK - Reference case [NOK]	**Present tariff**	**Subscribed-effect**	**Measured-effect**	**Capacity-limit**
Grid tariff	5196.3	5294.9	8712.1	5234.0
Energy price	6881.0	6881.0	6881.0	6881.0
Combined cost	12077.3	12175.9	15593.1	12115.0

6.5 Results With EMS Without Demand Limit - Danish Price Market

This case is set up to highlights the load-shifting potential for energy cost savings. The EMS is controlled to save on energy prices, and there is no limit to energy consumption. As the Danish price market are more volatile, which should make for a better saving potential than the similar case with a Norwegian price market in section *"6.2 Results With EMS Without Demand Limit"*.

6.5.1 Electric Water Heater

Figure 38 shows the hot water temperature and the power consumption for the EWH. The figure shows that the EWH heats up in a different pattern than with the Norwegian market prices. With the Danish market prices, there are often energy peaks during the middle of the day. While with the Norwegian prices, the EWH wants to heat during the night. In this case, the temperatures vary between 60°C and 90°C during the week, and the EWH often has hours at full load to heat the water.

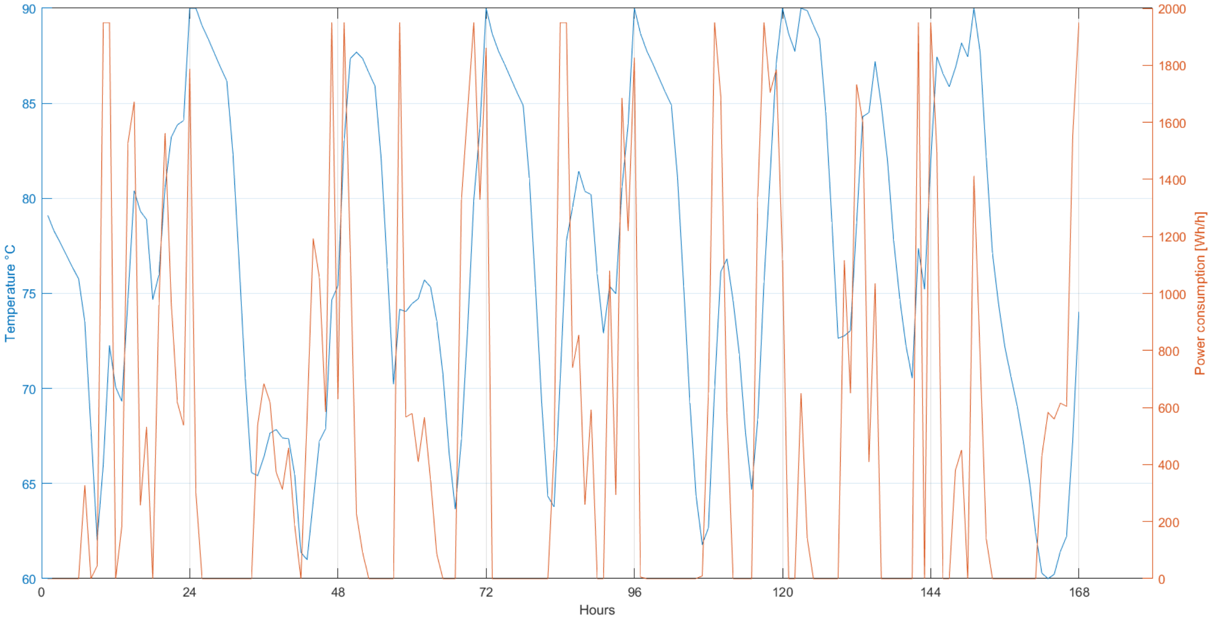

Figure 38: Water heating with EMS and Danish prices.

The simulated energy cost for the EWH with EMS and Danish market prices, for 2019 is at 1658.3 NOK, and the consumption is at 4681.0 kWh.

6.5.2 House Heating

Figure 39 shows the temperature in the household and the power consumption for the heat, for the case with EMS without DL. In the figure, the temperature varies between 19°C and 21°C. Even with these temperature changes, the power consumption for the house heating rarely is at full capacity.

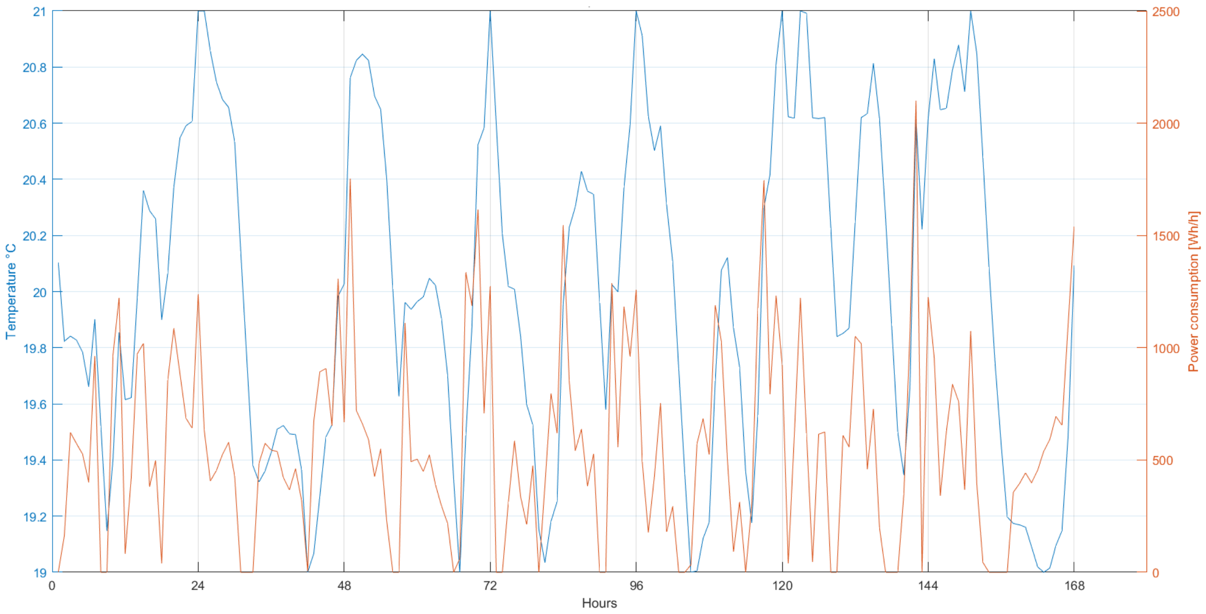

Figure 39: House heating with EMS and Danish prices.

The simulated energy cost for the house heating with EMS and Danish market prices, for 2019 is 977.1 NOK, and the consumption is at 2721.0 kWh.

6.5.3 Electric Vehicle Charger

Figure 40 shows the charging of the EV together with the battery charging state with EMS without a DL. In this case, the battery level varies between 75% and 100 % while the charger often draws the maximum capacity during an entire hour during the night.

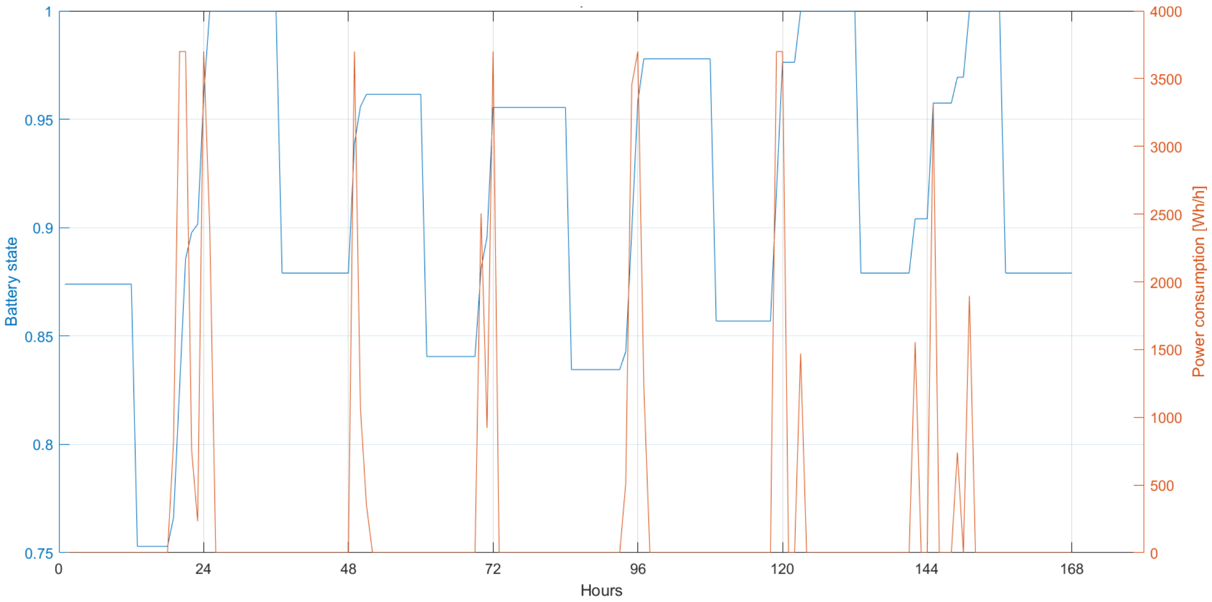

Figure 40: Electric vehicle charging with EMS and Danish prices.

The simulated energy cost for the EV with EMS and Danish price market, for 2019 is at 796.2 NOK, and the consumption is at 2759.4 kWh.

6.5.4 Total Load

The total load for the household with EMS without the demand limit, as shown in figure 41. The case with EMS without a DL is shown in blue, while the reference case is in red. In this case, the household's total load has increased during the night compared to the reference case. In the figure the highest consumption peaks is generally higher than the consumption for the EMS with Danish market prices. The consumption peak is around 7.6 kWh/h while the case with EMS has one high peak of 8.2 kWh/h.

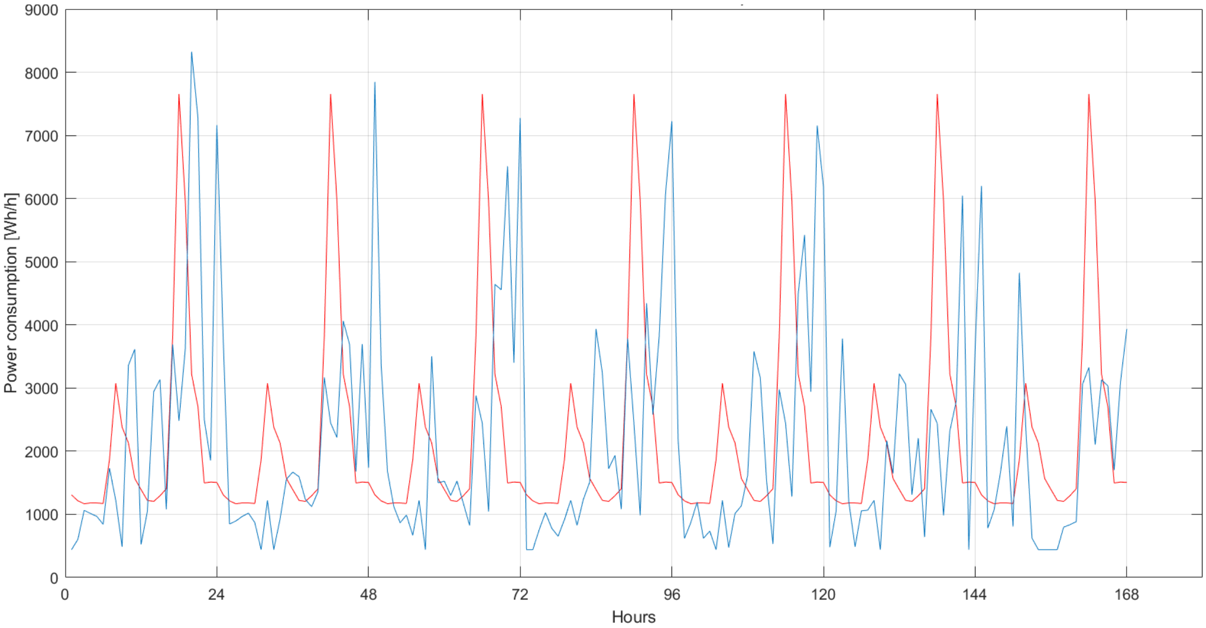

Figure 41: Total load with EMS and Danish prices.

6.5.5 Peak Reduction

The highest consumption peak for a year recorded in the reference case with danish market prices is on the 28 of February 18:00 with a value of 7687.2 Wh/h. The highest consumption peak, for the case with EMS without a DL, is on the 3 of January 01:00 with a value of 9 479.5 Wh/h. This is a peak increase of 23.31% compared to no EMS.

6.5.6 Energy Prices

The energy prices for the reference case with Danish price market data are 6881 NOK. In the case with EMS, but without the DL, the energy prices are 6191 NOK. which is a reduction of 10.02%.

6.5.7 Grid Tariffs

In this case, the most cost-efficient solution for the Subscribed-effect grid tariff was at 4,7 kWh/h, and the Capacity-limit tariff is set to 9479.5 W due to the highest power consumption during the year. The prices for the different grid tariffs can be seen in table 17. Here it shows that the Measured-effect is much higher than the other grid tariff solutions due to the highest consumption peak during the year.

Table 17: Grid tariffs with EMS and Danish prices [NOK].

Subscription: 4700 W Max Load: 9479.5 W	**Present tariff**	**Subscribed-effect**	**Measured-effect**	**Capacity-limit**
DK - EMS	5221.2	5083.3	7989.9	5855.5

6.5.8 Total Price

Table 18 includes grid tariffs, energy-prices, and the combined cost for each case under Danish market prices with EMS without DL.The subscription at its cheapest at 4.7 kWh/h. The cheapest alternative is using the Subscribed-effect grid tariff. The most expensive is the Measured-effect tariff.

Table 18: The combined energy cost with EMS and Danish prices [NOK].

DK - EMS without DL [NOK]	**Present tariff**	**Subscribed-effect**	**Measured-effect**	**Capacity-limit**
Grid tariff	5221.2	5083.3	7989.9	5855.5
Energy price	6191.0	6191.0	6191.0	6191.0
Combined cost	11412.2	11274.3	14180.9	12046.5

6.6 Results With EMS and Demand Limit - Danish Price Market

This case will show how EMS and DL work together under Danish market prices. The most economical DL was, as with Norwegian prices, 2.7 kWh/h. The lowest DL tested, this as critical loads surpass 2.6 kWh/h and a DL less than that would affect user comfort. See section *"6.3 Results With EMS and Demand Limit."*

6.6.1 Electric Water Heater

The hot water temperature and power consumption with EMS and a DL on 2.7 kWh/h are shown in figure 42. In this case, the temperatures during the week vary between 55°C and 88°C. These is within the acceptable interval, so legionella does not grow in the water, and user comfort is preserved. This is a good indicator that the DL works for the EWH with Danish market prices as well.

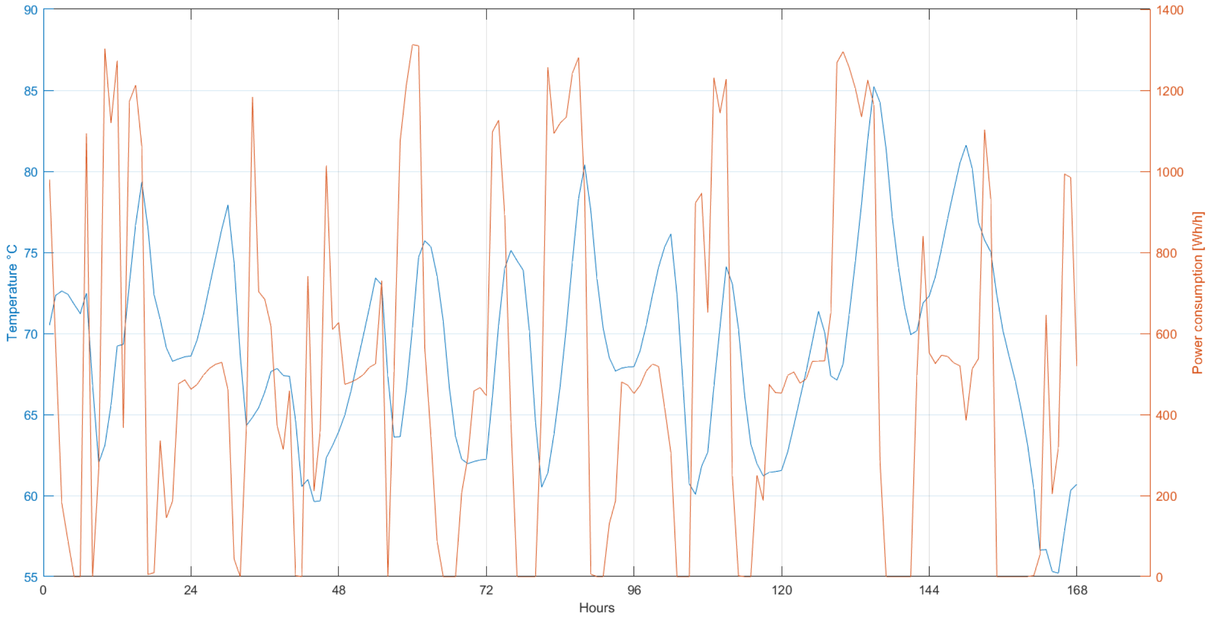

Figure 42: Water heater with EMS, a demand limit of 2.7 kWh/h, and Danish prices.

The simulated energy cost for the water heater with EMS, DL, and Danish prices for 2019 is at 1651.7 NOK, and the consumption is at 4581.8 kWh. The lowest recorded temperature in the EWH during the year is at 53.62°C.

6.6.2 House Heating

Figure 43 shows the house heating for the case with EMS and a DL of 2.7 kWh/h. Here the temperature is much more stable around 19.5°C and the power drawn from the house heating is never higher than 1400 Wh/h. At the coldest periods during the week, it is a little colder then the set temperature range, so the user comfort may be a little compromised.

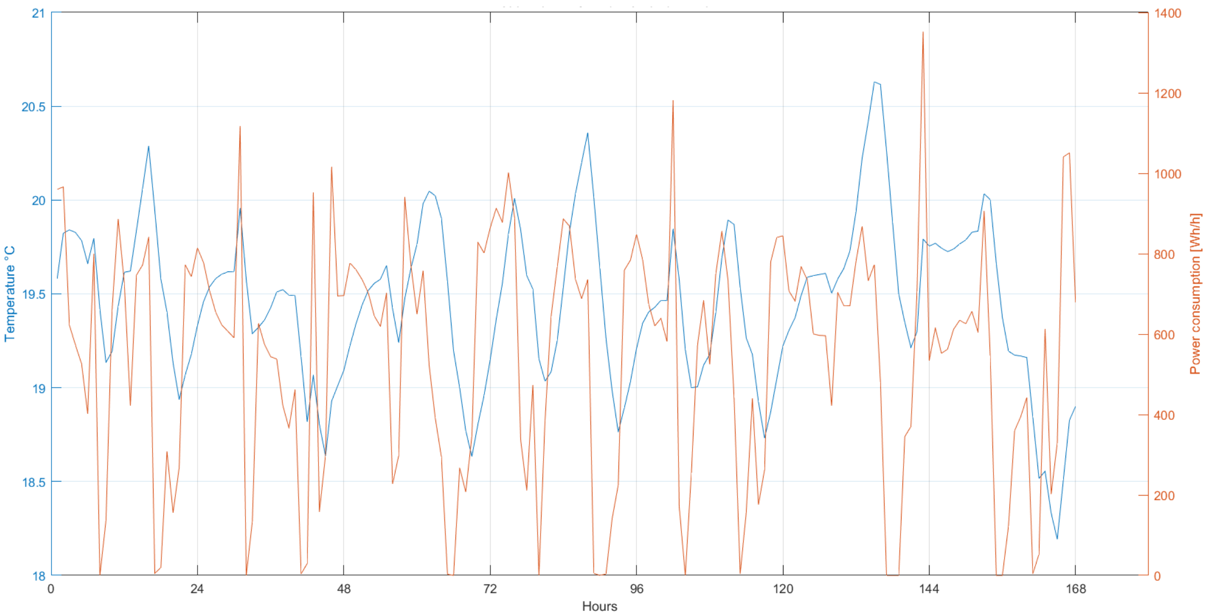

Figure 43: House heating with EMS, a demand limit of 2.7 kWh/h, and Danish prices.

The simulated energy cost for the house heating with EMS, DL, and Danish price market for 2019 is at 939.8 NOK, and the consumption is at 2620.3 kWh. The lowest recorded temperature for the house during a year is at 18.10°C.

6.6.3 Electric Vehicle Charger

The EV charging with Danish market prices, EMS, and a DL of 2.7 kWh/h is illustrated in figure 44. The lowest battery charge rate during the week is at 74% battery capacity, while the highest charge rate during the week is at 89% when the vehicle charges are usually charges between 800 W and 1 kW.

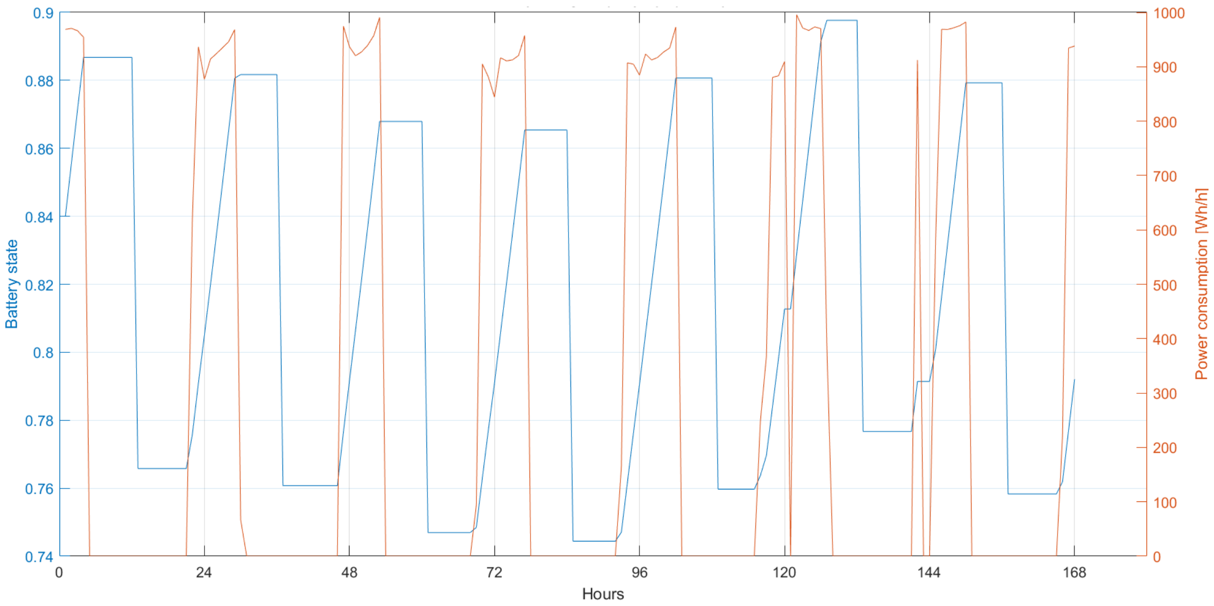

Figure 44: Electric Vehicle charging with EMS, a demand limit of 2.7 kWh/h, and Danish prices.

The simulated energy cost for the EV charging with EMS, DL, and Danish price market for 2019 is at 856.3 NOK, and the consumption is at 2749.8 kWh. The lowest recorded charging state for the vehicle during a year is at 47.52%.

6.6.4 Total Load

The total load for the household with EMS, a DL of 2.7 kWh/h, and Danish market prices is shown in figure 45. As seen in the figure, the load never exceeds 2.7 kWh/h, while the total load for the reference case exceeds 7.6 kWh/h every day. It shows that the DL works in the Danish market, but due to the more aggressive price variations, the willingness to use power is overall lower.

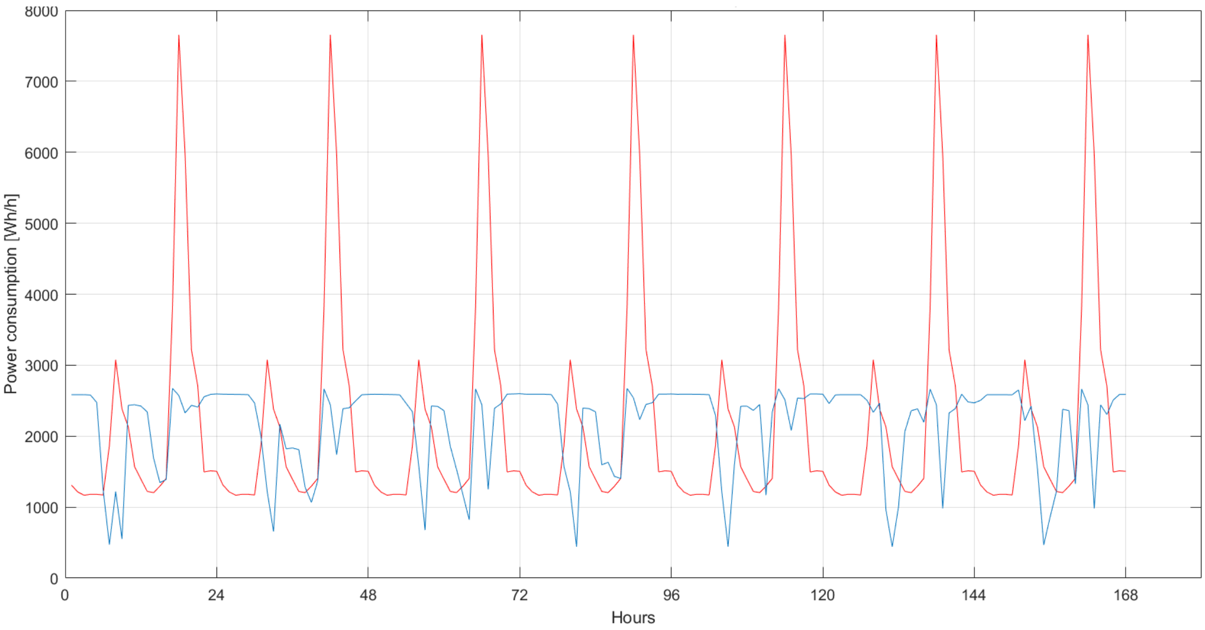

Figure 45: Total load for the household with EMS, a demand limit of 2.7 kWh/h, and Danish prices.

6.6.5 Peak Reduction

The highest load for the reference case is 7687.2 Wh/h, and the highest load with DL during the year is 2699.8 Wh/h. The highest load peak during the year is reduced by 64.89% for the case with EMS and a DL of 2.7 kWh/h. Same as with the Norwegian price market.

6.6.6 Energy Prices

The energy price for this case is 6210.8 NOK; this is a reduction of 9.7% compared to the reference case of 6881.0 NOK.

6.6.7 Grid Tariffs

The grid tariffs for the case with Danish market prices, EMS, and a DL of 2.7 kWh/h is calculated in table 19.

Table 19: Grid tariffs with EMS, a demand limit of 2.7 kWh/h, and Danish prices [NOK].

Subscription: 2600 W Max Load: 2699.8 W	**Present tariff**	**Subscribed-effect**	**Measured-effect**	**Capacity-limit**
DK - EMS and DL	5182.3	2629.9	4885.8	3519.6

6.6.8 Total Price

The combined cost with the EMS, DL, and danish price market are calculated in table 20.

Table 20: The combined energy cost with EMS, a DL of 2.7 kWh/h, and Danish prices [NOK].

DK - EMS & DL [NOK]	**Present tariff**	**Subscribed-effect**	**Measured-effect**	**Capacity-limit**
Grid tariff	5182.3	2629.9	4885.8	3519.6
Energy price	6210.8	6210.8	6210.8	6210.8
Combined cost	11393.1	8840.7	11096.6	9730.4

A table with results for the different DLs was created to find the optimal DL. In table 21, the combined cost with different DLs, grid tariffs and energy prices are compared to each other. Based on the results from table 21, the DL for these simulations is chosen as the most economical value. With the new grid tariff models, the most cost-effective DL is at 2.7 kWh/h for the case; therefore, the DL is chosen to be 2.7 kWh/h for these simulations. With lower DL, user comfort is more compromised than if the DL is at a higher level. Therefore for a real-life implementation, it is recommended that the DL is at a higher level.

Table 21: Total prices for the different grid tariffs with EMS, demand limits and Danish prices [NOK].

DL/ Capacity [Wh/h]	**Subscription value [Wh/h]**	**Present tariff**	**Subscribed-effect tariff**	**Measured-effect tariff**	**Capacity-limit tariff**	**Energy price**
2700	**2600**	11393.1	8840.7	11096.6	9730,4	6210.8
2800	**2700**	11387.7	8875.7	11184.2	9755.5	6201.1
2900	**2800**	11383.1	8934.4	11175.6	9783.0	6192.5
3000	**2900**	11380.8	8996.8	11249.0	9812.1	6186.7
3100	**3000**	11377.8	9058.4	11315.7	9841.4	6180.6
3200	**3100**	11375.2	9122.0	11389.5	9871.0	6175.2
3300	**3100**	11373.5	9171.6	11460.8	9901.8	6171.3

7 Discussion

This chapter discusses the simulation results and how the different components, tariffs, models behave if implemented on a large scale.

As the proposed tariffs from NVE that are up for hearing, and our results show almost identical prices, but a significant potential to save money for the consumer by drastically reducing load peeks with little compromise for consumer comfort, EMS systems will be an important part of our power system.

The topics treated will be related to the *"1.1 Problem Statement"*. First some of the results will be represented in new tables facilitating comparisons in section *"7.1 Comparing Results"*. Then some technical, and consumer relevant aspects in *"7.2 Technical"* and *"7.3 Consumers"*. In *"7.4 Society"* and *"7.5 Adaptability for EMS"* some more general descriptions of economic and societal affects. While in *"7.6 Grid Tariffs"*, grid tariffs are compared and discussed.

7.1 Comparing Results

There are six cases in the chapter *"6 Results";* reference cases, cases where the EMS act on energy prices, and where a DL is included for Norwegian and danish prices as the foundation for the willingness and reference curves.

This section presents some of these results again, and the ratio between some of them. The objective is to see what the EMS and DL does, how different price data will give different results, and compare the grid tariffs combined cost and incentives to reduce load peaks.

7.1.1 Total Load Shifting

Figure 37 in section *"6.3.4 Total Load"*, shows electric load during the reference case, and with EMS and DL during the same week. The total load shifting for both the Norwegian and the Danish market, was reduced by 64.89%, from 7687.2 Wh/h to 2.7 kWh/h.

7.1.2 Energy Prices for Components

The energy cost for the components controlled by the EMS are shown in table 22. The costs are the accumulation for the entire year of 2019.

Table 22: Energy prices for the EMS controlled components.

With Norwegian prices [NOK]			
Component	**Reference Case**	**EMS**	**EMS with DL**
EWH	1830.3	1774.3	1740.4
House heating	1112.9	1113.9	1067.2
EV	1107.3	982.1	993.2
Total consumption	6762.6	6579.3	6515.1
With Danish prices [NOK]			
Component	**Reference Case**	**EMS**	**EMS with DL**
EWH	1874.1	1658.3	1651.7
House heating	1034.8	977.1	939.8
EV	1204.8	796.2	856.3
Total consumption	6881.0	6191.0	6210.8

The savings each component in percentage is shown in table 23.

Table 23: Energy price savings for each component given in percent.

Savings with Norwegian prices			
Equipment	**Reference Case**	**EMS**	**EMS with DL**
EWH	0%	3.06%	4.91%
House heating	0%	-0.09%	4.11%
EV	0%	11.31%	10.30%
Total consumption	0%	2.71%	3.66%
Savings with Danish prices			
Equipment	**Reference Case**	**EMS**	**EMS with DL**
EWH	0%	11.51%	11.87%
House heating	0%	5.58%	9.18%
EV	0%	33.91%	28.93%
Total consumption	0%	10.03%	9.74%

7.1.3 Energy use for Components

Table 24 shows, the energy consumption for the EMS controlled components are compared. The overall energy consumption is a little lower for the water heater and house heating with EMS and DL. This is because the average temperature is a little lower, and therefore the energy losses are higher.

Table 24: Energy consumption for the EMS controlled components.

Energy use with Norwegian prices [kWh]			
Equipment	**Reference Case**	**EMS**	**EMS with DL**
Water heater	4636.9	4672.3	4561.7
House heating	2653.0	2727.7	2614.6
Electric Vehicle	2737.5	2745.5	2737.5
Energy use with Danish prices [kWh]			
Equipment	**Reference Case**	**EMS**	**EMS with DL**
Water heater	4636.9	4681.0	4581.8
House heating	2653.0	2721.0	2620.3
Electric Vehicle	2737.5	2759.4	2749.8

7.1.4 Grid Tariffs, and Energy Prices

Table 25 shows grid tariffs calculated for Norwegian and Danish prices, for power consumption without EMS, with EMS, and with EMS and DL. The lowest grid prices for both Norwegian and Danish prices occur with the use of EMS and DL, respectively, at 2627.6 NOK and 2629.9 NOK.

Table 25: Comparison of grid tariffs.

With Norwegian Prices [NOK]					
	Present tariff	**Subscribed-effect**	**Measured-effect**	**Capacity-limit**	**Energy price**
Reference Case	5196.3	5294.9	8712.1	5234.0	6762.6
EMS	5218.3	4929.8	7850.0	5675.9	6579.3
EMS with DL	5175.2	2627.6	4883.7	3517.4	6515.1
With Danish Prices [NOK]					
	Present tariff	**Subscribed-effect**	**Measured-effect**	**Capacity-limit**	**Energy price**
Reference Case	5196.3	5294.9	8712.1	5234.0	6881.0
EMS	5221.2	5083.3	7989.9	5855.5	6191.0
EMS with DL	5182.3	2629.9	4885.8	3519.6	6210.8

7.1.5 Combined Cost

Table 26 shows the combined cost for the four grid tariffs and three EMS options for both Norwegian and Danish prices. The lowest grid tariff for both Norwegian and Danish energy prices is the option with EMS and DL using the Subscribed-effect tariff, at respectively 9142.7 NOK and 8840.7 NOK per year. Measured effect and reference energy use are the most expensive with both price-sets.

From the reference case with the present tariff to the cheapest alternative with the proposed tariffs, there is saving of 23.55% or 2816.2 NOK with Norwegian prices, and 26.80% or 3236.6 NOK with Danish prices. This is a substantial reduction.

Table 26: Comparison of combined costs, Tariff and energy prices.

With Norwegian Prices [NOK]				
	Present tariff	**Subscribed-effect**	**Measured-effect**	**Capacity - limit**
Reference Case	11958.9	12057.5	15474.7	11996.6
EMS	11797.6	11509.1	14429.3	12255.2
EMS with DL	11690.3	9142.7	11398.8	10032.5
With Danish Prices [NOK]				
	Present tariff	**Subscribed-effect**	**Measured-effect**	**Capacity - limit**
Reference Case	12077.3	12175.9	15593.1	12115.0
EMS	11412.2	11274.3	14180.9	12046.0
EMS with DL	11393.1	8840.7	11096.6	9730.4

7.1.6 Savings

Table 27 shows the percentage of combined cost savings, power, and grid tariff, for the different grid tariffs when EMS and EMS with DL are used. The top table shows the cases with Norwegian power prices. The bottom table shows the cases with Danish power prices. All the proposed grid tariffs give significant price reductions when DL is introduced. With only EMS, the price reduction is lower, and as the peek demand is higher, the capacity limit-based tariff ensures slightly higher combined costs.

The combined cost for the Present tariff is slightly lower with EMS and just some lower with the EMS with DL. This can be explained by the lower energy cost and a slight difference in total energy use in the three cases.

When simulating with Norwegian power prices, the total energy price is 2.7% lower with the EMS, and 3.66% with EMS and DL. The DL reduces the total energy use as it forces a lower average indoor temperature. With Danish prices, the DL decreases the power cost savings from 10.03% to 9.74% as it forces the system to use power even when it is not cheap. With prices from the NO2 market area, DL has the opposite effect. This is most likely due to high installed effect heating the building up while the prices decrees, and the DL delay some of the power-consumption to spread out during the willingness top. This could also be achieved by introducing a delay, for example, in floor heating or increased thermal mass in the building.

Table 27: Savings in percent compared to the reference case

With Norwegian prices					
	Present tariff	**Subscribed-effect**	**Measured-effect**	**Capacity - limit**	**Energy price**
Reference case	0%	0%	0%	0%	0%
EMS	1.35%	4.55%	6.76%	-2.26%	2.7%
EMS with DL	2.25%	24.17%	26.34%	16,37%	3.66%
With Danish prices					
	Present tariff	**Subscribed-effect**	**Measured-effect**	**Capacity - limit**	**Energy price**
Reference case	0%	0%	0%	0%	0%
EMS	5.51%	7.40%	9.06%	0.57%	10.03%
EMS with DL	5.67%	27.39%	28.84%	19.68%	9.74%

Table 28 shows total savings when changing to the proposed tariffs in percent, compared to the Present tariff. Positive numbers describe savings in the form of lower tariffs, and negative numbers how much more expensive the energy bill will be. This table demonstrates what tariff to choose for each consumption pattern. In the reference case, Present tariff, Subscribed-effect tariff and Capacity-limit cost about the same. For both the case with EMS and with EMS and DL, the Subscribed-effect tariff has the lowest cost.

Table 28: Savings in percent compared to the Present grid tariffs

With Norwegian Prices				
	Present tariff	**Subscribed-effect**	**Measured-effect**	**Capacity - limit**
Reference Case	0%	-0.82%	-29.40%	-0.32%
EMS	0%	2.45%	-22.31%	-3.88%
EMS with DL	0%	21.79%	2.49%	14.18%
With Danish Prices				
	Present tariffs	**Subscribed-effect**	**Measured-effect**	**Capacity - limit**
Reference Case	0%	-0.82%	-29.11%	-0.64%
EMS	0%	1.21%	-24.26%	-5.55%
EMS with DL	0%	22.40%	2.60%	14.59%

7.1.7 Peak Reduction

The peak reduction/gain for each of the cases is given in table 29. With the EMS without DL, the peak is increased by 16.53% and 23.31% when simulated with Norwegian and Danish prices. With the EMS and DL, the peak is reduced by remarkable 64.89% using price data from both Norwegian and Danish markets.

Table 29: Combined consumption peak reduction in percent

With Norwegian Prices		
	Highest consumption peak [Wh/h]	**Peak reduction**
Reference Case	7687.2	0%
EMS	8958.3	-16.53%
EMS with DL	2699.0	64.89%
With Danish Prices		
	Highest consumption peak [Wh/h]	**Peak reduction**
Reference Case	7687.2	0%
EMS	9479.5	-23.31%
EMS with DL	2699.8	64.89%

7.2 Technical

This section provides a discussion about how the different technical solutions worked and did not, based on the simulation results.

7.2.1 Electric Water Heater

In modeling an EWH, we have not taken stratification into account, but instead focused on the overall energy stored in the tank. Stratification can lead to sensor failure and, therefore, problems with the control system controlling power to the EWH. However, stratification will lead to stable high temperatures near the top where most storage tanks are drained.

By comparing the results in table 22 and 23 in section *"7.1.2 Energy Prices for Components"*, it can be seen that it is possible to reduce the energy prices for the EWH by load shifting. Even though it is less price variations for the Norwegian market, it can be seen that the potential is higher with Danish market prices. The EWH can be used as thermal storage.

7.2.2 House Heating

By comparing the results in table 22 and 23 in section *"7.1.2 Energy Prices for Components*, it can be seen that there are less savings in the house heating when it comes to setting varying temperatures depending on the electricity prices. The main explanation is that with higher indoor temperatures, the losses also increase. This makes it harder to store energy in house heating from cheaper periods to periods with higher electricity prices. Nevertheless, with EMS and a low DL, the lowest recorded energy during a year is at 18.24°C with Norwegian prices, and 18.10°C with Danish prices. This indicates that it is possible to even out the energy consumption for the house heating by implementing a DL, without affecting the user comfort significantly.

House heating does not have a significant effect on power-price savings. The reduced energy can also be contributed to by the DL that reduces average temperatures and, therefore, losses and power consumption to heating.

7.2.3 Electric Vehicle

When the results in table 22 and 23 in section *"7.1.2 Energy Prices for Components"* is studied, it is observed that there are significant savings for the EV by implementing the EMS system. With the energy prices from 2019 and both EMS and DL, there is a saving of 10.30%, and with the danish prices, there is a saving of 28.93%. Despite these savings, the lowest battery state for the case with Norwegian prices, EMS, and DL is 60.50%. For the case with Danish power prices, EMS, and DL, the lowest battery state recorded is at 47.52%. This indicates that it can be beneficial to have a system like this connected to the EV, both when it comes to the energy prices and when it comes to the total grid tariffs.

EVs represent one of the most significant changes in electricity use in Norway. As mentioned in section *"1.7 Load Demand for Norway"*, too many EVs connected to charge at the same time in one area can cause overloading substations. Nevertheless, the daily average energy need is only 7.14 kWh/h And can without consumer comfort be shifted to reduce grid tariffs and power prices.

7.2.4 Building Standards

The building losses used in our calculations represent a reasonably good insulated home build after the newest technical standards and do not represent the average home in Norway.

The technical standards for insulation, ventilation, and air infiltration have become stricter and more focused on environment and energy conservation. Older buildings with higher heat losses use more energy, leaving higher loads to be moved, but higher heat losses also reduces the time heat energy can be stored.

To evaluate a specific building or building type, simulations should be based on values close to the buildings in question. To assess the grid impact of EMS and energy storage, building masses in areas should be categorized based on size, age, and materials. Big apartment buildings in materials with high thermal mass and modern insulation methods have significantly different energy storage and demand profiles, both with and without EMS. See table 4 in section *"3.9.2 Transmission losses"*. for energy losses based on different technical standards.

7.2.5 Estimators

With further development of EMS after the implementation of the NVEs proposed, effect based grid tariffs, EMS will most likely include estimators for critical load and power need. This can allow for planning energy use differently based on different energy carriers. For example use a heat-pumps to heat the house before temperature drops and more advanced energy management then discussed here.

With more intermittent renewable energy sources in the grid, the Norwegian energy prices will be more dependent on precise weather forecasting. Since the EMS uses *day-ahead* prices as base for the willingness and consumption, and there can be a split between the predicted energy prices and the prices at the time of consumption. Both the DSO and the consumer will have significant benefits from a precise weather prediction when it comes to production and consumption planning.

7.2.6 Load Shifting

With the price dependent EMS based on willingness end energy prices, the total load peek was moved from the early evening hours to the hours just around midnight, see figure 33 in section *"6.2.4 Total Load"*. The energy consumption peeks derby been shifted toward low demand, and low price periods.

The EMS with DL was able to lower the loads to never surpassing 2.7kWh/h, significantly lower than the two other cases with Norwegian prices, that were at 7687.2 Wh/h. See figure 37 in section *"6.3.4 Total Load"* This reduction leaves the energy consumption more even throughout the day, leveling out at the DL itself still limiting the use at the high demand, and price hours around noon and early evening, 17:00. The low DL significantly reduces load-peeks. Moreover, the grid has no new high load-peeks.

7.2.7 Time-of-use Tariffs

Using the models for grid tariffs suggested by NVE for planning future energy-use requires a consumption estimate. They are based on hourly power consumption, and as consumers control some of the most power-consuming components, such as water boilers, coffeemakers and electric stoves.

NVE's hearing proposal suggests that time-of-use tariffs can be included in the three other models. This incentive could be baked into willingness,and move loads towards particular periods within a zone. However, this incentive could not be targeted to specific substations without price discrimination being addressed.

As the total electricity bill can not be determined before the use occurs, planning that includes the proposed grid tariffs can not occur before the time-of-use.

To allow planning, estimators could be used. Using estimators will significantly affect the savings based on how regularly the individuals use energy, or if the individual lives in the way the estimations assumes.

Time-of-use would be a clear signal on when to use energy, allowing willingness to include a part of the grid-tariff in the input price prediction. Energy storing would also not be interfered with by users controlling critical loads such as electric stoves and lighting. Time-of-use tariffs might be advantageous to reduce congestion in grid as it would both lower the willingness during hours of higher tariff and raise the willingness for the rest of the hours. More recherche is needed.

Cheaper electricity can make electricity a preferred energy source for transportation and industries, which today use gas, oil, or coal, like cement- and food-processing, further reducing climate and environmental impact imposed by other fuels. Electrification is one of the most efficient ways to reduce climate and environmental impacts.

7.3 Consumers

This section provides a discussion regarding the consumer and the consumer's benefits. We discuss the economic advantages and disadvantages, and how the user comfort is preserved.

The subscription tariffs meant to replace the Present tariffs for homes is, together with the Capacity-limit, almost exactly as expensive as the Present grid tariff. Both with Norwegian and Danish prices, the three tariffs are within 100 NOK of each other when no EMS is used. See table 25 in section *"7.1.4 Grid Tariffs, and Energy Prices"*. This means that households with their current energy use will pay about the same when changing to either Subscribed-effect or Capacity-limit tariff. However, When EMS based on prices are used, the consumer will save 4.55% and 7.40% in with Norwegian and Danish prices on the combined cost using the Subscribed-effect tariff. Furthermore, they will save 24.17% and 27.39% under the same condition but with a DL at 2.7 kWh/h. See table 27 in section *"7.1.6 Savings"*. From table 26 in section *"7.1.5 Combined Cost"* this is 2914.8 NOK with Norwegian power prices, and 3335.2 NOK with Danish power prices per year. These are substantial savings for a consumer.

7.3.1 Electric Water Heater

With a electricity cost reduction from 1830.3 NOK for the reference case to 1740.4 NOK for the case with EMS and DL. It is a small cost reduction for the energy prices at 89.9 NOK or 4.91% for each year with the Norwegian prices, see table 22 in section *"7.1.2 Energy Prices for Components"*. For the Danish prices, it is a cost reduction from 1874.1 NOK to 1651.7 NOK. This leads to a cost reduction of 222.4 NOK or 11.87%. This shows that the consumer has some economic benefits regarding the power prices with Norwegian prices and even better economic benefits with Danish power prices. Since the lowest recorded temperatures for the EWH is 53.71°C for the Norwegian market, and 47.52°C for the Danish market during a year, the user comfort is preserved. There also is little or none wear on the equipment due to the EMS system. As temperatures daily reach much higher, Legionella is not a problem in this case, see figures 34 and 42.

7.3.2 House Heating

As heating is one of the most significant energy-consuming posts, it is also one of the most significant posts on load-shifting, particularly to even out the consumption tops. However, it is a complex topic with many factors, such as thermal mass, irradiation, and outdoor temperature changes.

With an energy cost reduction from 1112.9 NOK, for the reference case, to 1067.2 NOK for the case with EMS and DL, this is a tiny cost reduction of 45.7 NOK or 4.11% for each year with Norwegian prices. For the Danish prices, there is a cost reduction from 1034.8 NOK to 939.8 NOK. This is a cost reduction of 95.0 NOK or 9.18%. These results show that it is less economical for the user to install an EMS system to control the house heating than the EWH, both when it comes to savings and cost reduction in percentage. Especially when it probably is higher energy losses for the household than for the simulations.

The lowest registered indoor temperature for the house heating is 18.24°C for the Norwegian prices and 18.10°C for the Danish prices. This means that the user comfort is slightly affected on the coldest days during the year. It is also little or none wear on the equipment due to the EMS system.

7.3.3 Electric Vehicle

EV chargers are getting smarter, and there is a good reason for that. As long as the energy user-pattern is reasonably predictable, and the user can fully charge the vehicle before long trips, there is a lot to save on smart charging.

For the EV charging, there is an electricity cost reduction from 1107.3 NOK for the reference case to 993.2 NOK with EMS, DL, and Norwegian prices. This is a cost reduction of 114 NOK or 10.30% for the Norwegian prices. For the Danish prices, it is a cost reduction from 1204.8 NOK to 856.3 NOK. That is a cost reduction of 348.5 NOK or 28.93% in terms of power prices. These results show that there is an excellent potential for EV in terms of savings in power prices.

The lowest charging state for the EV during a year is simulated to be 60.50% with the Norwegian price pattern and 47.52% with the Danish price pattern. This shows that user comfort is preserved when it comes to EV charging with EMS and DL.

When it comes to wear for the EV, there is always wear on the battery. By setting reasonable limits for how much the EV is allowed to charge, these wear can be reduced compared to the standard reference case. By not fully charging the battery every day, this will have a beneficial effect on the battery lifetime.

As the consumer already can buy power based on hourly prices, smart EV chargers can already help the consumer save on the electricity bill. Allowing the growing number of EVs to contribute to the electrification of transport by valley filling.

7.3.4 Active Load Shifting

Consumers control a portion of their energy use directly without any control systems. They turn-on and off dishwashers, washing machines, dry tumblers, and other energy-demanding equipment. By moving these loads, the economic benefit of an EMS will be effected. However, this demands the incentives are high, and the consumers take the time and effort to perform the changes.

7.3.5 Low Demand Limit

Saving energy cost with the present tariff does today mean limiting energy use. Often this is done by better insulation and lower indoor temperatures.

Both cases with the Norwegian and Danish prices, showed that the lowest demand-limit considered, at 2.7 kWh/h is the cheapest alternative. We chose this as the minimum DL as it is the minimum value without affecting critical loads. Experimental runs with lower DLs showed that temperatures and battery charge-states minimum values dropped considerably and that heaters, EWH, and EV charger were not able to draw the energy needed.

As consumers aim to save money, and many buildings today do not have alternative heating sources such as oil and wood stove, they might choose a DL that does not enable them to heat their buildings during cold periods. This could lead to reduced user comfort, or consumers removing DL during cold periods, reintroducing peeks that the grid no longer is designed for.

7.4 Society

Cheap and reliable electric power is one of the essential drivers of increased electrification. Both; reducing grid investments and balancing production and demand will help reduce the cost of electric power.

A more stable and predictable energy demand will help in planning and implementing renewable energy sources and, at the same time, avoid the need for peeker-plants.

7.4.1 Economical Benefits

By allowing consumers to take part in peek reduction and benefit from installing EMS', particularly with the proposed new grid tariffs, widespread adoption of similar systems, as discussed in this study, is likely to happen. The potential savings for a household is significant.

A widespread implementation will contribute to lower consumption peeks and higher low points in the consumption curve, see figure 2 and 5, evening out the power consumption.

If wide spread implementation of EMS systems contribute in load shifting, like indicated in figrue 37 in section "6.3.4 *Total Load*", there are three main economical factors that can be affected.

- **Lower transmission cost:** As seen in table 29 in section *"7.1.7 Peak Reduction"* The peek is reduced by 64.89% for a single household. As other households have similar but not identical patterns, the total consumption peak reduction for a substation in a residential area is probably lower, but still significant. This will eradicate the need for upgrades in residential areas without new construction. Maintenance and replacement of old grid infrastructure will persist. It will also reduce the need for high voltage grid investments.
- **More stable power prices:** As presented in section *"1.11 Electricity Prices and Consumption"* and *"2.9 Correlation Between Consummation and Power Prices"* there is a correlation between power prices and demand. As the EMS shifts loads from high demand towards low demand hours, the combined variation within each day will be reduced.
- **Lower combined cost:** Use of EMS will contribute to lower total power cost for the end-user in the two ways above. By lowering the cost of transmission, and by reducing the extremities in the power markets. The extremities in the market raise the costs by either letting water and wind bypass the turbines as marginal costs are not covered, or by engaging peeker plants, and expensive imported power.

7.4.2 Environmental Benefits

By managing to use energy smarter, it is easier to implement intermittent renewable energy sources into the energy grid. By implementing new renewable energy sources, it is possible to phase out fossil fuels. This can have significant health benefits, WHO estimates that 4.2 million people die every year as a result of air pollution [42]. Also, if an EMS can manage to reduce energy prices, it is less economical to run power plants from fossil fuels. Particularly peeker-plants who often are expensive, polluting plants used to meet peek-demand.

Three ways successful EMS can contribute to lower environmental impact.

- **Fewer grid upgrades:** As mentioned in section *"7.4.1 Economical Benefits"*, peek reduction will reduce the need to upgrade and replace substations, cables, and other infrastructure. Increasing the lifetime and avoiding the construction of large transmission lines are important steps to save the environment and reduce climate impacts.
- **More renewable energy:** Several of the available renewable energy sources in northern Europe, such as wind, solar, and run of river plants, are intermittent and can not regulate power production without cutting back on power production and thereby loos the

power. With more stable power prices and less loss, renewable energy investments get more profitable.

- **Increased electrification:** There are many energy sources available for different purposes. Even though electric power is already widespread, many still rely on fossil fuels within both transport and industry. Keeping the price of electric power low will help the effort to replace fossil fuels.

7.5 Adaptability for EMS

An EMS system can be programmed in many different ways with different goals. Bellow, it is listed some examples for how an EMS system can be used for different purposes, by having an adjustable DL.

- The DL for the EMS system could be adjusted at a maximum level. By doing this it can be made sure that it isn't any high consumption peaks that affects the grid tariffs or the DSO.
- When the grid gets smarter, the EMS system could communicate with the local Substation. This way, the EMS system could be allowed to use more power in periods when the grid has better capacity, and use less when the grid is heavily loaded. With this solution, it would not be any problems with having consumption peaks, as long as they come when the grid allows for it.
- The EMS system could communicate with the power production in the electricity grid. This way it could use more power when it is being produced much power from intermittent renewable energy sources. By doing this, the EMS could help to stabilize the power grid, allowing more intermittent renewable energy to be connected to the grid.

As each substation covers smaller or larger areas with multiple buildings connected, EMS systems will impact the grid and substation differently depending on how widespread the implementation is. An EMS with DL will always reduce the load peeks, but an EMS without DL might help create counter-cyclical loads or unfortunately create new and bigger loads. We can break it down to three scenarios for implementation of EMS without DL:

- **Low implementation of EMS.** Only one house per substation has installed an EMS system. In this case, it would be beneficial for the grid locally and nationally that energy-use is when the price and demand are at the lowest. Any load shifted towards the cheapest priced hours will help to lower the peeks. The only capacity problem will be for the consumer household with the EMS

- **Every house connected to one substation has an EMS installed.** However, only households connected to this one substation. The substation and grid close to this substation would experience new consumption peeks, close to the lowest prices. This peek can potentially be extremely high as EWH, house heating, and EV will use at max capacity simultaneously. This would again lead to investments in substation capacity.
- **An even but high percentage has installed EMS.** In this case, the results from NVE about the economic gain that can be achieved by coordinating the charging of EV's [7]. If DSM successfully even out prices, the willingness will have a more moderate increase and might avoid sudden power consumption peaks.

7.6 Grid Tariffs

The proposed tariff is all three designed to lower the consumption peeks, and not promote counter-cyclical consumption. The difference between the different grid tariff models is provided in this section, and it is discussed which tariffs models that are beneficial for the EMS system.

New grid tariff models should represent, and must cover the cost of DSO's for maintaining the grid. A rapid transition to the proposed tariff models could cut income for the DSO's by as much as it cuts tariffs for consumers. If the reduced cost of grid investments is not equal or close to equal to the reduced income for the DSO, re-regulation, and tariff adjustments will occur and reduce investments in EMS systems.

7.6.1 Present Tariff

Table 27 in section *"7.1.6 Savings"* shows that the combined energy cost for present grid tariff can be reduced by 2.25% for the case with EMS and DL with Norwegian prices. For the Danish prices, the combined costs can be reduced by 5.67%. These economic benefits come mostly of that the system uses less energy. The present tariff do not give the consumer any incentives to reduce the power peaks.

7.6.2 Subscribed-effect

The subscription tariff is the best-suited tariff for a consumer who is interested in saving money. See table 26 and 28 in section *"7.1.5 Combined Cost"* and *"7.1.6 Savings"*. For the reference cases, the Subscribed-effect tariff is slightly more expensive than the present grid tariff. However, the subscription grid tariff give a much better incentive to reduce the energy peaks. The combined energy costs can be reduced by 24.17% for the case with EMS and DL with Norwegian prices, as seen in table 27. With Danish prices, the combined energy cost can be reduced by 27.39%. Compared to the present grid tariff where the combined energy cost is reduced by 2.25% for the Norwegian prices and 5.67% for the Danish prices. It is approximately the present tariff with the reference load. Nevertheless, implementing EMS and Demand-limit, the subscription tariff give the cheapest total cost for the consumer with both Norwegian and Danish prices. See table 26.

7.6.3 Measured-effect

The Measured-effect tariff is not meant for houses with year-round residents. This is particularly visible in table 28 in section *"7.1.6 Savings"* as it is 29.40% more expensive than the present tariff for the reference case in our simulation. In the simulation with EMS and DL, this tariff gives a total saving of 2.49%, compared to the present tariffs for the Norwegian market. For the Danish market, the total savings is at 2.60%, which is the most expensive alternative among the tree new suggested grid tariff models from RME for a house with the consumption given in this thesis.

If the Measured-effect tariffs in the case with both EMS and DL can be seen in table 27, compared to the reference case with Measured-effect, it is possible to cut the combined energy cost by 26.34% for the Norwegian prices, and 28.84% for the Danish prices. These results show that, even if the Measured-effect tariffs are the most expensive grid-tariff solution for the reference case, it gives the consumer an economic incentive to reduce the consumption peak.

7.6.4 Capacity-limit

The Capacity-limit tariff is slightly cheaper then subscription and measured effect tariffs without any EMS or DL, see table, 25, 26 and 28, in section *"7.1.4 Grid Tariffs, and Energy Prices"*, *"7.1.5 Combined Cost"* and *"7.1.6 Savings"*. This is if the Capacity-limit is equal to the highest use during the year. As the tariff is based on the fuse capacity and EMS in this report on energy consumption per hour, this will most lightly result in many periods where the fuse capacity is an overreach, and a higher capacity limit and fuse should be considered. This tariff gives the second best incentive to use EMS with DL with a savings of 14.18% compared to the Present tariff with the Norwegian prices. For the case with Danish power prices, the savings are 14.59% compared to the current tariffs.

If the capacity limit tariff with EMS and DL is compared to the reference case as seen in table 27 in section *"7.1.6 Savings"*, the savings is at 16.37% for the Norwegian prices. If the Danish prices are used, the total savings is at 19.68% compared to the reference case. The Capacity-limit grid tariff model gives less economic initiative to reduce the consumption peak than both the subscription tariffs and the measured effect tariffs for a house.

7.6.5 Time-of-use Tariff

The time-of-use tariff that is proposed as a way of regulating power away from the top load hours to allow DSO to signal when their distribution grid is near capacity and incentives load shifting.

A simple way of implementing a time-of-use tariff would be to add the time-of-use penalty for the hours in question to the power prices before calculating the willingness. This will lower reference temperatures and batteries reference state at the respective hours, but never to less than the minimum values. See figure 37 in section *"6.3.4 Total Load"* for the total load shift from reference case to the case with EMS and DL, as this is the most economical case with EMS. Critical load that is not controlled by EMS spikes during the early evening price peek, while willingness reduces the consummation until lower prices are available.

If we compare this with the willingness curve in figure 14 in section *"3.5 Willingness"*, adding a time-of-use tariff to the top energy price would increase the willingness and, therefore, also the reference curves and stored energy, in every hour except the ones with time-of-use penalties. This helps reducing loads in these hours, but only if the storeable loads, such as heating, EWH, and EV charging is not already above their reference curves.

For the time-of-use tariff to work, they must be published ahead of time so that EMS' can use in automated consumption planning.

8 Conclusion

To provide a comprehensive understanding of what the results acquired through this study means we present our conclusions sorted by topic and area of impact. In *"8.1 Technical Implementation"* we focus on the technical aspect, while in section *"refconcon Consumer"* gives from the consumers point of view. Section *"8.3 Society"* present some economic and environmental benefits. The proposed grid tariff in *"8.4 Grid Tariffs"*. *"8.5 Energy Storage"* and *"8.6 Load Shifting"*. Furthermore we suggest some further research in *"8.7 Further Research"*

There are many variations that has an impact on our calculations. The calculations in this study is limited to the building described in section *"3.9 House Heating and Losses"* and *"4.4 House Heating Model*", equipped with the EWH described in section *"3.8 Electric Water Heater and Losses"* and *"4.3 Electric Water Heater Model"*, and a household owning an EV as described in *"3.10 Electric Vehicle and Losses"* and *"4.5 Electric Vehicle Charging model"* on which they use the same amount of energy every day. Result may vary if any component behave differently, and other price or weather data is considered.

8.1 Technical Implementation

EMS can move electrical loads and store energy by taking advantage of the thermal mass and the flexibility of EV charging. The most exciting result is the EMS with DL, which reduces simultaneous demand and does not risk new local consumption peaks, like the EMS without DL risk.

The EMS with DL moves energy consumption, reduces power peeks by 64.89%, and evens the consumption throughout the day, compared with the reference case. The EMS with DL also gives the lowest combined cost with the proposed tariffs. Savings for the different components are only given as savings in power cost, and does not include tariffs, as tariffs are dependent on the total load.

The proposed controller-logic for an EWH is simple, as most homes only have one unit, and the primary energy loss in the EWH is the hot water use. It has a positive impact on power prices as the load can be moved in time and restricted in periods almost without implications. The EMS with DL can reduce the energy cost for the EWH without tariff by 4.91% or 89.9 NOK per year based on Norwegian prices, and 11.87% or 222.4 NOK per year based on Danish prices.

Load shifting for house heating is complex to make and to simulate as many factors play significant roles, the most important contribution from house heating will come by the DL as a contribution to limiting demand peeks. The EMS with DL can reduce the energy cost for the house heating without tariff by 4.11% or 45.7 NOK per year based on Norwegian prices, and 9.18% or 95.0 NOK per year based on Danish prices.

EVs have a considerable potential to charge when power is available. A limitation is that the car is not connected to the charger in parts of the day, but as it is when power prices are at their lowest, and usually the EVs are connected to the charger when prices are at their highest, the potential is huge. The EV is the component that saves the most on power prices, but as a flexible load, it also contributes to enabling a low capacity limit. The EMS with DL can reduce energy cost for the EV charger without tariff by 10.3% or 114.1 NOK per year with Norwegian prices, and an impressing 28.93% or 348.5 NOK per year with Danish prices.

8.2 Consumer

From the reference case with the present tariff to the cheapest alternative with the proposed tariff, there is a saving of 23.55% or 2816.2 NOK with Norwegian prices, and 26.80% or 3236.6 NOK with Danish prices for a consumer with the considered user pattern, for EWH, EV, and house heating.

Most of the savings for the consumer comes from grid tariff reduction. With prices from the Norwegian power, market *NO2* the amount of energy, and the price variation is low. Market prices from DK1 enable higher savings. The most significant driver for load-shifting is the grid tariffs. This study does not take into account taxes and fees. The total energy bill will, therefore, be higher, and the savings proportionately lower.

8.3 Society

Implementing an EMS system with DL can have significant advantages for society, both economic and environmental.

8.3.1 Economical Benefits

From an economic point of view, a single household can reduce its energy peak by 64.89% by implementing an EMS with a DL. If more houses install such a system, it leads to better exploiting the grid and reduces the consumption peak and transmission costs for both the DSO and TSO.

The power prices will also be affected since there is a correlation between the power prices an consumption in both the Norwegian and the Danish market. The strong correlation between consumption and price indicates that short term price variation will be lowered by lowering the short term variation in demand. More stable power prices lead to better exploiting of the excising renewable power plants.

8.3.2 Environmental Benefits

It is easier to implement new intermittent renewable energy sources into the grid by managing to even out the consumption. Renewable energy sources pollute less than gas and coal that is often used in grid to which we trade power. This makes it easier to phase out power production from fossil fuels. Also, if the EMS manages to reduce energy prices, it is less economical to produce power from fossil fuels. Particularly peeker-plants who often are expensive, polluting plants used for meeting the peek-demands.

Reduced power prices will also facilitate the electrification of industries and transport replacing among others polluting combustion-based fuel sources.

8.4 Grid Tariffs

The combined cost for the Measured-effect grid tariff is much more expensive for a household. For the reference case, it is 29.40% more expensive than the present grid tariffs with Norwegian prices. For the Danish prices, it is 29.11% more expensive. Nevertheless, this tariff give an excellent incentive to reduce the energy peak. For the case with EMS, DL, and Norwegian prices, the combined energy cost is reduced by 26.34% compared to the reference case. For the Danish prices, the combined energy cost is reduced by 28.84%. This grid tariff solution is most likely better suited for a holiday house or a cabin.

The Subscribed-effect tariff is more or less the same as the present tariff for the reference case. Here the tariff is only 0.82% more expensive with both the Norwegian and Danish prices for the reference case. Nevertheless, the subscription tariff give a good incentive to reduce the consumption peaks. The combined energy cost for the subscribed grid tariff with EMS, DL, and Norwegian prices is reduced by 24.17%, compared to the present grid tariff. With the Danish prices, the combined energy prices are reduced by 27.39%.

The combined cost for the Capacity-limit subscription is more or less the same as the present tariff for the reference case. For the reference case, the combined cost with the capacity limit tariff is reduced by 0.32% compared to the Present tariff with Norwegian prices. For the reference case with Danish prices, the capacity limit tariff are reduced by 0.64% compared to the Present tariff. These tariffs give less incentive to reduce the consumption peaks. The combined energy costs are reduced by 16.37% for the case with EMS and DL compared to the reference case, with Norwegian prices. With Danish prices, the combined energy cost is reduced by 19.68%.

Among these grid tariffs, it appears to be the Subscribed-effect that appears to be the best grid tariff solution for a household. That is because the grid tariff has the same costs as the present tariff during a typical power consumption. However, those with higher consumption peaks pay more, and those with lower power peaks pay less—this way, the grid tariff cost represents the electricity grid's cost in a better way.

Time-of-use tariffs can be used by the DSO to add an additional price for power consumption during given hours. These measures can be used to lower the power consumption when the grid is at high capacity. Time-of-use tariffs can also be used to lower the power tariffs during periods with lower power consumption. This reduces the energy peaks and exploit the grid in a better way.

8.5 Energy Storage

This study investigates how energy can be stored in the three main components, EWH, house heating, and EV, and if loads can be shifted.

- **EWH:** The load shifting appears to be unproblematic. The EWH manages to save thermal energy from periods with lower power prices to periods with higher, without affecting the user comfort.

- **House heating:** This is the most uncertain calculation. A small variation in average temperature has a significant impact on overall energy consumption, and building specifications such as insulation, and choice of materials also impact energy storage. For households, especially with a older standard than TEK17, it can be problematic to store thermal energy form periods with lower energy prices to periods with higher.

- **EV:** The EV charging is a smart place to start to implement load shifting. EVs use much energy, and the time of charging does not affect losses, nor does it affect the user as long as it is not restricted so much that it cannot recharge to the minimum battery charge state.

8.6 Load Shifting

The proposed grid tariffs give strong incentives to reduce hourly consumption. Therefore, the recommended solution with EMS and DL gives a peak reduction of 64.89% compared to the reference case. The power consumption is more evenly distributed, by the DL from the afternoon and though the night.

Aiming for counter-cyclical power demand will save on power-prices for EWH and EV charging, not house heating, but also increase max power consumption per hour.

8.7 Further Research

The Norwegian electricity grid is a complex technical and economic system, interconnected with other European countries. Therefore, including consumers in demand-side management is also complex. The results from this study are promising on peak reduction. However, more detailed assessments of the grid, counter-cyclical loads, and how it affects power prices will reveal more information about the potentials in this technology.

8.7.1 Values Worth Verifying

To allow a broader understanding of EMS for private homes and households, the initial values used in this thesis should be verified and adjusted to the building mass and pattern of use that represent the area of research. To better approach the Norwegian energy market, the study should divide the building mass into several groups with different thermal losses, thermal masses, boiler sizes, and behavior patterns.

Values and objects that should be verified or considered:

- Thermal mass of a building.
- Insulation and ventilation losses for different buildings.
- Calculations on infiltration losses.
- Solar irradiation for different building types.
- Re-integrate heat from EWH and critical load to house heat.

- Water use patterns.
- Critical Load patterns.
- Outdoor temperature profiles.
- Heat from humans.
- Simultaneity of energy peaks in Norway.

8.7.2 Outdoor Temperature Profile

In this study, the cheapest combination is the one with a grid tariff based on the subscribed effect at 2.6 kWh/h and a DL of 2.7 kWh/h. With monthly average temperatures, this allows heating to cope and never fall under one degree below the lowest set temperature. In practice, the lowest outside temperatures will be far below the monthly average. If consumers during a cold period all raise the DL to cover the heat demand, grid investment planning based on old estimations will not cover the new demand. Therefore, we recommended that the consumer, DSO, and TSO plans for a higher DL than 2.7 kWh/h. Especially if the consumer lives in a climate that is colder than Kristiansand.

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