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Utilizing EV Batteries as a Flexible Resource at End-user Level

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Abstract

As part of the agreement 195 countries signed in order to lower GHG emissions and reduce global warming, Norway has through the Paris Climate Agreement agreed to lower GHG emissions significantly in the future. While other countries are mainly reducing their emissions in the power production sector, Norway's electricity production is accountable for only 3 % of the national GHG emissions (1), due to a high share of hydro power. Responsible for 19 % of national GHG emissions, the road transport sector is a more efficient sector to cut CO_2 emissions. Through extensive subsidies of electric vehicles (EVs) and photovoltaic (PV) panels, the goal is to have a carbon neutral state by 2050 (2).

With more than 300 GW installed PV power worldwide by the end of 2016 (3), Norway is barely taking part in the solar revolution, being only accountable for 27 MW installed capacity (4), with 11 MW being installed in 2016. In comparison, worldwide installed capacity in 2016 was 75 GW. PV is experiencing this massive growth due to sinking costs, increased energy demand and more climate oriented policies. Meanwhile, because battery costs together with PV costs, have been dropping massively in the last decade (5), the question of profitability for such distributed energy systems has reached Norway, in spite of low energy prices, semi-low solar irradiation and high investment costs.

Due to massive subsidies, Norway reached 100 000 EVs in 2016. Although reducing national GHG emissions, an increased share of EVs could lead to problems in the distribution grid due to high power demand during charging (6). Meanwhile, an average vehicle is parked 95 % of the time (7), which results in a huge amount of high power high energy batteries being connected to the grid at all times. These are batteries that in theory could be utilized for load balancing.

With increased amount of unpredictable renewable energy production, new challenges arise. Increased distributed energy production leads to bidirectional power flow in the distribution grid, and can result in certain problems related to overloading and voltage deviations.

In order to face the challenges that come with increased distributed energy production in the shape of PV, the implementation of smart meters (AMS) will take place in every Norwegian residence before the beginning of 2019. With AMS, distribution grid operators can reshape their grid tariff structures, creating price incentives to control load in order to utilize the grid more efficiently. AMS also opens the possibility to use smart control to buy cheap energy from the spot price market for storage, in order to either sell or consume when the prices are higher. In order to promote efficient grid use, NVE is developing new grid tariff structures that assures economic advantage for those who take advantage of these (8). Four grid tariffs have been utilized in this thesis; energy based, power based, time based and subscription based.

By modelling a battery, PV and residence load by using load and irradiation data, a household is simulated throughout one year. Utilizing dynamic programming, an optimization algorithm is developed in order to find the optimal operation of the battery that ensures minimal cost for the customer, given that load, spot price, grid tariffs and PV production is known (deterministic model). At the same time, the new grid tariffs are used to see how new price structures can lead to more efficient use of the grid, especially through optimized use of distributed energy production and storage such as PV and battery utilization. The optimization is performed with both a stationary house battery and an EV battery, in order to compare how an EV battery can potentially replace a house battery.

Results show that PV as of 2017 in Norway is not profitable, but that it with lower investment costs and higher energy prices can be profitable in the future. In addition, EV batteries increases the savings by working as a balancing element, utilizing variations in the spot price and grid tariffs to provide 12.0 - 19.2 % savings in symbiosis with PV (depending on grid tariff structure), compared to the 8.9 - 14.4 % when using a house battery with PV (depending on grid tariff structure).

While only the subscription based tariff resulted in the decreasing load peaks, the remaining tariffs either increased or kept the existing load peaks of the household. The higher peak loads did not interfere with classic peak load hours on a national basis. To conclude, the new grid tariffs resulted in more efficient use of the grid while at the same time having potential for improvement.

Sammendrag

Som del av avtalen 195 land undertegnet for å senke klimagassutslippene og redusere graden av global oppvarming, godtok Norge gjennom Parisavtalen å senke klimagassutslippene sine i fremtiden. Der andre land kan fjerne store punktutslipp i kraftsektoren, står norsk elektrisk energiproduksjon for kun 3 % av de nasjonale klimagassutslippene på grunn av høy andel vannkraft. Med ansvar for 19 % av nasjonale klimagassutslipp, er veibasert transport en mer effektiv sektor å kutte utslipp i. Gjennom omfattende subsidier av elbiler og solcellepanel, er målet å ha en karbonnøytral stat innen 2050.

Mens den verdensomspennende installerte solcellekapasiteten var mer enn 300 GW ved utgangen av 2016, tar Norge knapt nok del i solrevolusjonen med kun 27 MW installert kapasitet, hvorav 11 MW ble installert i 2016. Til sammenligning ble det installert 75 GW i verden i samme periode. Solceller opplever massiv vekst på grunn av synkende kostnader, økt energibehov samt mer klimaorientert politikk på internasjonal basis. Samtidig har batteriprisene sammen med solcelleprisene sunket massivt det siste tiåret, og dermed kommer muligheten for økonomisk gevinst for slike distribuerte energysystemer også til Norge, til tross for lave strømpriser, forholdsvis lav solinnstråling samt høye investeringskostnader.

Med hjelp av enorme subsidier, nådde Norge 100 000 elbiler i 2016. Selv om elbiler reduserer de nasjonale klimagassutslippene, er en økt andel elbiler et problem for distribusjonsnettet grunnet deres høye kraftbehov ved lading. Samtidig står en gjennomsnittlig elbil stille 95 % av tiden, som betyr at det til enhver tid står en stor andel høyeffekt- og høykapasitetsbatterier tilkoblet nettet til enhver tid. Dette er batterier som i teorien kan utnyttes til lastbalansering.

Med økt mengde uforutsigbar fornybar energiproduksjon, oppstår nye utfordringer. Økt distribuert energiproduksjon fører til toveis kraftflyt i distribusjonsnettet, og kan resultere i problemer som overbelastning av transformatorer eller endringer i spenningsnivået.

For å blandt annet kunne møte problemene som følger med økt distribuert energiproduksjon i form av solceller, blir smarte målere (AMS) installert i alle norske husstander innen starten av 2019. Med AMS kan distribusjonsnettoperatører omforme nettleiestrukturene sine, og med dette, lage prisinsentiver for å styre eller flytte last slik at nettet utnyttes mer effektivt. AMS åpner også muligheten for å bruke smart kontroll til å kjøpe billig energi på spotmarkedet, slik at den kan lagres til senere bruk, enten i form av salg eller forbruk når prisene er høyere. For å promotere effektiv nettbruk, utvikler NVE nå nettariffstrukturer som sikrer økonomisk vinst for de som anvender disse strukturene til sin fordel. Fire forskjellige nettleiestrukturer har blit brukt i denne oppgaven; energibasert, effektbasert, tidsbasert og abonnert effekt-basert struktur.

Ved å modellere et batteri, solenergiproduksjon og boliglast ved bruk av last og innstrålingsdata, modelleres en husholdning gjennom et år. Gjennom bruk av dynamisk programmering, har en optimeringsalgoritme blitt utviklet for å finne den optimale anvendelsen av et batteri som forsikrer minimale kostnader for kunden, gitt at last, spotpris, nettleie og solenergiproduksjon er kjent (deterministisk modell). Samtidig benyttes de nye nettleiestrukturer for å belyse hvordan nye prisstrukturer kan føre til mer effekt nettbruk, spesielt med denne optimerte bruken av distribuert- energiproduksjon og lagring slik som solceller og batteri. Optimeringen blir gjennomført både med et stasjonært husbatteri samt et elbilbatteri med mål om å sammenligne hvordan et elbilbatteri kan erstatte et potensiellt husbatteri.

Resultatene viser at solceller i 2017 i Norge enda ikke er lønnsomt, men at med lavere investeringskostnader og høyere energi- og nettleiepriser kan det bli lønnsomt i framtiden. I tillegg sparer elbilbatterier ved å fungere som balanserende kraft gjennom utnytting av variasjoner i energi- og nettleiepriser, mellom 12.0 og 19.2 % i samarbeid med solenergiproduksjon, avhengig av nettleiestruktur. Til sammenligning sparte husbatteriet sammen med PV 8.9 - 14.4 %, avhengig av nettleiestruktur.

Der kun den abonnert effekt-baserte tariffstrukturen reduserte de høyeste lasttoppene, økte eller oppretteholdt de andre tariffene husholdningens lasttopper. De økte lasttoppene sammenfalt ikke med eksisterende lasttopper på nasjonal plan. Med dette som basis, er det grunn å til si at de nye tariffstrukturene førte til mer effektiv bruk av nettet, samtidig som de kan forbedres.

Abbreviations

SSB	Statistisk Sentralbyrå
NVE	Norges Vassdrags- og Energidirektorat
EV	Electric Vehicle
BEV	Battery Electric Vehicle
PHEV	Plug-in Hybrid Electric Vehicle
ICE	Internal Combustion Engine
V2G	Vehicle-to-Grid
V2H	Vehicle-to-Home
SOC	State of Charge
DSO	Distribution System Operator
TSO	Transmission System Operator
LV	Low Voltage
AMS	Automatic Measuring and control System
GHG	Greenhouse Gas
IEA	International Energy Agency

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Chapter 1

Introduction

Chapter 1 contains the background and motivation for use of the PV and battery system presented in this thesis. Chapter 2 describes the relevant economic aspects, whereas chapter 3 explains the model used and has a short introduction to relevant technical aspects. Chapter 4 and 5 describe the method and data used in the model. Results are then presented in chapter 6, and further discussed in chapter 7. The conclusion is presented in chapter 8, with future work potential displayed in chapter 9. The dynamic programming algorithm used for this thesis is available in appendix A.

1.1 Motivation

With 228 GW worldwide installed PV capacity in the beginning of 2016, the PV market is rising exponentially (3). Due to low electricity prices and semi-low irradiation, Norway is barely taking part in this growth with its 27 MW installed power (4). Still, the average irradiation is only 20 % lower than the second largest PV nation in the world - Germany(13). The Norwegian power market is close to completely supplied with hydro power. However, the hydro power is dependent on a classic power grid, transporting energy from producer to consumer, resulting in transmission losses. With PV, power can be produced where it is consumed, reducing the losses in the grid. With new technology and lower production prices for batteries and PV panels, such installations have become a competitive alternative to the traditional hydro power.

With new technology, new possibilities appear. When AMS (smart meter) is installed in every household by the start of 2019, new pricing structures, specifically grid tariffs can be utilized to promote efficient use of the grid. Today there is an ongoing discussion on how grid tariffs can reflect the cost of the distribution system operator to a bigger extent. As of yet, there is no incentive for using the grid efficiently.

Norway is rapidly changing its car park from standard fossil fuel cars to electric vehicles (EVs). This does not only increase the electric energy needed from the grid, but also represent a high power load mostly in peak load hours, creating both problems for LV and MV distribution grids (6).

This thesis illuminates to what degree these high energy and high power batteries in EVs could serve the purpose that house batteries are doing today in symbiosis with roof mounted PV panels. In order to simulate the cooperation between PV, battery and grid, a dynamic programming optimization algorithm has been developed to reduce annual electricity costs for a residence in Trondheim. In addition, the simulations are performed with different grid tariff structures in order to determine which structures are suitable for more efficient use of the distribution grid. Because an EV battery will only be usable at certain times during the day compared to a house battery, it has a disadvantage. However, the EV battery is free in the sense of already being invested in, and also provides higher energy amounts and higher power output.

1.2 Norway's energy and emission status

Remark: Subchapters 1.2 and 1.3 builds on the project thesis which was a part of specialization project TET4520, and as such there is extensive reproduction/usage of the content therefrom (18).

In a recent published bill, the Norwegian government suggests a climate law where Norway promises to reduce its GHG emissions by 40 % compared to the agreed 1990 level. While the Norwegian electricity grid in 2015 was covered by 95.7 % renewable hydro power (19), the reduction has to be done in other sectors than the energy sector, unlike many of its European neighbours whose main goal is a green transfer in the energy generation sector. With these conditions, Norway's transport sector is a natural place to start cutting emissions. An electrical fleet of cars would also complement the country's green energy production. In 2015, Norway's GHG emissions were 53.9 million tons CO_2 equivalents, and the road traffics share was 10.3 million tons, or 19.1 % (1). The emissions are as shown in figure 1.1.

As can be observed, the energy supply is only responsible for 3 % of the GHG emissions, which could be expected with such a high renewable share.

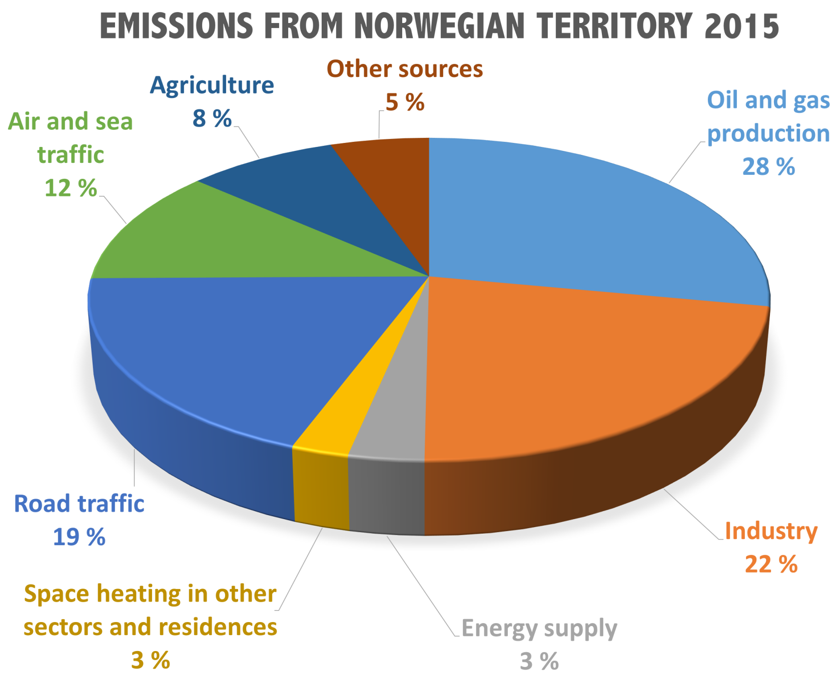


Figure 1.1: Overview of GHG emissions in Norway 2015

However, with the liberalized EU green certificate regulation, physical and economic flow are no longer necessarily equal. With guarantees of origin, energy producers may sell their power to any customer. In other words, there does not have to be any physical connection between production and consumption. With the idea of letting the customer choose whether to use renewable power or not, the result is according to NVE , that only 9 % of Norwegian consumed electric energy is 2015 was renewable (20), making the remaining 91 % part of the EU power mix. While it can be discussed whether one is to calculate emissions from EVs with hydro power emissions or EU power mix emissions, it is inevitable that EU's power mix is shifting towards a high renewable share. In a long perspective, EVs are a good solution, as electricity can, and will be produced from renewable sources.

1.3 Electric vehicles in Norway

Already in January 2008 the Norwegian government signed what is referred to as Klimaforliket (climate policy agreement), which declared a carbon-neutral state within 2050. As the transport sector is responsible for 19 % of the GHG emissions in Norway, but also responsible for various local polluting like PM10, PM2.5, NO_X etc, the government formed a resource group shortly after Klimaforliket to plan the electrification of Norway's transport sector. In May 2009, a 53-page article was released, written by members from different climate groups, distribution grid operators, transport committees, and other relevant parties, called *Handlingsplan for elektrifisering av veitransport* (21) (Plan of action for electrification of road transport). The resource group suggests a combination of focus on more efficient combustion engine vehicles together with an integration of EVs. To reach the goal of carbon neutrality, the report suggests a large to full scale implementation of EVs by 2050. Today, eight years later, Norwegians have shown a great interest in EVs, resulting in more than 150 000 EVs on Norwegian roads as of May 2017.

According to SSB, Norway's transport sector in 2014, had an energy usage of 68 TWh. Road transport is responsible for 42.3 of those TWhs. 95.7 % of this energy comes from classic fossil fuel, and only 0.2 % of the energy came from electricity (6). While it's hard to predict EV sales, there is a possibility that most of the cars on Norwegian roads will be electric, BEV or PHEV, in 2050. According to SSB and NVE (6), the population in 2050 will be approximately 6.6 million, and we will have roughly one vehicle for every two inhabitants resulting in 3.3 million cars. In the example of 100 % EV penetration, NVE has approximated the future energy usage to be 14.6 TWh. The reason why this is far lower than 2014's 42.3 TWh, is simply the far more efficient electrical engines, allowing a far lower kWh per kilometre rate compared to the classic fossil fuel engine.

Norway has by far largest EV fleet per inhabitant in the world (5). A long-standing politic will to remove taxes on EVs and ensuring other pros, has resulted in massive increase in EV sales since 2014. Because classic combustion engine cars are heavily taxed, the popularity of EVs are skyrocketing, and do now represent 35 % of nationwide car sales as can be seen in figure 1.2 and 1.3 (9) (22).

Battery electric vehicles (BEV) have an 18 % market share and plug-in hybrid electric vehicles (PHEV) have a 17 % market share. For the rest of this thesis, the expression EVs will be used for all chargeable vehicles (both BEVs and PHEVs) in the name of simplicity.

With the increased sales, the number of chargeable vehicles has increased from a few thousand in 2010 to 152 000 at the end of march 2017 (23). In 2016, PHEVs stole market share from BEVs, resulting in a decrease in BEV

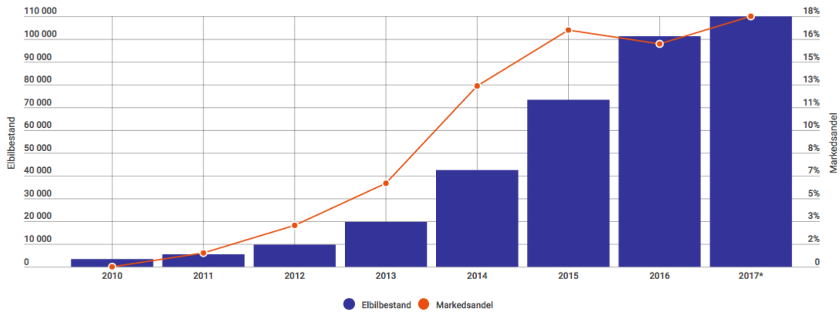


Figure 1.2: Amount of BEVs in Norway. Orange line represents the market share shown on the right hand y-axis. Figure from Elbilforeningen (9)

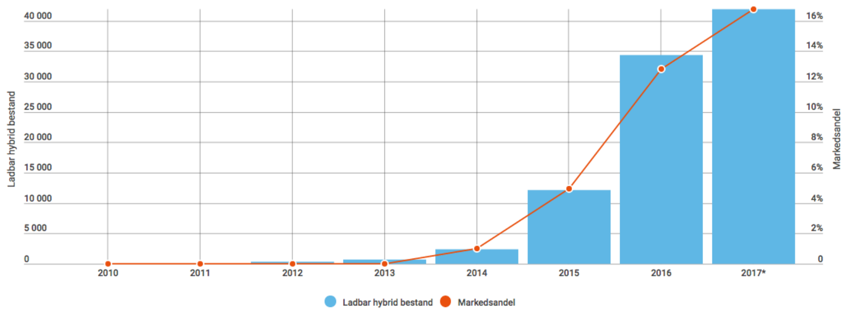


Figure 1.3: Amount of PHEVs in Norway. Orange line represents the market share shown on the right hand y-axis. Figure from Elbilforeningen (9)

sales growth. Although sales of hybrids are increasing, the classic BEV is still the biggest shareholder of EVs in Norway, with its 110 000 cars. The relationship between BEVs and PHEVs can be seen in figure 1.4.

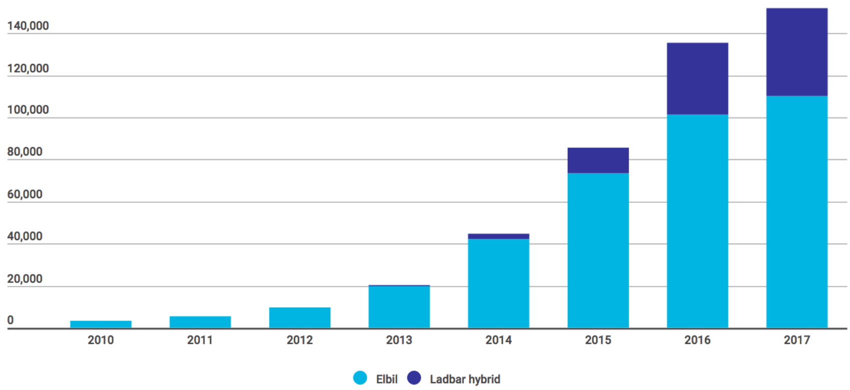


Figure 1.4: Amount of EVs in Norway. Dark blue are PHEVs and light blue are BEVs. Figure from Elbilforeningen (9)

Chapter 2

Economic aspects

2.1 The Norwegian power market

2.1.1 Spot market

As part of the Nordic energy market Nord Pool, energy companies buy energy on the day-ahead market to sell to their customers. Nord Pool is owned and operated by the Nordic transmission system operators in the different countries. Through providing all relevant market information, Nord Pool has provided an arena where energy companies trade on the day-ahead and intraday market, resulting in a specific spot price for every hour every day.

The price is a reflection of what the players are willing to pay for certain amounts of energy at different times of the day. Because the transmission system in Norway is incapable of transferring the entire production from some areas to others, five pricing zones have been created. In Norway, the south and west areas are very high on production, and do often have the lowest spot prices. Due to the limited transmission system capacity, eastern, mid and northern Norway tend to have higher energy prices during winter. The price zones are seen in figure 2.1.

2.1.2 Prosumers

Norwegian customers could since 2010 sell energy to the grid without signing a balance agreement with the transmission system operator Statnett. This was organized through the prosumer agreement, which also simplified billing small prosumers because they were no longer to be treated as market players. However the volumes and revenues were low, both due to primitive PV

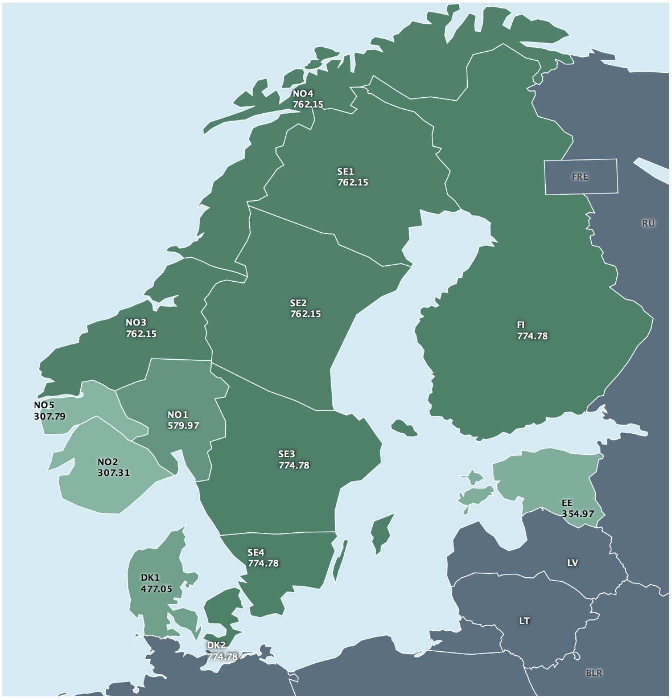


Figure 2.1: The Norwegian prize zones. Figures from Nord Pool Spot (10).

technology and the price of grid tariffs of feed in energy as every market player has to pay.

In 2017, NVE redefined a prosumer as a: *"Customer with consumption and production behind the point of connection, where feed in power in the connection point at no point in time exceeds 100 kW. A prosumer may not have a construction behind the point of connection that is required to have a concession, or a turnover business that requires turnover concession."* (24)

Resultingly, small prosumers are no longer required to pay grid tariffs for sold energy, creating an economic incentive for installing small scale power.

As the energy spot price can change throughout the day, there is a large savings and revenue potential if a household is equipped with battery storage and PV. Due to the mentioned structure of grid tariffs and taxing, economic benefit of a PV system mostly lies in the savings. As seen in figure 2.2, buying a kWh had a cost of approximately three times as much as earning from the sale of one in 2016 (25). This is because the customer pays grid tariff, grid taxes and energy taxes for every kWh consumed, while earning only the market spot price when selling one (24). In practise, the algorithm that is optimizing economical profit of a PV and battery system, would only consider selling energy if the prices were triple of the purchase price, or if the production exceeds consumption. Thus, the system would mostly buy or produce for own consumption.

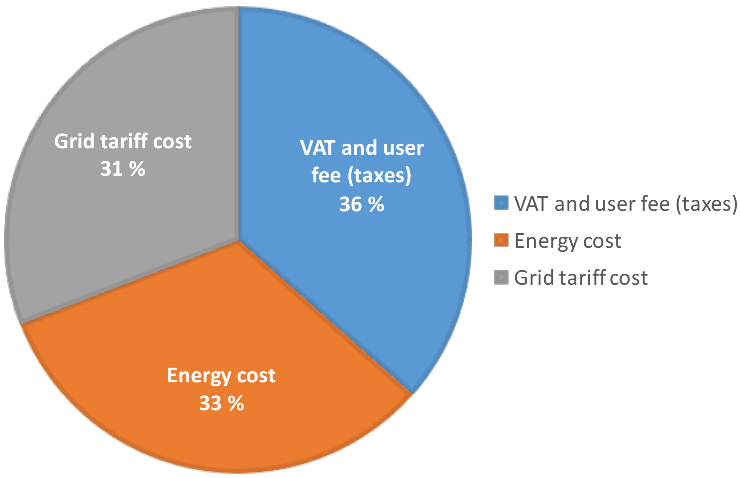


Figure 2.2: Overview of kWh pricing of purchases and sales for prosumers in Norway

When installing renewable energy production in Norway, certain subsidies apply. The most important ones are green certificates, Enova's investment support and feed-in tariffs.

Green certificates are provided for producers who want to sell or consume self produced renewable energy. The support is today is 18 øre/kWh, which is a fair amount. However, due to the application cost of 15 000 NOK for installations under 100 kW (26), this is considered fairly irrelevant for residences.

Feed-in-tariffs are a minimum price guarantee for produced electric energy, which is a support program meant to assure economic stability for energy producers, providing either a minimum price for energy or an extra premium addition to market price depending on production technology. This program is yet to be used in Norway, and is therefore considered irrelevant for this thesis. However, the use of such tariffs were central for the development of

PV in the worlds second largest PV energy producer, Germany (3).

Enova investment support is a subsidizing program meant to help private residences with the investment costs of PV or wind power installations. With 10 000 NOK per installation, with an additional 1 250 NOK per kW installed (27), this is a lucrative program for residences.

2.1.3 Grid tariffs

Grid tariffs are paid to the distributions system operator, and is a cost which is meant to cover the price of maintaining and operating the distribution grid, which is responsible for the transport of energy from the point of production to the point of consumption. For socioeconomic reasons, there is only one distribution grid operator available per residence, which means that there is a natural geography based monopoly on customers for DSOs. Due to the liberalization of the power grid, distribution system operators have fixed maximum revenues, to ensure that misuse of their monopoly position does not occur. These revenues caps are decided by NVE, the Norwegian Water Resource and Energy Directorate.

As producers of electric equipment are thriving for higher energy efficiency and lower energy usage, it is predicted that households in the future will have a lower energy use, but with more unstable power use (8). This means that the energy amount used throughout a year could be lower per household, but with high power at certain times throughout the day. This change is due to increased use of power demanding products such as induction heaters, water boilers and EVs. For the DSOs, this development makes grid operation more expensive. Due to this structure, NVE is cooperating with DSOs in order to create new and better grid tariff structures, such as a power based, time-of-use based or subscription based structure (8). The result of this is that high power charging of EVs can end up being unreasonably costly with the new tariff in comparison to the old tariff. This kind of pricing also promotes use of house batteries and solar panels to even out the power use of a household. The question remains, whether such installations are worth the cost or not, which is the main objective of this thesis.

A power grid has to be scaled for the most power intensive periods of the year. This means that even if the grid can handle the national load 99 % of the time, this is not sufficient, as the grid would break down in the remaining 1 % time period. Typically this is a cold winter day with high amounts of space heating. To optimize use of the grid, the trend of shorter but more intensive load profiles has to be changed. The means to reach this goal are AMS and smart grids. By shifting power demanding equipment use to night time, or increasing the amount of distributed energy resources in the LV grid, both increased voltage quality and more optimal grid utilization can be achieved.

2.2 Key economic definitions

2.2.1 Net present value

When calculating the ROI (return of investment) of a long lasting investment, net present value is used to normalize future cash flow (28). Target being to decide if an investment is viable or not, the value of future income is calculated given a certain interest value and discount rate. Net present value is positive if the investment is viable, and negative for the contrary. It is given as

$$NPV = \sum_{t=1}^{T} \frac{C_t}{(1+r)^t} - C_0 \tag{2.1}$$

where

C_t	is the net cash inflow during the period t (NOK)
C_0	is the total initial investment costs (NOK)
r	is the discount rate (%)
t	is the period (year)
T	is the number of time periods

The discount rate is the expected ROI of an alternative investment, meaning that a high discount rate results in a lower NPV. Different values will be used for the results and discussion, simply due to the fact that this value is very hard to determine with precision.

2.2.2 LCOE - Levelized cost of energy

Levelized cost of electricity is a measure of an energy producing power plant which compares different methods of electricity production (29). It can be regarded as the minimum cost at which electricity has to be sold with the goal of reaching break-even over the lifetime of an installation and is measured in NOK/kWh.

$$LCOE = \frac{\sum_{t=1}^{T} \frac{I_t+M_t+F_t}{(1+r)^t}}{\sum_{t=1}^{T} \frac{E_t}{(1+r)^t}} \tag{2.2}$$

where

I_t	is the investment expenditures in year t (NOK)
M_t	is the operations and maintenance expenditures in the year t (NOK)
F_t	is the fuel expenditures in the year t (NOK)
E_t	is the elctrical energy generated in the year t (kWh)
r	is the discount rate
t	is the period (year)
T	is the number of time periods

Note that F_t is considered to be zero when talking about renewable energy, due to a marginal cost of zero. In general, this model is hard to use in general because any assumptions in the discount rate, or insecurity in future cash flow changes the numbers widely. It will therefore not be used in this thesis, but should be mentioned as a possible way of calculating the ROI of a PV installation (30).

Chapter 3

System model

3.1 Residence model

The residence model in the the thesis is simplified and considered ideal, meaning that losses are not taken into account outside the application. The power balance is calculated as seen in figure 3.1 and 3.2 and equation 3.2.

$$P_{Grid} + P_{Photovoltaic} = P_{Load} + P_{Battery} \tag{3.1}$$

The system model is deterministic, meaning that the load and PV production is known at all times. Resultingly, P_{Grid} is a function of $P_{Battery}$.

$$P_{Grid} = P_{Load} + P_{Battery} - P_{Photovoltaic} \tag{3.2}$$

Note that when the battery is not available (when the EV is not connected), the system looks like described in figure 3.3 and equation 3.3.

$$P_{Grid} = P_{Load} - P_{Photovoltaic} \tag{3.3}$$

The grid is stiff, meaning that it has the balancing function, supplying and receiving power as a result of the balance equation. In other words, only power and energy balance is being investigated.

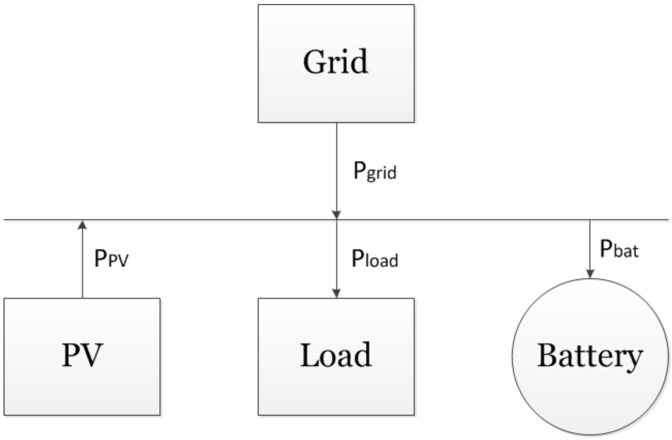


Figure 3.1: Model of the residence. Positive power flow direction is indicated by arrows.

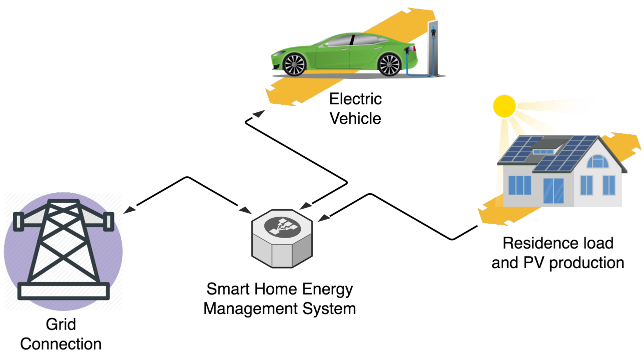


Figure 3.2: Residence model illustration.

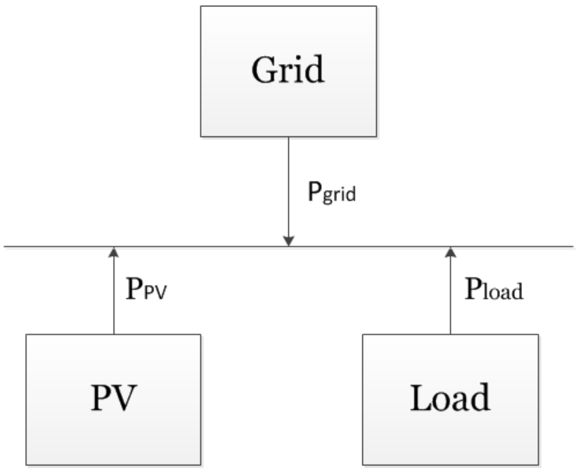


Figure 3.3: Model of the residence without connected EV battery. Positive power flow direction is indicated by arrows.

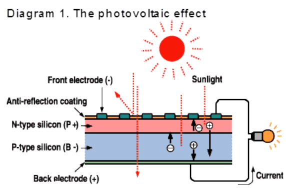
3.2 PV model

To calculate the power produced from the photovoltaics, two models are presented in addition to a very short introduction to photovoltaics.

3.2.1 Photovoltaic effect

The photovoltaic effect is the effect that occurs when a photon hits a PV panel and a current starts to flow. Solar power is electric energy produced by this effect when light hits a PV panel. There are many different PV technologies, however, crystalline PV panels are most common and cover approximately 80 % of global PV panel production (13). PV is in essence negative- and positive-doped semi conductor materials which resultingly work as electron donors and acceptors. This effect allows a current to flow, which is then greeted by two electrodes, one on each side of the semi conductors. With new technology, filters and film have been developed to increase radiation received by the PV panel. A very general illustration is shown in figure 3.4(b), with the finished roof mounted setup shown in figure 3.4(a).

(a) Roof mounted photovoltaic panels.



(b) Photovoltaics illustration.

Figure 3.4: Photovoltaics.

Most people do not think of Norway as a natural place to utilize PV, however, there are some advantages. First of all, PV panel efficiency increases with lower temperatures (31) (32). In other words, PV panels in cold countries have a higher efficiency compared to warm countries. Second of all, PV power is produced during day, which is when the power demand is the highest at daytime. Lastly, as shown in figure 5.4, PV production in for example Oslo and Kristiansand, which are at latitudes where the highest concentration of inhabitants in Norway are(south), is as high as in many European cities such as Paris, London, Vienna, Amsterdam and Berlin. Germany had until 2016 the largest PV production in the world, meaning that Norway should have sufficient potential to utilize PV. Trondheim, which is the city that is being investigated in this thesis, has about 80 % of the production potential compared to Berlin (13).

3.2.2 Realistic PV production model

By using specific data provided from Sanyo (a PV panel producer) (33), global irradiation and temperature data from LMT (Landbruksmeterologisk Tjeneste), a realistic set of PV production data can be created (34)(12). The production in the PV panel is calculated, and is a function of the global irradiation and the cell temperature. The resulting formula looks like this 5.10.

$$P_{PV} = P_{nom}\eta_{sys}\frac{G_T}{G_{T,STC}}[1 + \alpha_T(T_{cell} - T_{cell,STC})] \tag{3.4}$$

where

P_{nom}	is nominal installed power (kW)
η_{sys}	is the overall system efficiency
G_T	is solar irradiation on the PV panel
$G_{T,STC}$	is solar irradiation during standard conditions (1 kW/m^2)
α_T	is the temperature coefficient (%/°C)
T_{cell}	is the cell temperature (°C)
$T_{cell,STC}$	is the cell temperature during standard conditions (25°C).

Standard testing conditions are widely used to be able to compare PV cells' testing data. The standard values are:

- Solar irradiation $G_{T,STC} = 1000W/m^2$
- Temperature $T_{cell,STC} = 25°\text{C}$
- Air mass $AM = 1.5$

The irradiation used is as mentioned, taken from LMT's database. Because the cell temperature is not equal to the ambivalent temperature, a formula for calculating cell temperature is also used 3.5.

$$T_{cell} = T_{ambivalent} + \frac{NOCT - 20°C}{800\frac{W}{m^2}}G_T \tag{3.5}$$

where

T_{amb}	is ambivalent temperature (°C)
$NOCT$	is *normal operating cell temperature*.

$NOCT$ is the expected cell temperature during standard testing conditions, which are 20 °C, 800 W/m^2 irradiation and 1 m/s wind speed. $NOCT$ is always given in the data sheet provided by the PV panel producer.

Because equation 5.10 is correct for a horizontally placed PV panel, the transposition factor η_{transp} is introduced. It represents how much more irradiation is being absorbed due to inclination angle, which is typically 20 to 40 degrees if placed on a roof. With this new factor, equation 5.10 now looks like the following:

$$P_{PV} = P_{nom}\eta_{transp}\eta_{sys}\frac{G_T}{G_{T,STC}}[1 + \alpha_T(T_{cell} - T_{cell,STC})] \tag{3.6}$$

where η_{transp} is the inclination angle efficiency factor. This is further discussed in subchapter 5.3. Note that a south-oriented PV installations has been assumed. The consequences of this will be discussed in chapter 7.

3.2.3 Simple PV production model

A more effortless model can also be used, but will lack the precision of decreasing efficiency with increasing temperatures (31) (32). The simplified model uses global irradiation and an overall efficiency stated in the data sheet of a PV cell, and is shown in equation 3.7.

$$P_{PV} = \eta_{total}G_T A \tag{3.7}$$

where

η_{total}	is the total efficiency (%)
A	is the area of the PV panel (m^2)

Note that η_{total} includes both the efficiency of the PV panel module, and the power conversion system.

$$\eta_{total} = \eta_{sys}\eta_{module} \tag{3.8}$$

Equation 3.8 shows the simplified model efficiency. η_{sys} is as explained in subchapter 3.2.2, and represents the efficiency of power electronics, losses in cables and diodes. η_{module} is the efficiency of the cell itself, with the quantum effects of the given semi conductor.

3.3 Battery model

In this section, a short introduction to battery technology is shown, as well as a charging efficiency model.

3.3.1 Battery technology

A battery consists of one or more cells, depending on wanted voltage level. By connecting several cells in parallel and series, potentially any voltage and current level can be reached. A lithium-ion cell consists of two electrodes, an electrolyte separated by a separator, or membrane. By applying voltage to the conductors, the battery can be charged, and in the same way discharged if connected to a load. An illustrating model is shown in figure 3.5 (11).

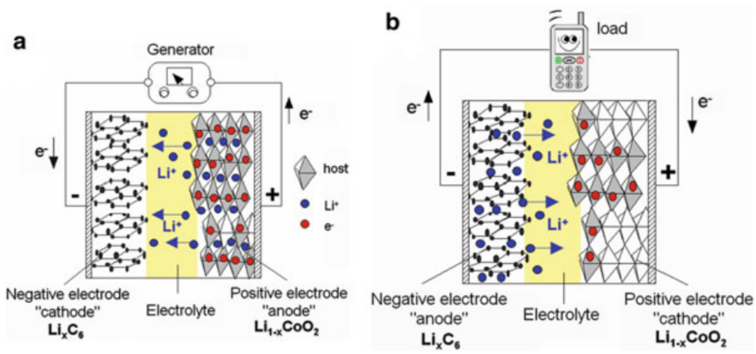


Figure 3.5: Overview of an lithium-ion electrochemical battery cell. Figure from (11).

Lithium-ion batteries are state of the art batteries, due to their high energy density, both per kilogram and per volume. This is shown in figure 3.6 (11).

Due to the ever sinking cost of batteries (5), use of lithium in batteries is rising rapidly in home electronics and in vehicles. Compared to its forfather, the lead-acid battery, lithium-ion batteries have a high energy density, without losing key characteristics such as lifetime and safety. Price development of batteries are shown in figure 3.7.

A simple equivalent circuit model for a lithium-ion battery can be seen in figure 3.8. For simplification reasons, this model will not be used, but is illustrated to show how a battery normally is modelled.

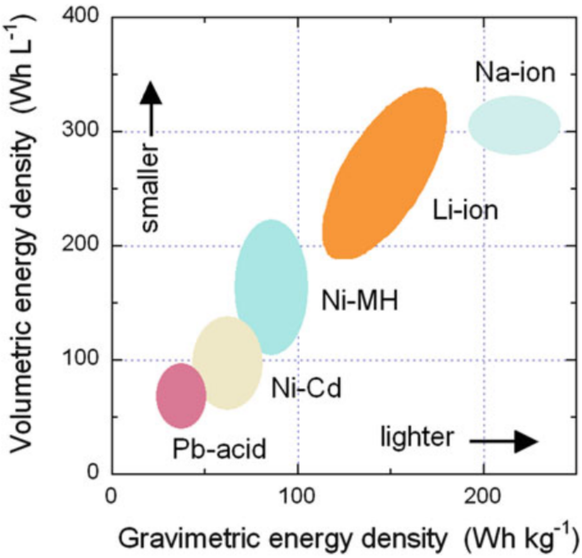


Figure 3.6: Overview of different energy densities for different battery technologies. Figure from (11).

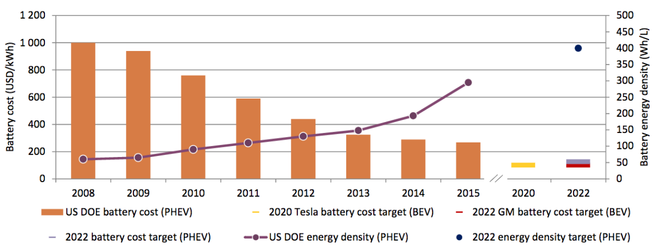


Figure 3.7: Price and energy density development for lithium-ion EV batteries from IEA's EV report (5).

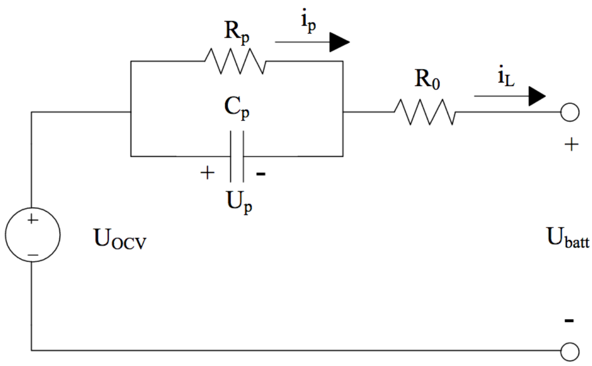


Figure 3.8: Equivalent circuit model for lithium-ion battery.

3.3.2 Battery charging efficiency

As this model covers any EV battery, it has to remain rather generic and simple. Therefore, the battery in this thesis is simply modelled as a load that is positive when being charged, and negative when being discharged which is shown in figure 3.1. It is assumed that there is a three phase connection from the EV battery to the residence in order to handle charging powers up to 15 kW. The efficiency decreases when the charging power increases, due to ohmic losses. Efficiency also changes as a function of cell temperature and SoC (35) (36), but is not included in this thesis. The power which is applied to the battery $P_{Injected}$ is given by

$$P_{Injected} = \eta_{Inverter} P_{Outlet} \tag{3.9}$$

where the efficiency of the converter $\eta_{Inverter}$ is set to 98.5 % (37). The power that is actually being charged is dependent on the battery efficiency, which is defined as

$$P_{Charge} = \eta_{Battery} P_{Injected} \tag{3.10}$$

where

$$\eta_{Battery} = \frac{P_{Charge}}{P_{Injected}} = \frac{P_{Injected} - P_{Loss}}{P_{Injected}} = \frac{\sqrt{3}U_N I_{Charge} - R_{eq.} I_{Charge}^2}{\sqrt{3}U_n I_{Charge}} \tag{3.11}$$

where R_{eq} is the equivalent resistance of the battery, I_{Charge} is the per phase charging current and U_N is the line voltage in the charger. The simplified charging efficiency of the battery is shown in figure 3.9. This figure does not include the inverter efficiency of 98.5 %, but is added later in the algorithm.

For the Tesla Power Wall 2, total efficiency for one charge and discharge cycle is 0.9 (38). The charge and discharge efficiency η_{ch} and η_{dis} has therefore been set to 0.95. See further specifications in chapter 5.

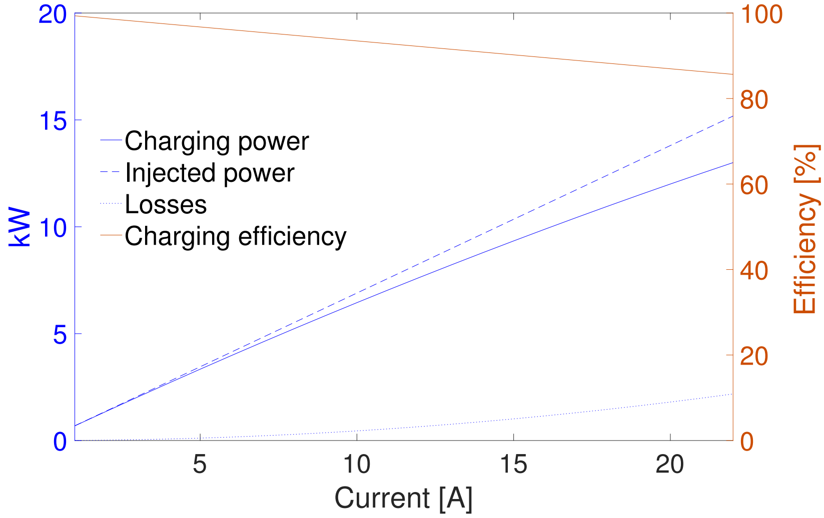


Figure 3.9: Charging efficiency and power illustrated as a function of the charging current.

Chapter 4

Method

4.1 Dynamic programming

In order to optimize the utilization of the battery, a dynamic programming optimization algorithm has been developed and used. The idea of dynamic programming is to split a complex problem down to very many, very small solvable problems, and then solve them with the help of computational power (39). For every small problem solved, the solution in stored in a matrix, and kept until the end of the optimization. After every local solution is calculated, a global solution can be found by finding the optimal path of local optimal solutions.

Dynamic programming is unlike greedy programming, guaranteed to find the best global solution, because every single possible step in the optimization is calculated and stored (40). While dynamic programming is a very solid method, it is time consuming when the problem size rises. For this thesis, every optimization had a duration of approx. 15 seconds, which is completely acceptable. With greedy programming, local optimal solutions are chosen without calculating every possible solution. Although time saving, it does not guarantee an optimal solution. In retrospect, a greedy programming algorithm is likely to have provided close to equal results, simply because the battery optimization proved to make decisions based on small local conditions.

4.2 Optimal battery utilization

In order to assess the economic potential of EV battery and PV utilization, an optimization algorithm is used. The algorithm has been developed in the following thesis (12), with help from other publications (41) (42). By utilizing dynamic programming, the algorithm calculates the price for every single charge and discharge possibility, when the spot price, grid tariff, load and PV production is known. The following mathematical formula is taken directly from the following thesis (12).

Minimize $f(P_{bat})$ so that

$$
\begin{aligned}
SOC(t+1) &\leq SOC_{max} \\
SOC(t+1) &\geq SOC_{min} \\
P_{bat}(t) &\leq P_{bat,max} \\
P_{bat}(t) &\geq -P_{bat,max} \\
E_{bat}(t+1) &= E_{bat}(t) + \eta_{bat} P_{bat}(t)\Delta t \\
SOC(t+1) &= \frac{E_{bat(t+1)}}{Q_{nom}}
\end{aligned}
\tag{4.1}
$$

where

t	= 1, 2, 3, ... , N is the period
SOC_{max}	is the maximum state of charge
SOC_{min}	is the minimum state of charge
$P_{bat,max}$	is the maximum (dis)charge power (kW)
E_{bat}	is the total energy amount in the battery (kWh)

While originally designed to optimize utilization of a wall mounted battery such as the Tesla Power Wall (38) throughout a year, the optimization algorithm has been rewritten to work for an EV battery. The major change is that the EV battery is only available when the owner is at home. Therefore, instead of optimizing charging and discharging for one year, it optimizes operation for the next 16 hours, or the time until the EV leaves again.

Availability in this thesis is chosen to be:

Weekdays:

- Available: 4 pm - 8 am
- Unavailable: 8 am - 4 pm

Weekends:

- Available: Always.
- Unavailable: Never.

With this new variable, the total time interval per optimization is T, or 16 hours divided into N discreet time steps, where Δt is one hour, due to the resolution of the load, PV and pricing data. In theory, these time steps could be made smaller to further optimize operation, but is for simplicity held to hour steps. After every 16 hour optimization, normal power flow is simulated as shown in figure 3.3, where the battery is excluded compared to the system shown in figure 3.1. During daytime, the algorithm has no variable input due to the lack of an available battery, and is therefore run without.

Furthermore, $P_{bat,max}$ is the maximum power of which the battery can be charged or discharged. Due to the fact that the available battery is an EV battery, the possible power output is large compared to normal wall mounted batteries. As all electronics, cables and fuses have to be scaled for $P_{bat,max}$, a limit of 15 kW is set to avoid the cost of any major installations. This is still more than enough to cover any load of both the household and the apartment which later will be presented.

The function f is a description of our optimization target. The goal of this thesis is to see how different grid tariffs can promote better use of the grid, and simultaneously see how customers with utilization of PV and EV batteries can benefit economically from these changes. Therefore, the function is given by the following equation:

$$f(P_{bat}) = C_{el} P_{grid} \tag{4.2}$$

where

$$P_{grid} = P_{load} + P_{bat} - P_{PV} \tag{4.3}$$

C_{el} is the accumulated price from grid tariffs, taxes and energy spot price. The simulations will be run with different grid tariffs, as described in subchapter 4.3. For $P_{grid} > 0$, both grid tariffs and energy price will be paid, both of which has taxes. For $P_{grid} < 0$, only the spot price will be received. This new regulation took place as of January 1st, 2017 (24). As equation 4.3 shows, P_{grid} consists of three variables, of which two are known; P_{load} and P_{PV}. Thus, P_{bat} is decided for every hour to minimize the cost from 1 to T.

Because the algorithm used as basis for this thesis already is well described in the respective thesis, only a summary will be given. In this thesis, the battery operation is being optimized, or in other words, the SOC, charge and discharge of the battery for every time step. When running the algorithm, every different decision comes with a calculated price. Finally, all possible paths through the problem has been calculated, and the optimal path is presented by the algorithm.

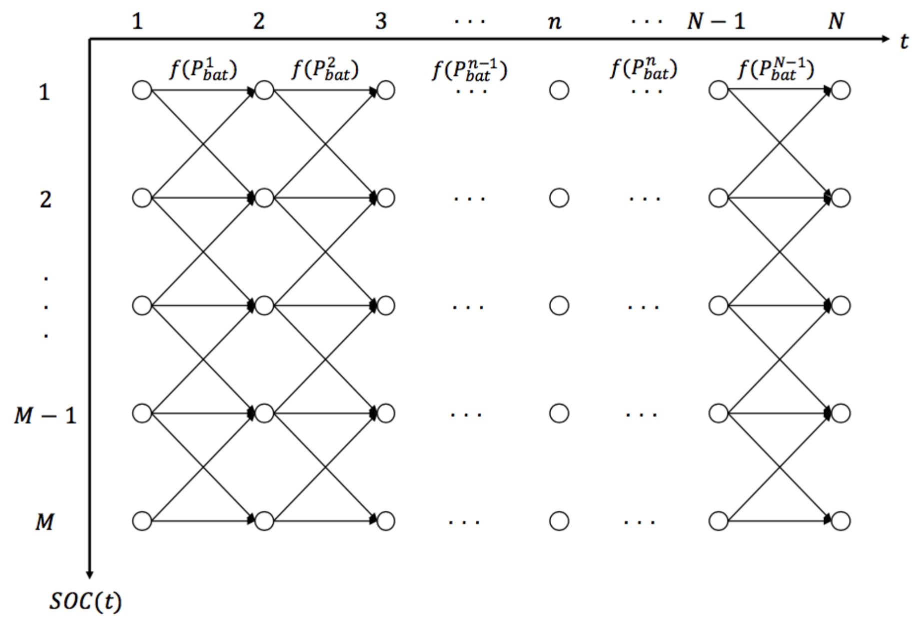


Figure 4.1: Illustration of dynamic programming with N time steps and M levels of SOC. Figure from (12).

In this thesis, 365 optimizations will be executed - one for each day of the year. The result is 365 grids of nodes, where different possible SOCs for every time step in T are calculated. The goal is to find the path of SOCs that result in the lowest possible price, given the input. Figure 4.1 illustrates how the dynamic programming with N time steps and M levels of SOC are calculated. Note that because the battery's maximum charging power $P_{bat,max}$, not all steps are legal, but are limited.

Every day at 8 am, the EV owner is supposed to be able to drive to work or any chosen destination. Therefore, every morning at 8, the battery has to be close to fully charged. By defining the objective function, the $SOC_{departure}$ is set to be 90 % at this time. As calculated in the project thesis leading up to this thesis (18), approximately 7 kWh are spent during day for driving, resulting in $SOC_{arrival}$ to be defined as $SOC_{arrival} = SOC_{departure}$ - $\frac{7kWh}{C_{bat}*100\%}$. The daily spent 7 kWhs is given the average efficiency of all EVs, and average driving distance of all cars in Norway (7). Depending on the capacity of the battery used in the simulations, the SOC will be a certain amount lower when the car arrives later in the day.

4.3 Grid tariffs

One of the main goals of this thesis, is to form new grid tariffs that promote better use of the grid, and to explore the customer's electricity bills will change with optimized charging. NVE is considering to introduce a power based grid tariff, where customers to a larger degree pay more for used power instead of consumed energy (43). With the introduction of new grid tariffs, customers are supposed to be billed for the extra cost they create for the DSO, also known as marginal cost.

In the next subchapters, different grid tariffs are presented. In order to achieve correct prices for the new tariffs, the annual price of the new tariffs were compared to today's structure. As advised by senior engineer at NVE (44), the price of the new grid tariffs were calculated to be exactly the same as existing tariffs, before any optimization of battery or installation of PV was introduced. The idea behind this is that DSOs still require annual income from their customers, but that pricing can change depending function of month, day or hour. When the new grid tariffs are known, the optimization algorithm can start finding new and smart ways to use power, which both benefits the DSO and the customer.

4.3.1 Grid tariff success criteria

The reason behind the increased focus on changing the grid tariffs, is continuously increasing electricity consumption, large grid investment costs, increased focus on renewable energy and electric vehicles. In the Norwegian energy law, paragraph §4.4 d, states that: "*Grid tariffs shall be formed so that they to a greatest possible extent provide signals for effective use and effective development of the grid. The tariffs can be differentiated after objective and controllable criteria based on relevant grid conditions.*" (45).

The general idea when forming a new grid tariff, is that it is supposed to be

- Fair - The tariffs are not to be discriminating to any customer group.
- Optimal - Optimally constructed to ensure optimal use of the grid. Give correct price signals to influence the consumption.

- Easy - Easy for the customer to understand, easy for the DSO to receive payments.
- Provide economic stability - Create stable annual income for the DSO and stable bills for the customer.

These characteristics are mentioned in NVE's hearing on new grid tariffs, and are also cited as important points by Hafslund and Thema (8) (46) (47) (48). The mentioned reports by Thema, NVE and Hafslund together with emails and phone conversations with employees at NVE have been used as main inspiration when creating these new grid tariffs.

4.3.2 Energy based tariff

The energy based tariff is the one broadly being used in Norway today (8), and is perhaps the simplest way of billing the customer. However, it creates no incentive for grid-friendly use. The grid tariff consists of an annual fixed cost and a variable cost which is based on kWh consumption. The structure is thoroughly explained in subchapter 5.5, and values are provided in table 5.4. These values are different for every DSO in Norway, and is regulated and controlled by NVE. With the liberalisation of the energy market, DSOs and their natural monopoly have a revenue cap decided by NVE. Resultingly, every DSO's grid tariff pricing is different. The price is mostly decided by geographical conditions and operating costs.

4.3.3 Time-of-use tariff

While still being consumption based, the time-of-use tariff utilized daily load profiles to create time zones where grid use is more expensive. The tariff separates between weekend and weekdays, as well as night, morning, afternoon and evening pricing. The prices are shown in figure 4.2 and in table 4.1. The figure shows a standard price during day, which is doubled during peak load hours, and divided to half during night.

Table 4.1: Overview of different price zones with the time-of-use tariff

Day		Hours	Price
	Night	23-05	0.121 NOK / kWh
Weekday	Standard	5-7, 10-18, 21-23	0.242 NOK / kWh
	Peak	7-10, 18-21	0.484 NOK / kWh
Weekend	Standard	00-24	0.242 NOK / kWh

As figure 4.2 shows, the price is at its lowest at night between 11 pm and

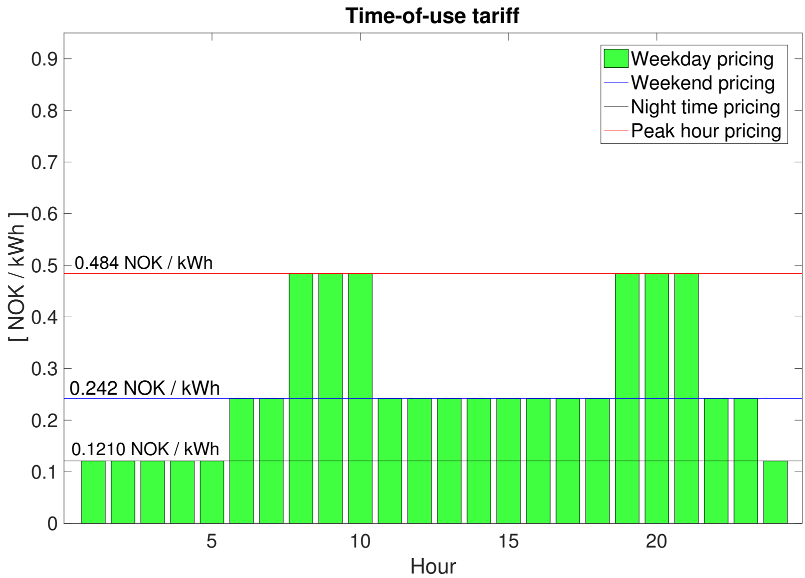


Figure 4.2: Time-of-use tariff prices during weekdays.

5 am. For daytime it doubles, with the exception of two peak load zones, where it is quadrupled. The two peak load zones (7-10 and 18-21) are chosen by advise from senior advisor at NVE (49). By increasing grid tariffs substantially during these periods, any optimizing mechanism would avoid use during these hours.

4.3.4 Power based tariff

The power based tariff is a very simple tariff which increases the price per kWh per kW used by the customer. By implementing this structure, customers who are using power demanding equipment, especially simultaneously, are "punished" for not distributing their load. The typical example is an electric vehicle being charged during the afternoon and early evening while residence load is high, instead of moving the charging to a later time. The prices are shown in figure 4.3.

The calculated price for the power tariff was 0.234 NOK/kWh/kW. Thus, when using less than one kW, the price per kWh is 23.40 øre/kWh. Between 1-2 kW, it's 46.80 øre/kWh etc.

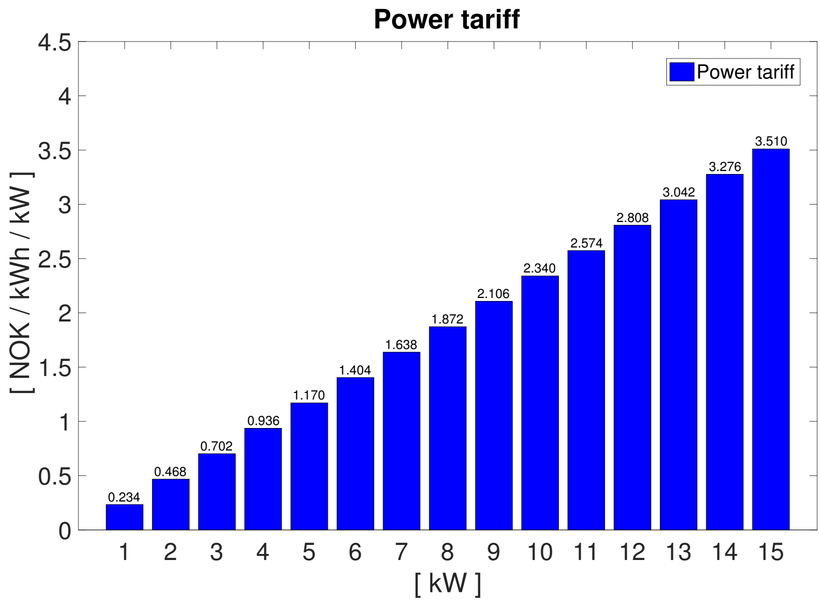


Figure 4.3: Illustration of the power tariff pricing. The price per kWh increases with each kW in use.

4.3.5 Subscription based tariff

The subscription based tariff is a tariff consisting of two parts. The first part is a subscription based price, where a customer chooses a certain amount of kilowatts he wants to subscribe to, and pays a fixed monthly price for each subscribed kilowatt. The second part is an energy based cost, where all energy used at a power above the subscribed power has a certain price. This price is split into two prices, one for low load hours and one for peak load hours. Peak load hours are 7-10 am and 6-9 pm, while the rest are low load hours. The fixed price is as following 4.4:

$$F(x) = C_{Fixed} + x * C_{Power} \tag{4.4}$$

where x is the subscribed power. The total annual price for this grid tariff is as described in equation 4.6.

$$C_{year}(x,t) = 12 * F(x) + C_{low} * \sum_{i=1}^{t} y(t) + C_{peak} * \sum_{i=1}^{t} z(t) \tag{4.5}$$

where

i	= 1, 2, 3, ... , N is the period (hour)
t	= hours per year
x	is the subscribed power (kW)
$F(x)$	is the monthly fixed cost (NOK)
C_{low}	cost per kWh bought above x kW during low load hours (øre/kWh)
C_{peak}	cost per kWh bought above x kW during peak load hours (øre/kWh)
$y(t)$	is energy consumed above x kW during low load hours (kWh)
$z(t)$	is energy consumed above x kW during high load hours (kWh)

To achieve equal prices with this structure compared to the structure that exists today, the prices were calculated to be the following:

$$
\begin{aligned}
C_{Fixed} &= 90 \text{ NOK} \\
C_{Power} &= 90 \text{ NOK} \\
C_{low} &= 45.2 \text{ øre/kWh} \\
C_{peak} &= 90.4 \text{ øre/kWh}
\end{aligned}
$$

The values were calculated with inspiration and help from employees at NVE (49) (50).

4.4 Energy prices

Due to the liberalization of the power market, a residence can freely select an energy company to deliver electric energy. Almost every energy company offers multiple price structures, including a spot price offer. For a spot price offer, there is usually a fixed monthly cost, and a few percent margin on every kWh bought, to assure revenues for the energy company. The calculation of the annual cost for the customer C_{annual} is given by equation 4.6.

$$C_{annual} = 12 * C_{fixed,mon} + \sum_{i=1}^{t} X_i * (C_{spot,i} + C_{margin} + C_{GC}) \tag{4.6}$$

where

i	= 1, 2, 3, ... , N is the period (hour)
t	= hours per year
X	is the kWh consumption for hour i
$C_{fixed,mon}$	is the monthly fixed cost
C_{spot}	is the Nord Pool spot price (øre/kWh)
C_{margin}	is the margin taken by energy companies (øre/kWh)
C_{GC}	is the fixed green certificate fee (øre/kWh)

Chapter 5

Data input

In the following chapter, data used for the simulations are presented. The main point of the chapter is to show which data are used, how they are used and to illuminate the sources that have provided them. Thus, only brief discussion of their precision and quality will be mentioned. Main discussion takes place in chapter 7.

Note that the word *data* is used as plural, although IEEE Computer Society suggest singular when used in the sense of computer data.

5.1 Load data

The load data are taken from two different residences in Trondheim, one apartment and one large house, from now on referred to as household. The data resolution is hourly, and is rounded to the closest 100 watts. Full load data from January 1st of 2013 till December 31st 2015 was provided by Trønderenergi, which gives full access to three years of load data.

While the load data are anonymous, Trønderenergi has specified the city as mentioned above. The load profiles can be seen in figures 5.1, with the power duration curve shown in figure 5.2.

The load profiles are fairly equal for all shown years, and the most important information is summarized in table 5.1.

Because a lot of space heating in is done with electricity, and the winters can be cold, it is to be expected that loads are higher in the winter compared to summer. For the sake of anonymity, it can't be concluded whether or not either of the residences have other heating sources. More discussion about

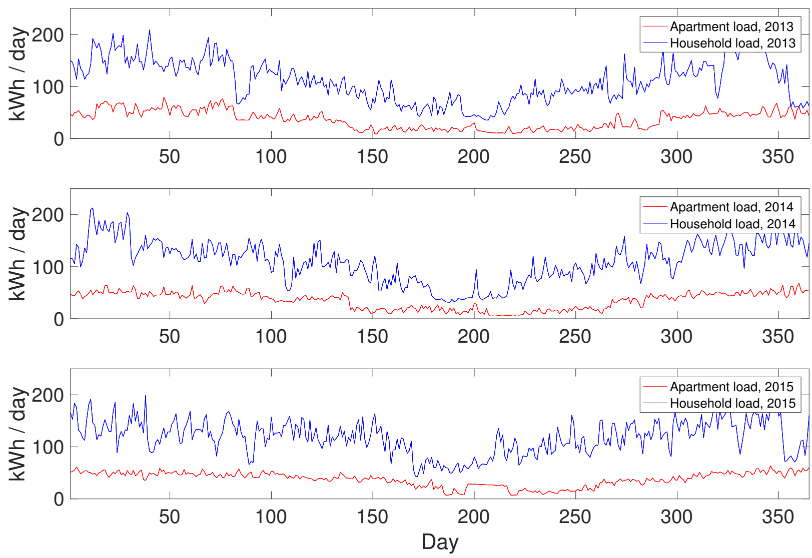


Figure 5.1: Daily load profile for both the apartment and the household from 2013, 2014 and 2015

Table 5.1: 2015's load profiles' key data

2015	Consumption	Average	Maximum
Apartment	13 830 kWh	1.58 kWh/h	5.1 kWh/h
Household	43 303 kWh	4.94 kWh/h	15.0 kWh/h

the data will take place in chapter 7.

Figure 5.2 shows the load duration curve of both residences. Both load profiles have the characteristic S-shape, with most hours balancing around the average load which is shown in table 5.1. If the earlier mentioned power tariff was introduced, customers could save money by shifting some of their load to hours with lower kW usage.

The heatmap in figure 7.10 shows when the household is spending the most power during the day, distributed by weekday. There is a clear peak from 17-22, meaning that the time-of-use tariff with a high price during these hours would punish this household with very high prices. This gives a potential for saving by shifting load. For the simulations, the household load from 2015 will be used, because it is more likely that a large household can install a decent amount of roof mounted PV panels compared to an apartment.

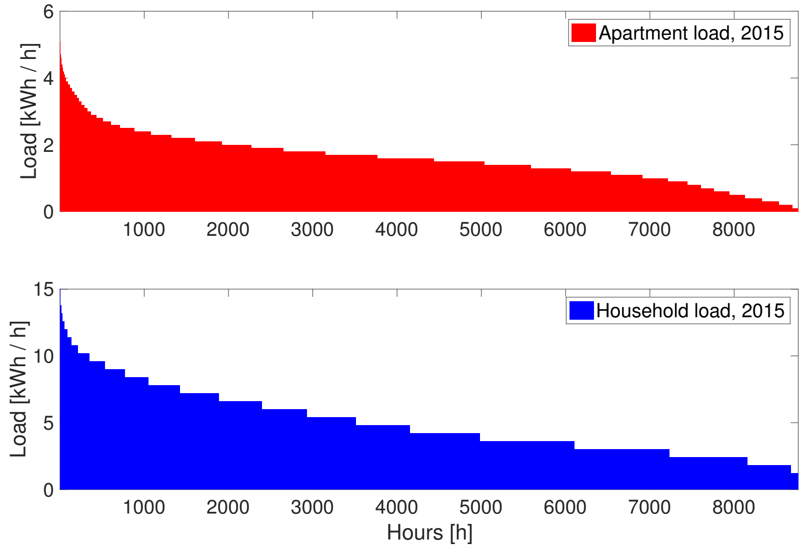


Figure 5.2: Power duration curve, 2015.

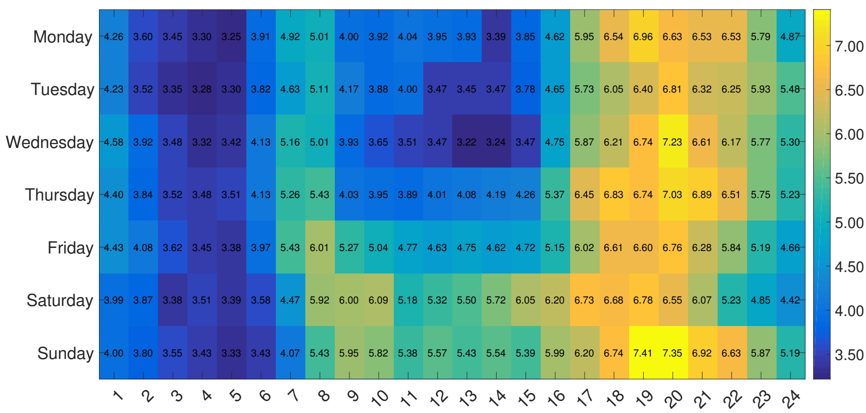


Figure 5.3: Heat map of the 2015 household load. The matrix shows the average kW consumption for the specific hour at the specific weekday.

5.2 Battery specifications

Two batteries will be used for these simulations. The first and most important one is an EV battery. The second one, is going to be a wall mounted house battery, to compare the results of using an EV battery compared to a house battery.

5.2.1 EV battery

In theory, any EV battery can be used, but because this is a simulation of the potential in future power systems (earliest potential utilization comes with AMS in 2019), it makes sense to simulate a future battery. With increasing range demands, battery pack sizes will also increase. In this thesis a battery pack with the following specifications will be assumed.

- $P_{bat,max} = 15$ kW
- $E_{capacity} = 80$ kWh
- $SOC_{max} = 1$
- $SOC_{min} = 0$

The efficiency is modelled as mentioned in chapter 3. Note that 80 kWh is enough for approximately 400 km range, if a 0.2 kWh/km efficiency is assumed (6). It is reasonable to assume that EVs in the future will have a range from 300 - 600 km in the future, as car producers will thrive to achieve equal range as ICE cars. The maximum power of an EV is normally above 100 kW, but a max limit of 15 kW to reduce losses and keep inverter costs down is set.

5.2.2 House battery

For the house battery, the Tesla Power Wall will be utilized (38).

- $P_{bat,max} = 7$ kW
- $E_{capacity} = 13.5$ kWh
- $SOC_{max} = 1$
- $SOC_{min} = 0$
- $\eta_{bat} = 0.90$

5.3 Solar data

Norway's large hydro power installations provided 95.7 % of the electricity production in 2015. With wind power 1.7 %, and thermal power's 2.5 %, solar power is negligible from the Norwegian power mix. Accenture together with WWF presented a report about future possibilities on solar power in Norway (13). Figure 5.4 is taken from the report, showing PV production potential for different cities around the world.

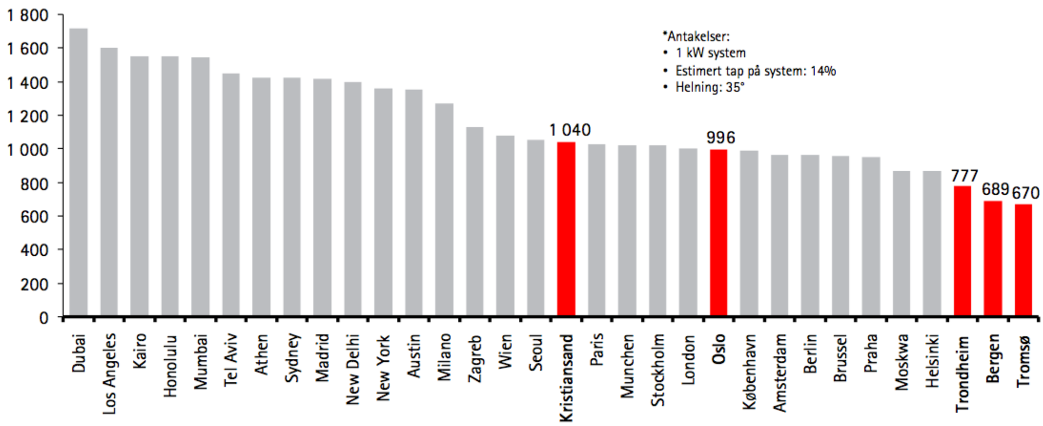


Figure 5.4: Annual PV energy production potential in different cities measured in kWh/kW/year. These data are given 86 % system efficiency, 15 % cell efficiency, 35 degrees inclination and a 1 kW installation. Figure from Accenture and WWF (13).

As the figure shows, irradiation is not in particular much lower in Norway compared to the rest of Europe. With price dropping as much as 75 % in just 10 years (13), good arguments against solar power in Norway are fading, especially in the south of Norway where e.g. PV production potential in Kristiansand matches the one in Paris.

5.3.1 Irradiation data

In order to run simulations with optimal data, solar radiation data from Trondheim would be preferred. As no real measured PV data in Trondheim were available, irradiation data from LMT, Landbruksmeteorologisk Tjeneste, was used. LMT is a governmental funded project operated by NIBIO (Norsk Institutt for Bioøkonomi) for measuring and publishing weather data from all over Norway. LMT has 52 stations and is providing data such as

- Temperature - Maximum, minimum and average air temperature and average soil temperature at various depths
- Global irradiation - Hourly resolution of watts per square meter
- Wind speed - Wind speeds at 5 second, 10 minute and 1 hour average
- Rainfall - Rain, snow and humidity

With the help of these stations, global irradiation and temperature data were downloaded. The irradiation data are shown in figure 5.5, and their accumulated irradiation is summarized in table 5.2.

The instrument used to measure these data, was CM11 and CM3 made by Kipp & Zonen (51). It measures the sum of direct and diffuse radiation in the wavelength area ultraviolet, visible light and infrared light, spanning from 285 to 2800 nanometres.

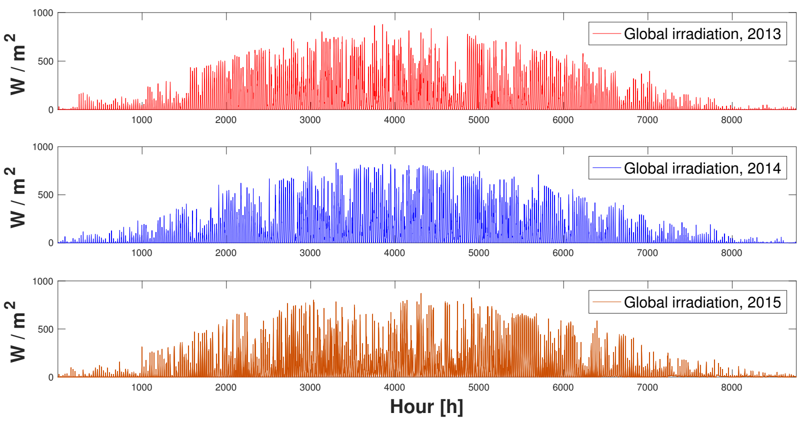


Figure 5.5: Global irradiation at Sjetlein from 2013, 2014 and 2015.

Table 5.2: Overview of accumulated irradiation for 2013, 2014 and 2015

Year	Total
2013	829 kWh
2014	866 kWh
2015	813 kWh
Mean	836 kWh

The data look promising when comparing to the numbers given in figure 5.6 (14), which suggests around 1100 kWh per square meter.

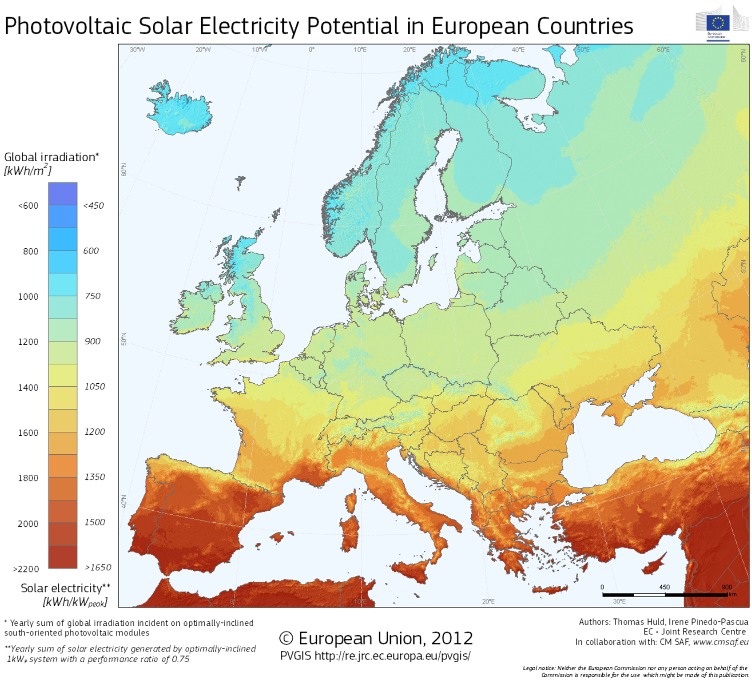


Figure 5.6: Overview of irradiation in Europe by PVGIS. Figure from (14).

This number is larger due to the condition that the irradiation is received on an optimally-inclined south-oriented photovoltaic module, while the one being used by LMT is lying horizontally. In order improve the data from LMT, inclination and direction orientation has to be taken into account. Multiconsult, which is a large consulting firm with a solar power division, presented a report on solar installations in Norway (15).

TRONDHEIM	Jan.	Feb.	Mar.	Apr.	Mai	Jun.	Jul.	Aug.	Sep.	Okt.	Nov.	Des.	År
Meteonorm	5,8	22,7	64,3	110,3	153,0	158,1	153,5	112,2	66,3	29,4	7,8	2,7	**885,9**
Nasa	5,0	19,3	57,0	106,8	153,8	155,7	144,5	113,8	72,0	32,9	9,0	1,9	**871,5**
PVGIS	4,6	19,7	56,7	100,5	143,5	156,9	144,2	107,0	58,5	26,7	7,7	2,1	**828,2**
Satellight	4,6	19,0	59,3	102,6	153,8	137,5	142,7	114,7	73,9	32,3	9,0	2,3	**851,8**
Gjennomsnitt	4,8	19,5	58,2	104,7	153,4	156,3	144,4	113,0	69,2	30,9	8,4	2,2	861,7

Figure 5.7: Overview of irradiation data in Trondheim. Figure from Multiconsult (15).

To compare different global irradiation databases, Multiconsult gathered data from many different organizations and science projects. The results are taken from (15) and is shown in figure 5.7. The sources used are Meteonorm, Nasa, PVGIS and Satellight. The results span from 828.2 to 885.9 kWh per square meter per year on a horizontal space, with a mean value of 861.7 kWh per square meter per year. Thus, there is reason to believe that the result from LMT shown in table 5.2 is realistic, and that the source is credible.

With the help of software such as PVsyst (52), one can calculate the optimal module angle of a PV panel as a function of position on earth. Multiconsult calculated these values for Trondheim, and found that the optimal installation angle is 45 degrees (4). Figure 5.8 shows that the power produced is 20 % lower when using a horizontal panel compared to 45 degrees, or the other way around - a 45 degree angle increases the efficiency of 25 % compared to a horizontal space. The figure also shows that angles between 20 and 45 degrees are fairly efficient. Senior advisor at Multiconsult (53), one of the biggest PV installation experts in Norway informed that the average inclination angle of roofs in Norway is 28 degrees. This inclination will be used. It gives 3.5 % less irradiation compared to the optimal 45 degrees for Trondheim. With zero degrees inclination, the transposition factor is 1. With 28 degrees inclination, this factor is

$$\eta_{transposition} = \frac{96.5\%}{80\%} = 1.206 \tag{5.1}$$

It will also be assumed that the house is facing south in this thesis. While the irradiation is slightly weaker for houses facing other directions, this will not be taken into account, but further discussed in chapter 7.

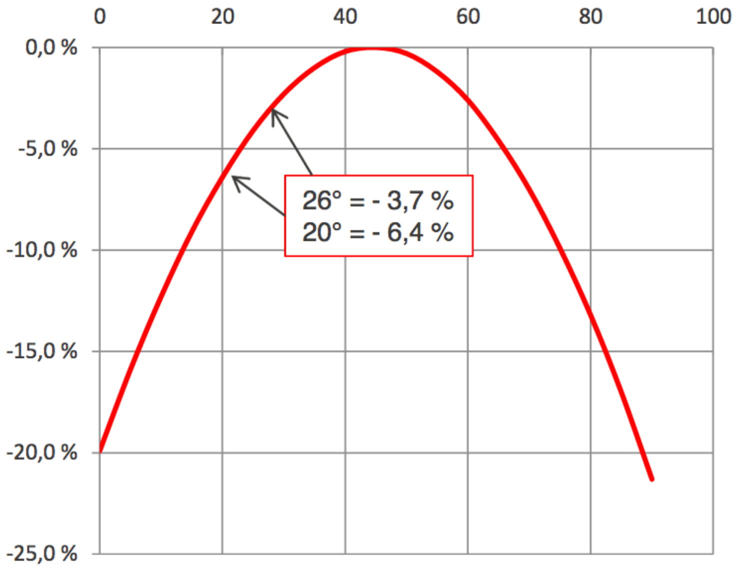


Figure 5.8: Transposition factor showing increase of absorbed irradiation in Trondheim as a function of inclination angle. Figure from Multiconsult (15).

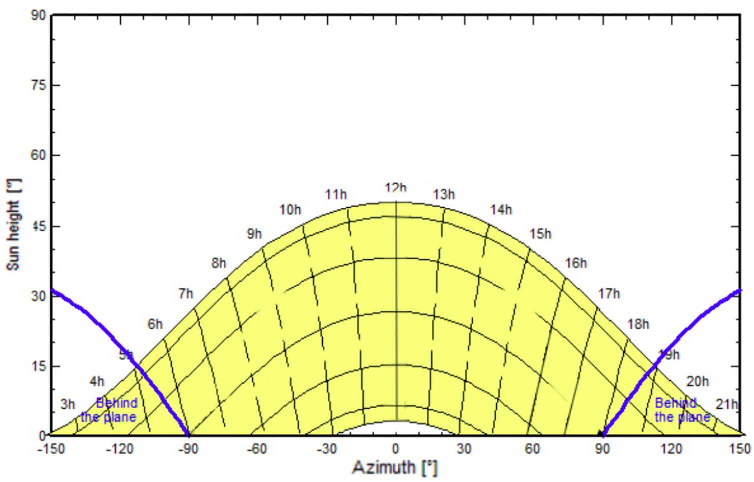


Figure 5.9: Sun path diagram over Trondheim. Figure from Multiconsult (15).

5.3.2 PV energy production

By using the model explained in subchapter 3.2.1, PV production data can now be created with MatLab. To calculate the exact values, the PV panel Sanyo HIT-240HDE4 is used. It is commercially available and is sold by one of Germany's largest PV panel distributors - IBC. The specification sheet (33) gives a $NOCT$ of 44 °C and an α_T of -0.3 %/°C. Nominal installed power P_{nom} is set to 7 kW after recommendation from a PV expert at Multiconsult (53). With 190 W/m^2, the installation is 36.84 m^2. The resulting produced power is shown in figure 5.10.

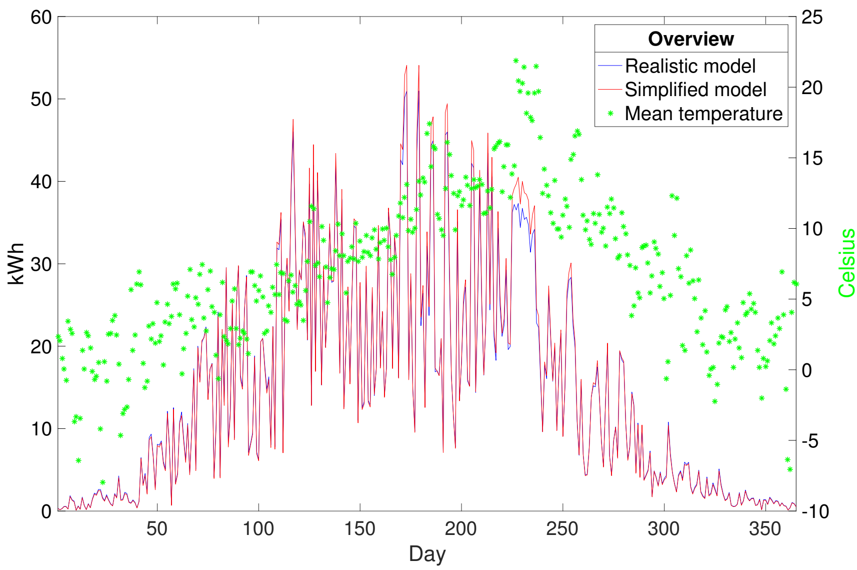


Figure 5.10: PV production from both the simple and the realistic PV model for 2015, with mean temperature shown in green.

The realistic model produces 5 324 kWh, while the simple one produces 5 425 kWh, which is a 1.9 % difference, as a result of taking temperatures into account. Still, the irradiation is by far the most dominant factor, as the production from both models are close to equal throughout the entire year.

A zoomed in version 5.11 from the summer is also included to illuminate how higher temperatures lead to lower the production in the realistic model. The figure shows how the production in the realistic PV model falls compared to the simplified PV model when temperatures are high. The month-hour

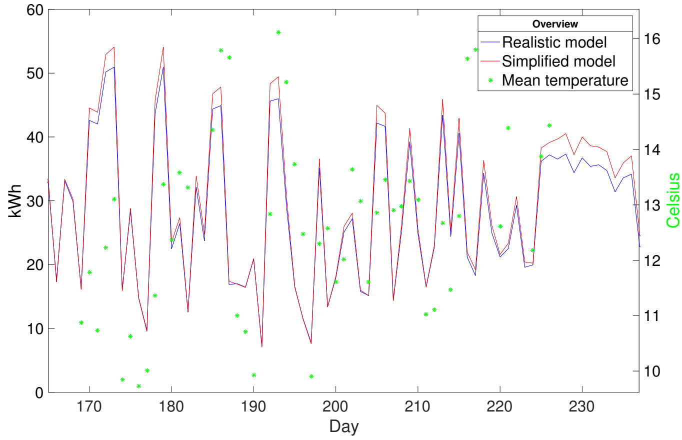


Figure 5.11: Zoomed in version of figure 5.10.

distribution of the PV production is shown in figure 5.12

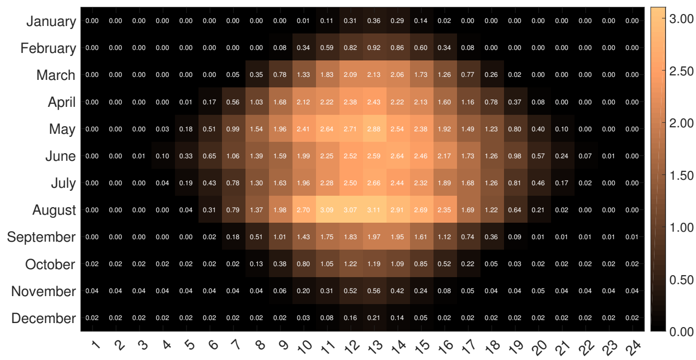


Figure 5.12: Heat map of the 2015 PV production using the realistic model. The matrix average kWh production per hour for the different months.

5.4 Energy prices

In order to gather realistic data, complete spot price data were downloaded from Nord Pool Spot's database (16). The spot price changes every hour, and can therefore be used to calculate the price of load very easily. As shown in figure 2.1, there are five different pricing zones in Norway, where Trondheim is located in NO3. Thus, spot prices were downloaded from 2013, 2014 and 2015 for this region.

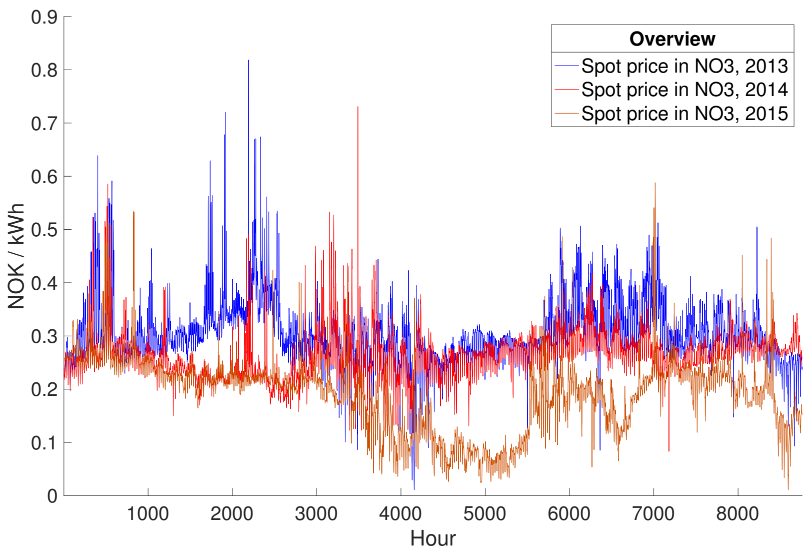


Figure 5.13: Spot prices in NO3 from 2013, 2014 and 2015 with hour resolution. Data download from Nord Pool Spot (16).

Figure 5.13 shows the prices downloaded from Nord Pool Spot (16). Table 5.3 shows some key values from the figure.

Table 5.3: Average, minimum and maximum prices of 2013, 2014 and 2015. All prices are presented in NOK per kWh.

Year	Mean	Variance	Min	Max
2013	0.3034	0.0034	0.0110	0.8185
2014	0.2636	0.0019	0.0831	0.7310
2015	0.1898	0.0047	0.0109	0.5880

Prices are mostly stable around 0.25 NOK per kWh. It can also be observed a mild seasonal change, with lower prices in the summer, especially for 2015.

In general, there are not many hours with very high prices. One could conclude that prices in Norway are low and stable compared to many places in Europe (54).

In Norway, the most deciding factor when it comes to spot price is the water situation. The water situation says something about how much water that are available in the water magazines, how much rain and snow that is expected to fall, and how much ice and snow that will melt as a result of temperature and irradiation (55). Other factors such as prices in neighbouring countries (including cable connections) also influence the Norwegian spot price.

While it would be a good idea to plot price as a function of all the mentioned factors, it is more interesting to see how the spot price correlates to the load. While the load profile of an apartment is not representative for the load profile in all of Norway, it still tells us something about how much savings potential there is if the residence load is flexible. To show this, the load is plotted against the spot price for 2015 in figure 5.14.

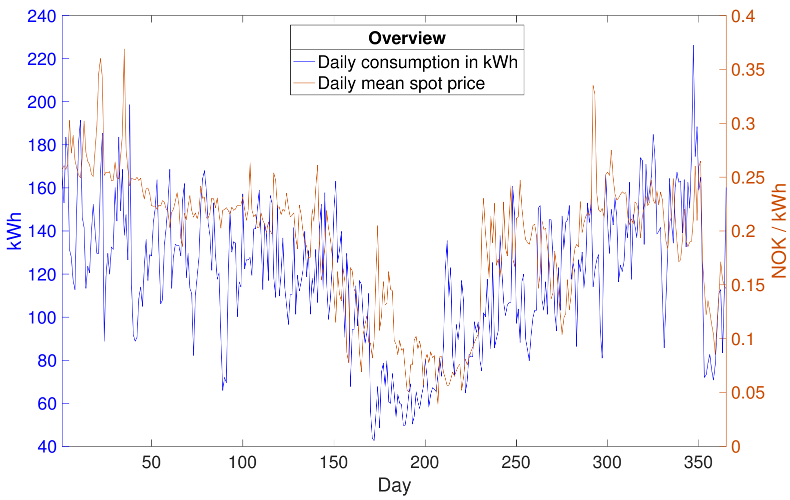


Figure 5.14: Daily average spot price versus daily energy consumption of the apartment in 2015

By looking at the price and spot price together, there appears to be correlation between the two. To achieve higher certainty of the correlation between consumption and price, larger amounts of data should be utilized. Either way, there is reason to believe that there is a relation between these two parameters. Note that the load profile of an apartment at best only represents the load profiles of households, and not the one of industry or public customers.

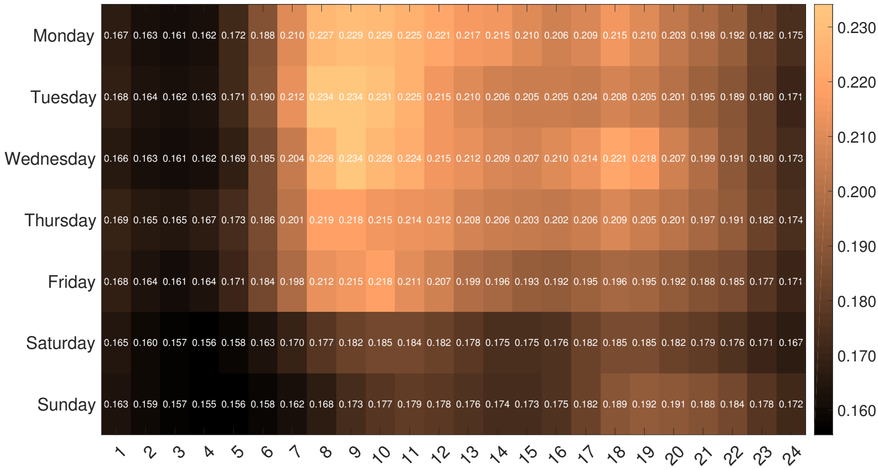


Figure 5.15: Heat map of the 2015 spot price. The matrix shows the spot price in NOK/kWh for the specific hour at the specific weekday.

As figure 5.15 shows, the prices are low at night, then rise around 7 when people wake up. The first peak from 8 am to 11 am is created by industrial, public and office customers together with residences that require large amounts of electricity in the morning hours. After sinking slightly throughout the afternoon, a new peak hits around 6 pm to 8 pm due to the previously mentioned residence load which occurs when people come home from work and start using power demanding equipment at home. It has to be noted that the spot price for 2015 is historically low, and the lowest since 2005 (56). The low prices can also be observed in figure 5.13. With low prices, the saving potential is reduced. This could influence the results, and results could appear weaker than they potentially are for normal years. This will be further discussed in chapter 7.

Due to the liberalization of the power market, a residence can freely select an energy company to deliver electric energy. For a spot price offer, there is usually a fixed monthly cost, and a few percent margin on every kWh bought, to assure revenues for the energy company. For Trønderenergi, the costs are

$$
\begin{aligned}
C_{fixed,mon} &= 37.6 \text{ NOK/month} \\
C_{margin} &= 2.5 \text{ øre/kWh} \\
C_{GC} &= 3.69 \text{ øre/kWh}
\end{aligned}
$$

In addition, there is a 25 % tax on all the above.

5.5 Grid tariffs

Grid tariffs in Norway make up about one third of the electricity bill of a household customer (57). It is built up by a yearly fixed price, and a fee for every kWh consumed. Typically, the fixed price is very low in urban areas and high in rural ones. The energy part of the grid tariff also varies, but depends more on whether or not the customer live close to power production. The prices are regulated by NVE, and are supposed to reflect the grid operation costs of the distribution system operators (58). The load data used are as mentioned from Trondheim, which belongs to the distribution grid under the jurisdiction of Trønderenergi Nett AS. Their grid tariffs for 2013, 2014 and 2015 are shown in table 5.4.

Table 5.4: Overview of total grid tariff prices including consumer fee and VAT (taxes). The sum reflects total grid tariff costs for the customer with an annual 20 000 kWh consumed.

Year	**Fixed cost**	**Var. cost**	**Cons. fee**	**VAT**	**Sum**
2013	1300 NOK	17.4 øre/kWh	11.6 øre/kWh	25 %	8 880 NOK
2014	1340 NOK	22.0 øre/kWh	12.4 øre/kWh	25 %	10 580 NOK
2015	1340 NOK	22.0 øre/kWh	12.4 øre/kWh	25 %	10 580 NOK
Mean	1327 NOK	20.5 øre/kWh	12.1 øre/kWh	25 %	10 013 NOK

If taxes and fees are excluded, the grid tariffs are reduced to only the fixed and variable cost as shown in the second and third column of table 5.4. For power based, time-of-use based and subscription based, see subchapter 4.3.

Chapter 6

Results

6.1 Total customer cost

The results shown in this subchapter are the total annual customer costs. This includes grid tariffs, taxes, fees and energy prices. In other words, the actual costs that the customer has to pay. Table 6.1 shows what values are plotted in figure 6.1. Figure 6.2 illustrates the savings potential from each scenario compared to the basecase scenario, while figure 6.3 shows the relative cost of each scenario, again compared to the basecase. Note that all scenarios with an EV battery, the cost of energy spent driving the EV was subtracted from the original sum, to avoid the results including the cost of daily transport. The values used were the average driving distance of a Norwegian car which was 33.9 km/day. With an average efficiency of 0.2 kWh/km, this accumulates to 6.8 kWh/day. All numbers are taken from this report (7).

Structure	**Basecase**	**Basecase incl. PV**	**House battery**	**EV battery**	**House battery incl. PV**	**EV battery incl. PV**
Photo-voltaic	-	X	-	-	X	X
EV Battery	-	-	-	X	-	X
House Battery	-	-	X	-	X	-
Energy Based	35 775	31 813	35 624	33 915	31 735	30 352
Power Based	35 498	31 574	34 724	33 333	30 790	29 704
Time-of-use	35 427	31 285	34 599	32 487	30 531	28 632
Subscr. based	35 442	32 531	35 126	33 629	32 229	31 191

Table 6.1: Total costs for customer for different scenarios and tariff structures. All numbers are given in NOK.

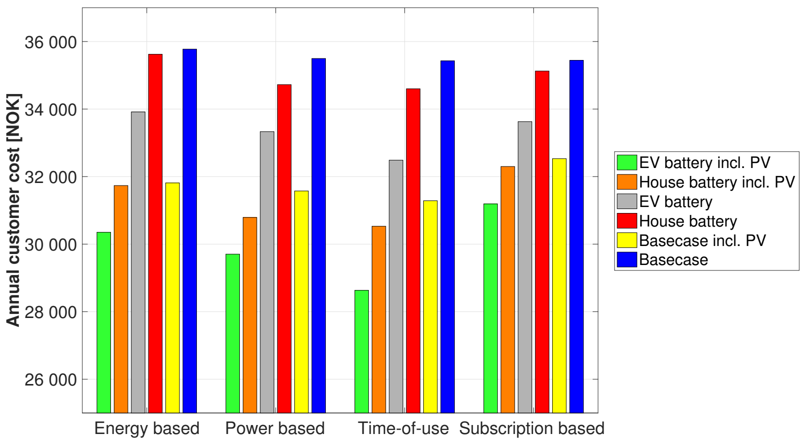


Figure 6.1: Total costs for customer with for the different scenarios.

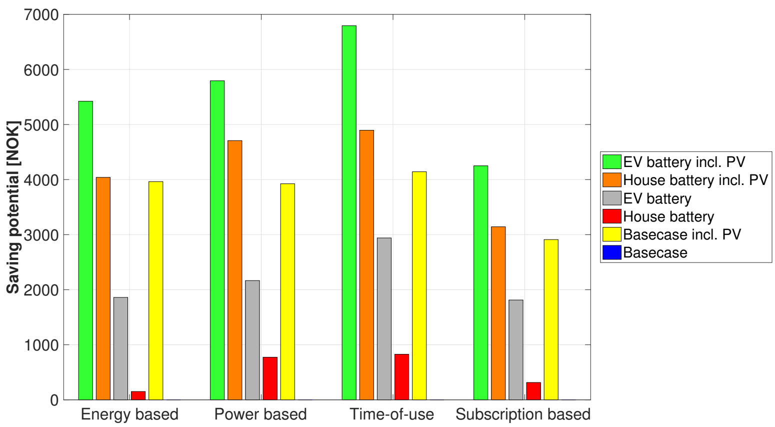


Figure 6.2: Total saving potential for different scenarios, all compared to the basecase cost.

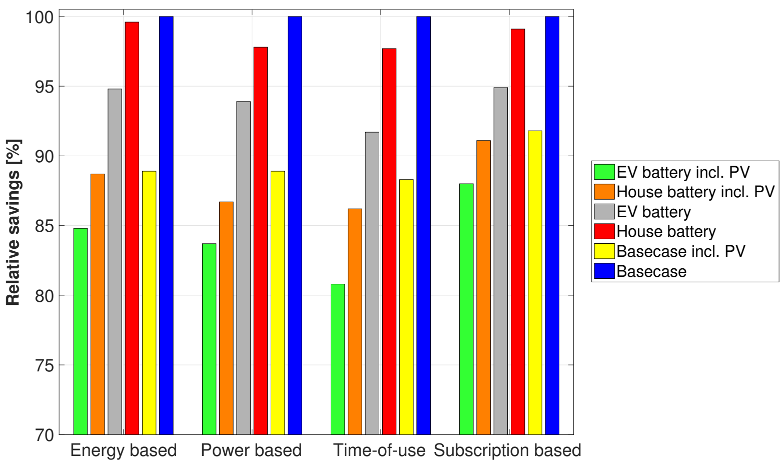


Figure 6.3: Relative annual cost for different scenarios, all compared to the basecase cost.

6.2 DSO's grid tariff income

6.2.1 Household

Table 6.2 and figure 6.4 shows that the DSO income for the different tariff structures are almost identical. Note that these results are calculated before any optimization or PV has been introduced. The idea is that the cost of grid use should be equal independent of structure, but that optimized utilization can lower the cost.

Table 6.2: Grid tariff costs for each tariff structure for the household.

Structure	Energy based	Power based	Time-of-use	Subscription
Grid Tariff	10 867 NOK	10 924 NOK	10 854 NOK	10 877 NOK

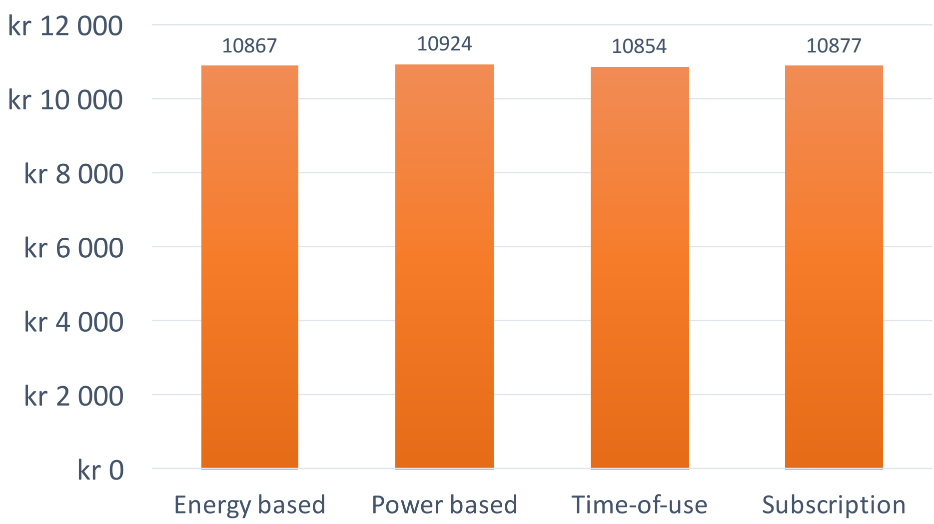


Figure 6.4: Total grid tariff income for DSO with the different structures for the household.

6.2.2 Apartment

The same income is presented with the given tariffs, however, in this section for the apartment. The results will be discussed furtherly in chapter 7.

Table 6.3: Grid tariff costs for each tariff structure for the apartment.

Structure	Energy based	Power based	Time-of-use	Subscription
Grid Tariff	4 383 NOK	4 206 NOK	3 387 NOK	4 437 NOK

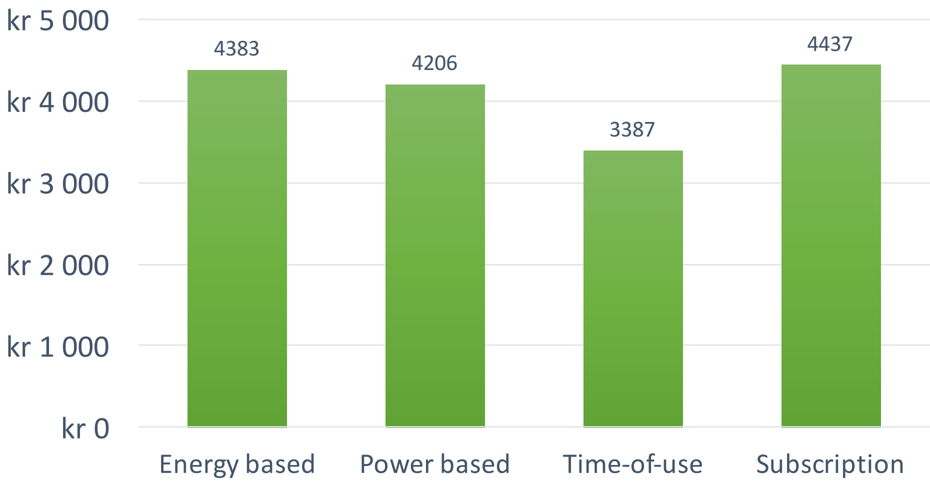


Figure 6.5: Total grid tariff income for DSO with the different structures for the apartment.

6.3 Load profiles

In this subchapter, the new load profiles after applying battery optimization and PV will be shown. The load profiles are sorted descending like in figure 5.2 to see how the grid is utilized with the battery optimization. Both load duration curves for the EV battery + PV, and house battery + PV scenarios are shown. Note that the plotted values are the kWh/h values withdrawn from the grid, often referred to as residual load.

6.3.1 PV and house battery

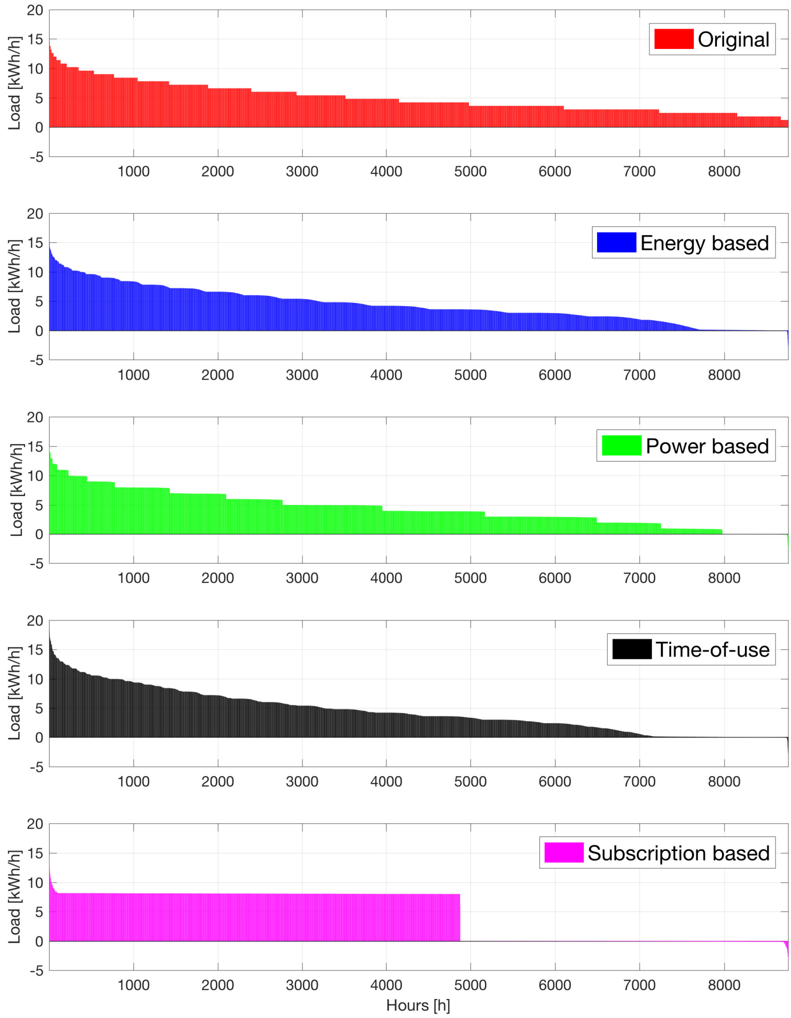


Figure 6.6: Load duration curves for the PV and house battery scenario, 2015. The top graph shows the original load duration curve, while the four other show the new load duration curves for the different grid tariffs.

6.3.2 PV and EV battery

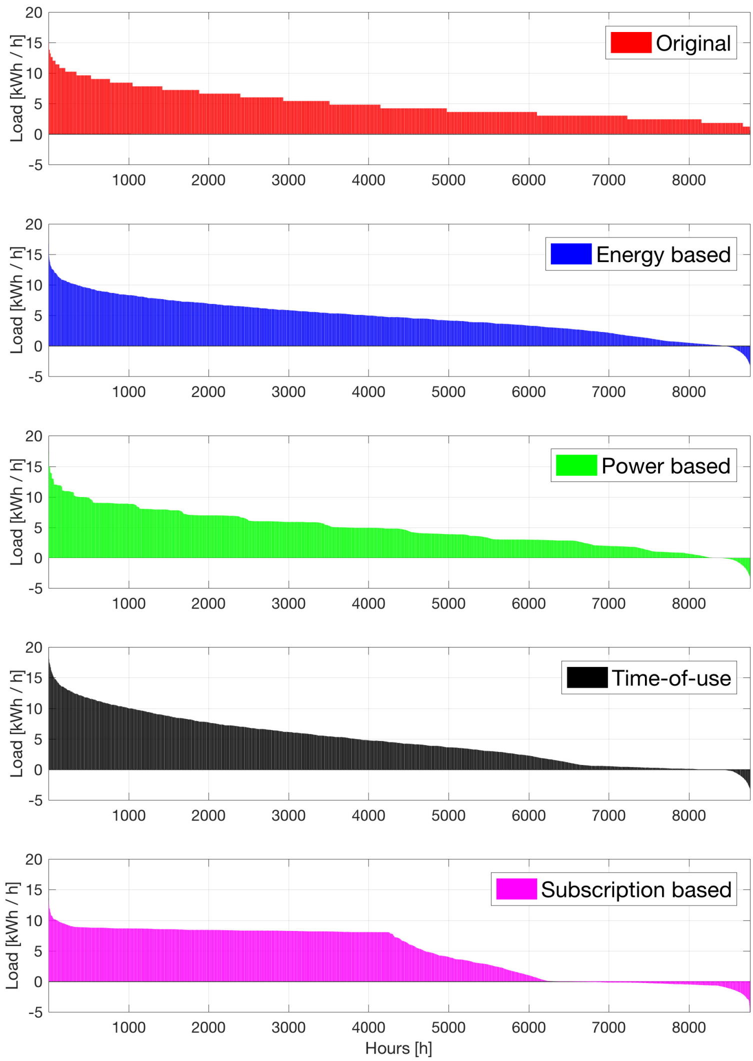


Figure 6.7: Load duration curves for the PV and EV battery scenario, 2015. The top graph shows the original load duration curve, while the four other show the new load duration curves for the different grid tariffs.

6.3.3 Key load values

In this subchapter, minimum and maximum values provided by the grid are provided for the basecase scenarios, PV + house battery scenario and the PV + EV battery scenario. The maximum kWh/h values are presented in table 6.4, while the minimum kWh/h values are presented in table 6.5.

Table 6.4: Maximum kWh/h values for the different scenarios in 2015.

Structure	Energy based	Power based	Time-of-use	Subscription based
Basecase	15.0	15.0	15.0	15.0
Basecase incl. PV	15.0	15.0	15.0	15.0
House battery incl. PV	15.0	15.0	20.0	15.0
EV battery incl. PV	16.7	17.7	21.0	13.8

Table 6.5: Minimum kWh/h values for the different scenarios in 2015.

Structure	Energy based	Power based	Time-of-use	Subscription based
Basecase	0.0	0.0	0.0	0.0
Basecase incl. PV	-3.5	-3.5	-3.5	-3.5
House battery incl. PV	-5.0	-4.71	-5.0	-8.4
EV battery incl. PV	-3.3	-3.3	-3.3	-5.1

6.4 Battery SOC utilization

The following figures show how much of the total battery capacity is being utilized for each day.

6.4.1 PV and house battery

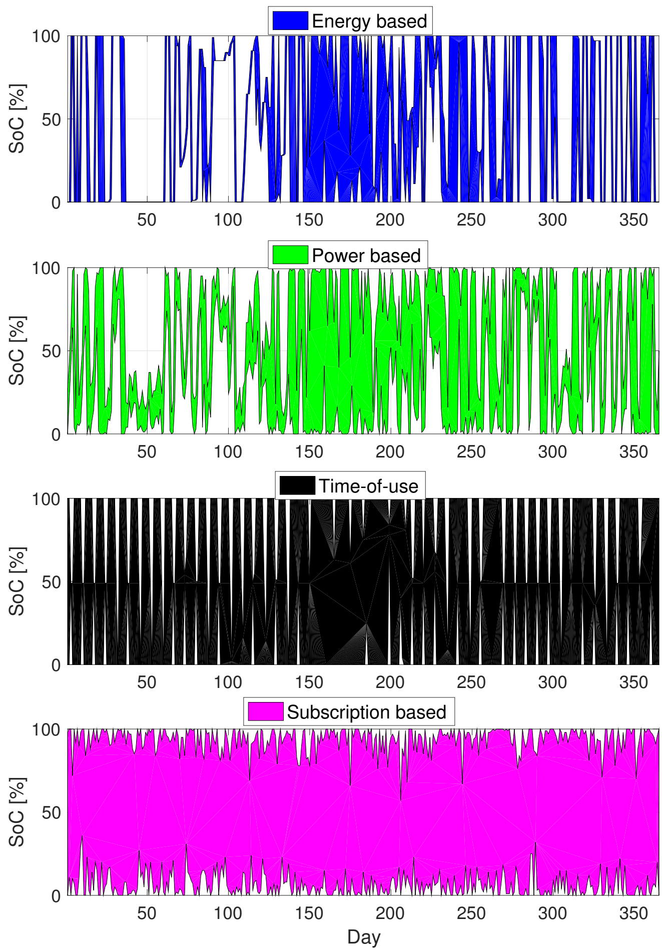


Figure 6.8: House battery SOC utilization - the filled area represents the span of SOC used per day.

6.4.2 PV and EV battery

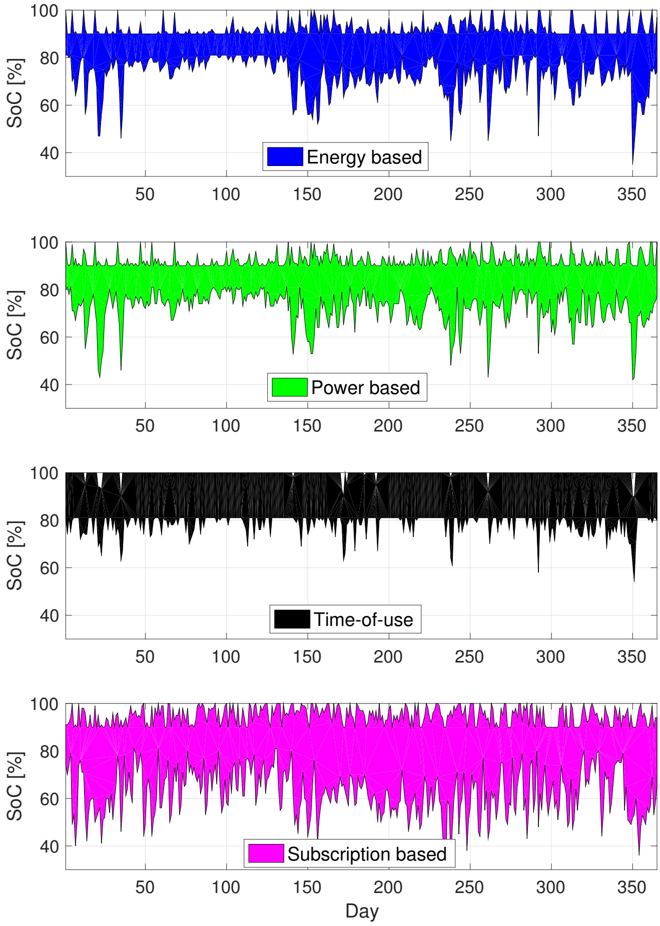


Figure 6.9: EV battery SOC utilization - the filled area represents the span of SOC used per day.

Chapter 7

Discussion

The subchapters in this chapter present different aspects of the results shown in chapter 6. Subchapter 7.1, 7.2 and 7.3 are discussions of the results presented in subchapter 6.1, 6.2 and 6.3, respectively. Therefrom, economic, model and scenario aspects are discussed further.

7.1 Annual customer cost

In addition to discussing the resulting prices and saving potentials shown in subchapter 6.1, extractions from interesting days are done to show how the optimization controls the battery in order to provide these savings.

7.1.1 Energy based tariff

With the energy based tariff, grid tariffs are the same for all hours. Thus, only the spot price would give incentive to shift load. The battery provides savings by charging during hours with low spot prices, and discharges when the spot prices are high. By installing a PV panel, 3 962 NOK can be saved annually, or approx. 11.1 %. The PV model shows a production of 5 324 kWh in 2015, which is approx. 760 kWh per installed kW, which was $P_{nom} = 7$ kW. Multiconsult's solar report claims that normal PV production in Norway should be approximately 800 kWh/year per installed kWp (15). Because most of the PV production takes place in the summer during day while the load is low, the PV panels were able to save 74.4 øre per kWh produced.

When implementing the battery and the PV, figure 6.2 shows that adding a house battery barely changes the savings. In fact, they are only 78 NOK greater than for PV only, or 0.2 % more. This is due to the fact that only variations in spot price can be utilized to save money, because the grid tariffs are constant. Another confirmation can be found by looking at the saving potential by installing a battery without PV, which would lead to only 151 NOK saved, or 0.4 %. In 2015, the spot price average was 18.98 øre/kWh, with a variance of 0.0047. These are very low values (56), which reduces the battery's potential to provide savings.

In general, this grid tariff gives no incentive to shift load, and with a low and stable spot price, there is altogether little reason to change energy consumption behaviour.

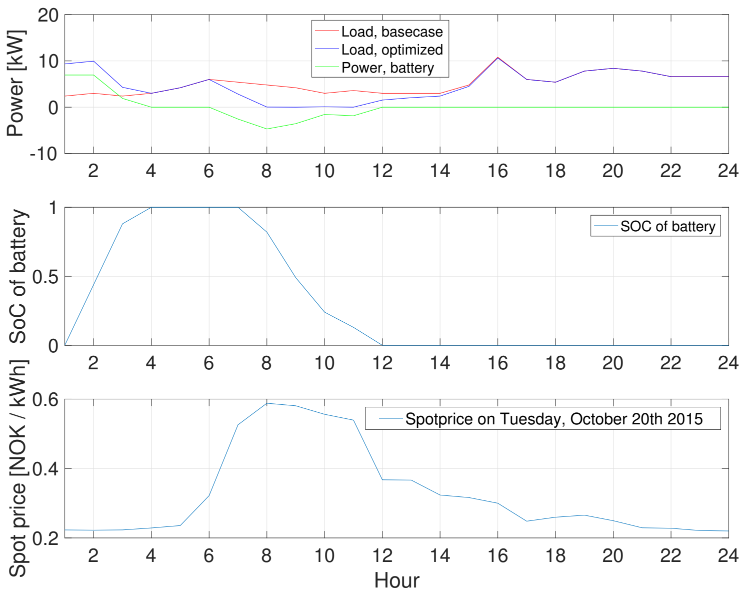


Figure 7.1: Overview of basecase load, optimizing load, house battery charge and discharge, SOC and spot price for October 20th, 2015.

When implementing the EV battery, savings increase slightly up to 5 423 NOK (15.2 %), which is 1 461 NOK more than with PV alone. The EV battery also provides 1 860 NOK savings (5.2 %), which is quite a bit more than the house battery was capable of. The reason for the improved savings is simply that the EV battery has a larger capacity, and a bigger charging and discharging power possibility.

Figure 7.1 and 7.2 shows day 293 of 2015, Tuesday 20th of October. Between

7 and 8, the spot price was the highest for all of 2015, at 58.8 øre/kWh. The figures shows how the batteries charge before this price peak appears, and discharges while the prices are high.

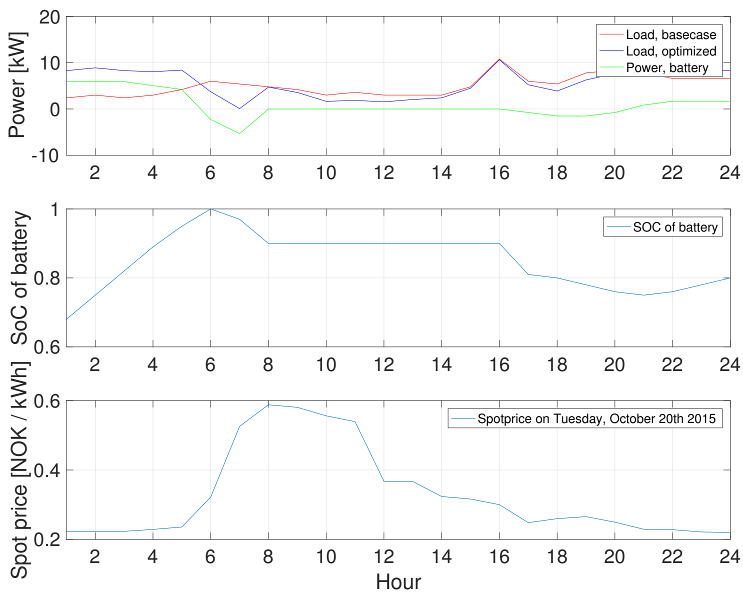


Figure 7.2: Overview of basecase load, optimized load, EV battery charge and discharge, SOC and spot price for October 20th, 2015.

Note that as shown in figure 3.1, positive power for the battery is defined as charged power, while negative power is discharged. Because the model is deterministic, the battery knows that a price peak is coming, and is charging during night. At 4 am, it is fully charged, and at 7 am it starts to discharge due to the price increase. At noon, the battery is fully discharged again, however, some PV production keeps the optimized load slightly lower than the basecase load as seen by the red and blue curves in the first subplot.

For the scenario with the EV battery, the results are different. Because the EV is unplugged from 8 am to 4 pm, the battery is unable to negate some of the power demand during some the peak price hours. However, it is capable of delivering higher powers and has a higher capacity, which in the long run makes it advantageous compared to the house battery which was confirmed by the savings shown earlier. Nevertheless, for this specific day, the house battery can use its stationary position to its advantage and provides greater savings.

7.1.2 Power based tariff

For the power based tariff, low use of power is rewarded with lower grid tariffs. In general, this tariff promotes evenly distributed use of the grid. For the basecase, the price was 35 498 NOK, and 31 574 NOK with PV only. This accumulates to 3 976 NOK saved, or 11.1 %. The house battery and EV battery alone respectively saves 756 and 2 165 NOK, which is significantly more than with the energy based tariff. With this in mind, one could already argue that this grid tariff to a larger degree promotes smart use of batteries, and also promotes use of PV as it lowers the power withdrawn from the grid when there is PV production. When adding PV and the house battery, savings are 4 708 NOK (13.3 %), while PV and EV battery savings are 5 794 NOK (16.3 %).

To look at the power based tariff, an overview of June 19th 2015 has been chosen as an example.

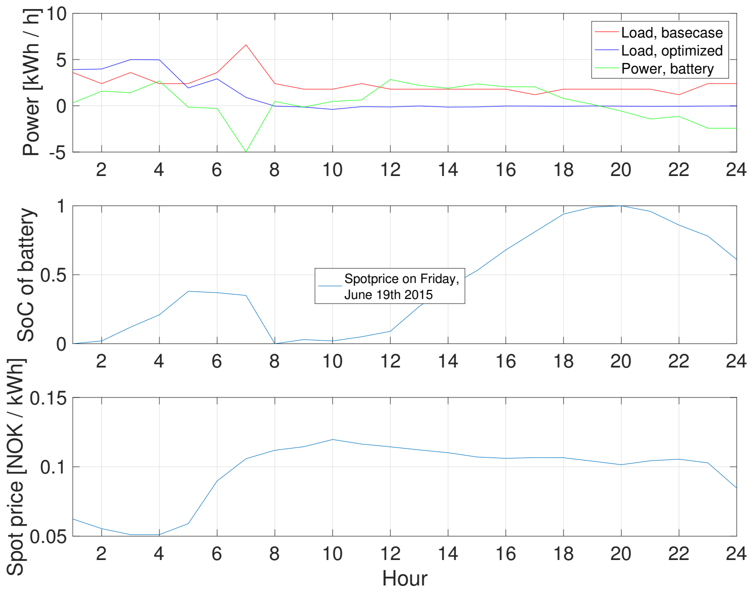


Figure 7.3: Overview of basecase load, optimized load, house battery charge and discharge, SOC and spot price for June 19th, 2015.

Figure 7.3 shows how the battery optimizes operation by charging during night (1-5 am), then discharges while the spot price increases (5-8 am), until PV production can handle the residence load itself, and during the day slowly charges to 100 % SOC with the PV that otherwise would be sold for a very low price, and saves it for later instead. When the PV production no longer sustains the load, the battery slowly starts providing the residence with power, ensuring that no electricity is bought from 8 am till midnight.

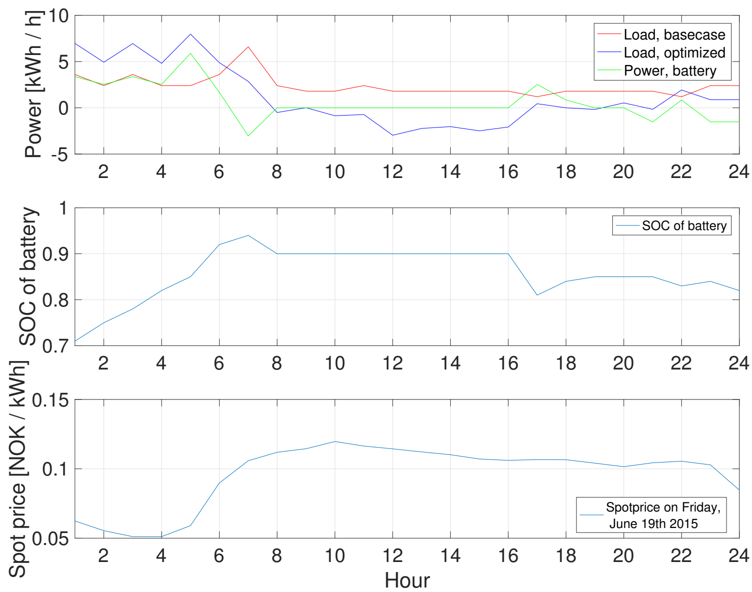


Figure 7.4: Overview of basecase load, optimized load, EV battery charge and discharge, SOC and spot price for June 19th, 2015.

The EV handles the case slightly different. In the charging conditions, the EV is set to have 90 % SOC at 8 am, to ensure that the driver has the necessary range. The battery therefore charges during night up to almost 95 % SOC at 7 am, provides some energy from 7-8 am, before it is unplugged at 90 % SOC. While it is gone, the high PV production of a sunny day has dealt with the residence load. However, because PV production was higher than the load, energy has been sold sold to the grid during day (8 am - 4 pm). As the lower graph shows, the spot price is very low and does not make selling a profitable choice, compared to saving the energy for later use which then can be spent without paying taxes or grid tariffs. When the car is plugged in at 4 pm, a decrease in SOC corresponding to energy used for driving. As of being plugged in, the EV charges with the extra

PV production still being available, before discharging slightly to keep costs low during the evening. While it is not shown in this graph, it is likely that the battery is planning to charge during night, and is therefore discharging slightly during the evening.

To conclude, one could say that the power based tariff gives more economic potential to installations such as PV panels and batteries, as there is now an incentive to shift load not only because of spot price, but to even out the load to reduce grid tariff costs. The saving potentials are fairly good, with about 15 % saved compared to the basecase when a PV and battery solution is chosen. However, it also punishes high power use equally every day, whereas overloading is rarely a topic during the summer. The question is if it is reasonable to have the same power tariffs for winter as for summer. By dividing the year into two or three different periods, where December-February would have their prices increased even more than in this thesis, while lowering the low load season March-November, one could create a tariff structure that makes more sense. To punish high loads during summer when there is plenty of available power and no transformer overloading, makes little sense.

7.1.3 Time-of-use tariff

The time-of-use grid tariff, consists of three different price levels every day as explained in chapter 4. It is based on rewarding customers who shift load from typical peak load hours to low load hours. The pricing zones created are based on the base load existing today, which peaks at around 9 am and 8 pm, and their neighbouring hours. By installing PV, the cost with this grid tariff is reduced from 35 247 NOK to 31 285 NOK, saving 3 962 NOK (11.7 %). The house and EV battery savings excluding PV are 828 NOK and 2 940 NOK, respectively. Note that the EV battery saves quite a bit more than the house battery scenario. When including PV, the house battery scenario saves 5 076 NOK (14.4 %), while the EV battery scenario saves 6 795 NOK (19.2 %), which is the biggest saved amount of all the scenarios mentioned. This is a substantial amount, and shows that when both spot price and grid tariffs are the highest during day, PV production contributes greatly to cost reduction. In addition, there are massive price differences from night to day, meaning that a battery could charge with PV or during the low grid tariff periods in order to spend during day. A fairly regular winter day is chosen to see how the batteries behave.

Figure 7.5 shows the tariff price in addition to the spot price on February 4th. The house battery firstly chooses to charge during night, due to the low

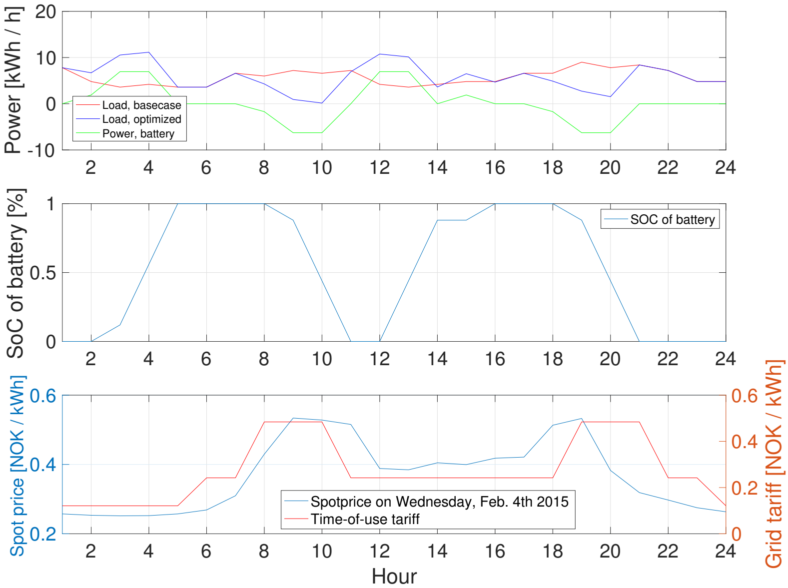


Figure 7.5: Overview of basecase load, optimized load, house battery charge and discharge, SOC and spot price for Feb. 4th, 2015.

energy and grid tariff prices shown in the lower subplot. Instead of discharging after being fully charged at 5 am, the battery waits with discharging because of the higher prices that kick in at 8 am, and discharges completely from 8 to 11 am, followed by a charging period again from noon to 4pm between the price peaks, and then again fully discharges from 6 to 9 pm when the prices are very high again. The optimized load curve is resultingly very high during night and in the day between the two usual national load peaks, but remains fairly low in the high cost periods. Due to the two price peaks, the battery performs two full cycles on this day.

The story is slightly different for the PV and EV battery scenario shown in figure 7.6, where the battery discharges due to a very low price at exactly 3 am. However, it has to be mentioned that as seen in the lower subplot, the saving potential is minimal, with just a few øre difference in price. While the algorithm has found a saving potential, this is hardly efficient use of the battery when cyclic aging is taken into account, and suggests that the optimization algorithm should be fine tuned to remain calm during very small price differences. For example, there could be a limit to how small the price difference can be to activate activity from the battery. At 4 pm, the

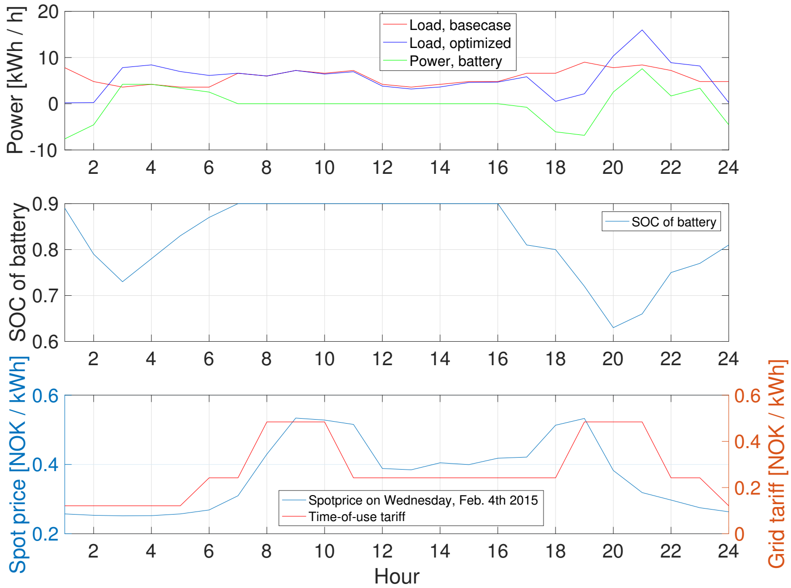


Figure 7.6: Overview of basecase load, optimized load, EV battery charge and discharge, SOC and spot price for Feb. 4th, 2015.

battery discharges until 8 pm to avoid the high prices, but starts charging slightly again at 8 pm. It is not certain why the battery chooses to charge at this time while the prices are still fairly high when looking at this figure. However, by a close inspection it is due to high price during night, not visible in this figure.

A potential pitfall for this structure would be the case where many choose to shift their load away from peak load hours, resulting in a equally complicated, but shifted peak load. However, if such a development was spotted, the price increase could be lowered, or even out on more peak load hours on a monthly basis.

7.1.4 Subscription based tariff

The subscription based tariff is based on subscribing to a certain amount of power, and paying fairly high prices per kWh if this amount is surpassed. The idea is that by subscribing to a self decided kW-limit, customers remain motivated to assure low consumption above the set limit. The basecase scenario has a cost of 35 442 NOK, which is by PV implementation reduced to 32 531 NOK - a saving of 2 911 NOK or 8.2 %. The house and EV battery scenarios without PV have an annual cost of 35 126 NOK and 33 629 NOK. When implementing PV in addition to the batteries, the cost is 32 299 NOK for the house battery, and 31 191 NOK for the EV battery, which respectively are savings of 3 143 NOK (8.9 %) and 4 251 NOK (12.0 %). Again it is observed that the EV battery is with its capability of moving more load than the house battery, capable of creating larger savings. When looking at figure 7.5, which represents the house battery and PV scenario, it can be observed that the battery either chooses to let the residual load (net load) remain at the subscribed 8 kW, or at zero kW. This is interesting, because it is very observable that the battery will either let the load be the full subscribed kW limit, or nothing, which leads to a very "unsmooth" load curve for the residence. It is also imminent that the spot price is less interesting, because the cost of surpassing the subscription limit is more expensive than buying slightly expensive electric energy, due to the cost of 45.2 and 90.2 øre/kWh which was stated in chapter 4.2.5.

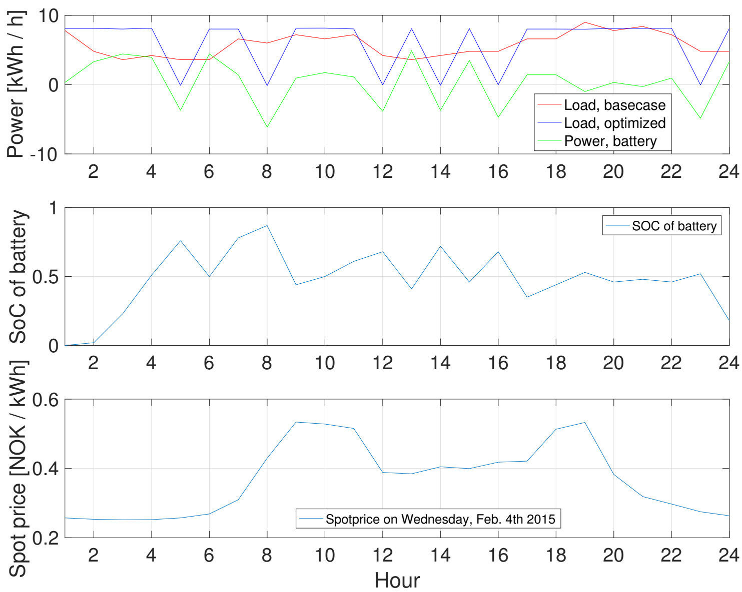


Figure 7.7: Overview of basecase load, optimized load, house battery charge and discharge, SOC and spot price for Feb. 4th, 2015.

For the scenario with the EV battery and PV installation visualized in figure 7.8, the battery charges right under the limit of 8 kW during night, and starts discharging greatly from 90 % SOC to 45 % SOC from 4 pm to

8 pm due to the high spot price, and in order to keep the load under 8 kW. From 8 pm and until midnight, it charges slowly, by again utilizing as much power as possible without exceeding the kW-limit.

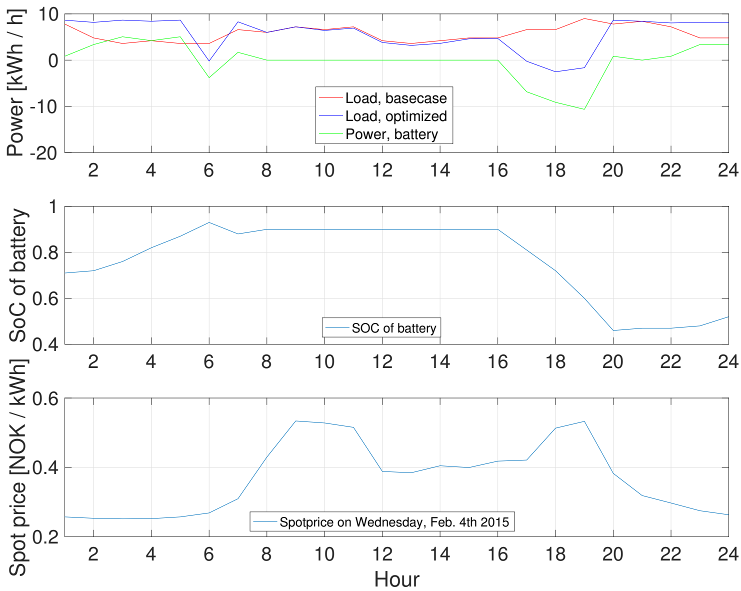


Figure 7.8: Overview of basecase load, optimized load, EV battery charge and discharge, SOC and spot price for Feb. 4th, 2015.

7.1.5 Summary - annual customer cost

There is no doubt that variable grid tariff costs can help utilize the distribution grids in Norway more efficient by using price signals to shift load. When the grid is utilized efficiently, DSOs can slowly start to lower their grid tariffs, or more likely, lower the increased price in grid tariffs.

Even though there are some variations in the annual cost, there overall clear tendency shown in the results, is that the EV and PV battery solution is the highest saving solution, with savings from 4 to 7 thousand NOK per year depending on tariff structure. In general, the house battery installations were not satisfying economically, with only very minor contribution to savings, even with PV.

7.2 DSO's grid tariff income

When calculating the new grid tariff prices, the main goal was to create new structures that resulted in the exact same income for the distribution system operator, while at the same time were promoting more efficient use of the grid. Thus, when assuming same tax levels, and same spot price levels for all the different tariffs, the electricity bills are fairly equal in the end. Figure 6.2 shows that the grid tariffs were close to identical for the different scenarios when calculated for the big household, which was the main focus of this thesis. However, figure 6.3 shows that the grid tariffs were fairly unequal when using the same price levels for the apartment as the house. The biggest difference was 1 050 NOK, or 23.7 %, which is too big a difference.

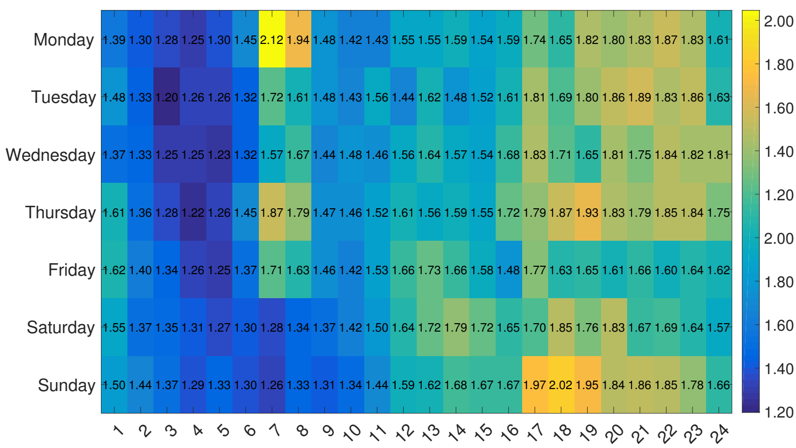


Figure 7.9: Heatmap of the apartment load, 2015.

When looking at the two heatmaps 7.9 and 7.10, it is imminent that the apartment has a more evenly distributed load than the household, which can be seen by the lack of strong dark blue color in addition to the bright yellow. With only these two data sets, it is hard to say which of the two is more representative for the average residence load in Norway. Additional load data would be helpful to compare these results to the mean. It is imminent that this should be taken into account if these values are to be used or interpreted for later use.

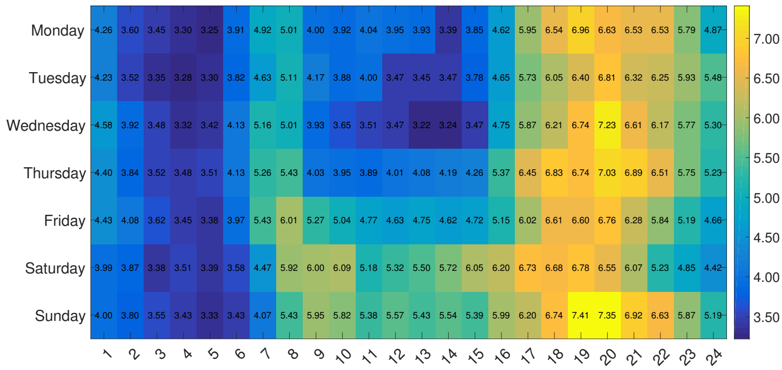


Figure 7.10: Heatmap of the household load, 2015.

7.3 Load profiles

7.3.1 Peak values

For the new grid tariffs to make sense, they must have resulted in use that to a smaller degree results in residential peak loads at during the normal peak load hours. When looking at table 6.5 and 6.4, the most troubling number are the ones created by the time-of-use tariff. For the PV and EV battery scenario, the highest power withdrawn from the grid is 21 kW. When looking closer at the data, this happened at hour 8396, which is between 7 and 8 pm on the 16th of December - a typical time and season which is problematic. However, when looking even closer, the temperature at the time was -3 °C(not particularly cold for December), and the spot price was at a low compared to its neighbouring hours with 27.7 øre/kWh. With the assumption that high spot price corresponds with high consumption, this hour was not a problematic hour, and therefore the extra power withdrawal is acceptable.

When looking at the 20.0 kWh/h value which was experienced with the house battery with PV scenario given the time-of-use tariff, the peak load hour was hour 3208, which was April 14th between 3 and 4 pm. This is normally not a load peak hour, and when looking at the very standard temperature (5.4 °C) and the spot price (17.7 øre/kWh), there is no reason to believe that this peak overlaps with a national peak load. The reason for the high power usage however, is due to the spot price being slightly lower than its neighbouring hours, which were between 18.2 and 20.0 øre/kWh. In other words, for both scenarios there does not appear to be an overlap of national peak load with the new residential peak loads created by these new grid tariff structures.

7.3.2 Load duration curves

Figures 6.6 and 6.7 show how the load duration curves change with optimized operation given the different grid tariffs, with the top red one being the original load. The reason for what appears to be a low resolution curve, is simply due to the resolution of the data which are rounded off to the closest 600 watts.

The first observation that can be done, is that both the house battery and the EV battery try to avoid selling energy to the grid, thus the low amount of negative power hours. This is due to the previously discussed prosumer scheme, in which sold energy is only given the market spot price, while bought energy has an added grid tariff and tax. Because the house battery is available at all times, it sells less energy than the EV battery, which is why figure 6.6 has less negative power hours compared to figure 6.7.

Both the **energy based** tariff and the **power based** tariff keep the maximum power withdrawn from the grid to the same level as before optimization when using a house battery, whereas the EV battery results in slightly higher powers withdrawn. However, the **time-of-use** tariff has several hours where more than the 15 kW is being withdrawn. Nevertheless, this was discussed in the previous subchapter, and confirmed to be hours that are not already in conflict with normal peak load hours.

The **energy based** tariff is very straight forward, and was not economically viable for the customer. The **power based tariff** is more interesting, because there are larger potentials for savings. Due to the grid tariff increasing with every surpassed kW, it can be observed that the battery will try to keep the grid drawn power as close to a kW limit as possible which makes the duration curves almost look like stairs (less so for the EV battery due to it being unavailable at daytime). In general, the power based tariff promotes customers with even use of power. This was also confirmed by the fairly large saving potential given by this tariff structure. In retrospect, limiting the grid tariff increases to every kW-step was perhaps not the best choice. To assure completely fair tariffs, this step could be lowered to every 100 or 10 watts. However, this makes the tariff harder for the customer to understand, and could result in more confusion for the customers, which again results in more customer contact for the DSO. Still, low consumption customers like the apartment load shown in chapter 5, can easily navigate between the 1 and 2 kW steps with help from an optimal utilized battery. This could potentially result in unfair billing of customers.

As shown in figure 7.9 and 7.10, the reason for the low DSO grid tariff income when using the **time-of-use** tariff, was due to more evenly distributed load from the apartment compared to the household. While the price scaling of the tariff could be adjusted, it still shows that even use of energy is rewarded by the DSO. Still, it is recommended that the time zones where the grid tariff is more expensive can be changed, in case of a national load shift as a result of widespread optimization. This could happen if many residences choose to invest in PV and batteries, resulting in a high number of players avoiding high cost time zones. If these zones and/or prices can be changed, this problem can be solved on the go.

The **subscription based** tariff gives very interesting load duration curves. Both the house battery and the EV battery look like they are dedicated to keeping the power either at 8 kW (the subscribed limit) or at 0 kW. This can be explained by looking at how the algorithm works. Because there are no extra grid tariffs within the 8 kW range, there is either profit in selling or buying energy (because the model is deterministic, it knows all future prices). As the figure shows, the house battery is capable of eliminating almost all loads except a few high power hours and a few negative power hours. The negative ones are from days with excessive PV production compared to consumption, whereas the high power ones are from dark winter days with low PV production and high residence load. However, for both battery scenarios, the maximum load is lower than the original load, which is good news for the distribution system operator.

7.3.3 High load amounts

When studying figures 6.6 and 6.7 closely, one can observe that the amount of high load hours is not equal for all the tariff structures. As shown in chapter 5, the average load is close to 5 kWh/h, with a maximum load of 15 kWh/h. In order to see how much the amount of high loads have changed with the PV and house battery system, an overview is presented in figure 7.11. Note that all the data in the figures below are powers extracted from the grid.

While both the power based and subscription based structures result in lower amounts of high energy hours, the time-of-use tariffs results in a large increase of high load hours. While not necessarily in conflict with national peak load hours, it is definitely problematic that the amount of high load

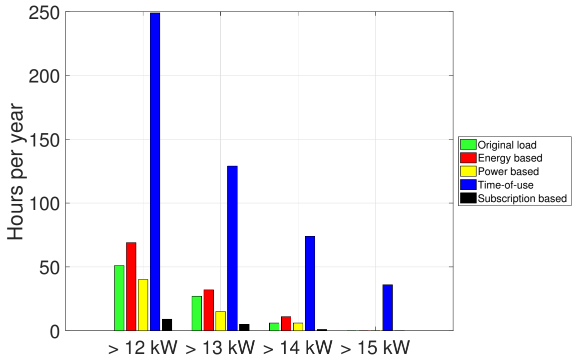


Figure 7.11: Amount of load hours exceeding 12, 13, 14 and 15 kWh/h for the PV and house battery system. Green is the original load.

hours increases by a factor of approximately 5 for the 12 kW limit. If many customers were to implement a system as shown in this thesis, trouble would be caused with a time-of-use tariff.

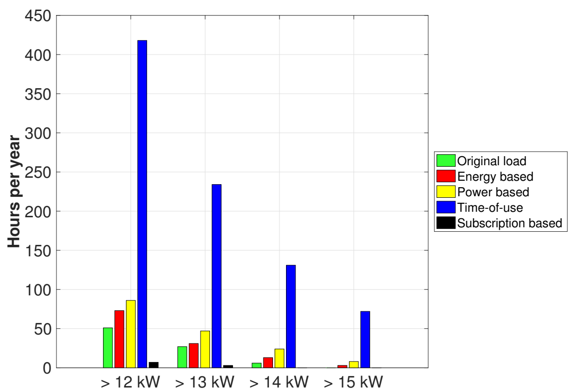


Figure 7.12: Amount of load hours exceeding 12, 13, 14 and 15 kWh/h for the PV and EV battery system. Green is the original load.

The same statistics for the PV and EV battery system is shown in figure 7.12.

The results shows the exact same trend, with high amounts of high load hours for the time-of-use tariff, increasing by more than a factor of 8 for the 12 kW limit. With this scenario, the power based tariff has more high load hours than the original, unlike the PV and house battery system. Again, the subscription based tariff is the most grid friendly

7.4 Break even energy price

In order to determine which energy price is required for this investment to pay for itself, the net present value method described in chapter 2 is used. In order to calculate future PV production, the average of 2013, 2014 and 2015 shown in table 7.1 has been used, which is 5 453 kWh per year. It is assumed that annual production remains at this level for the lifetime of the PV panels. Figure 5.4 also shows that assumed production per kWp installed in Trondheim is 777 kWh. With the 7 kWp used in this thesis, this assumed production is 5 439 kWh annually, which is very close.

Table 7.1: Annual PV production for 2013, 2014 and 2015.

Year	2013	2014	2015	Average
Annual PV Production	5 427 kWh	5 607 kWh	5 324 kWh	5 453 kWh

Discount rates of 3, 4 and 5 percent are analyzed to determine the break even cost of energy. According to reports, the cost of installing roof mounted PV in Norway is approximately 20 000 NOK per kWp (13). For the simulated 7 kWp installation, investment costs end up at 140 000 NOK. Even though the life time is guaranteed to be 25 years by most Norwegian PV merchants (59), the general statement is a life time of 30-40 years. 25 years is used as life time in these calculations. Because the primary use of an EV battery is to provide fuel for transport, the EV battery investment is considered to be zero. Due to few available house batteries at the market, with Tesla's Powerwall costing 80 500 NOK (38), break even calculations for PV and house batteries are not included. All assumptions made for these calculations are summarized:

Installed power photovoltaic	7 kWp
Cost per installed kWp	20 000 NOK/kWp
Life time	25 years
EV battery investment cost	0 NOK
Annual PV producton	5 453 kWh

The result break even price is shown in table 7.2. Note that the annual potential savings shown in figure 6.2 with the PV and EV battery system span from 4 251 - 6 795 NOK depending on grid tariffs, which with 5 453 kWh saves 82.91 - 124.61 øre/kWh. In other words, those are the numbers which have to stand in comparison.

Discount rate	**3%**	**4%**	**5%**
Break even energy price	147.5 øre/kWh	164.4 øre/kWh	182.2 øre/kWh

Table 7.2: Break even energy cost for different discount rates. Note that the cost is the average saved cost per kWh saved or produced from the PV and battery, and includes all taxes and grid tariffs.

When Enova's investment support described in chapter 2, the calculations look somewhat different. With 7 kW installed, the support provided by this governmental organ adds up to 18 750 NOK. The new investment cost will now therefore be 121 250 NOK. The new break even price for this scenario is shown in table 7.3

Table 7.3: Break even energy cost for different discount rates including Enova support. Note that the cost is the average saved cost per kWh saved or produced from the PV and battery, and includes all taxes and grid tariffs.

Discount rate	**3%**	**4%**	**5%**
Break even energy price	131.7 øre/kWh	146.8 øre/kWh	162.7 øre/kWh

Installation costs of PV in Norway is approximately 4 500 NOK/kWp, compared to 2 500 NOK/kWp in Denmark and 1 900 NOK/kWp in Germany (13). If it assumed that the installation costs are reduced to danish levels, and that the PV panel cost is reduced to the German shelf price level which was approximately 12 000 NOK/kWp in the second quarter of 2017 (60), the investment cost is significantly reduced, and is with these prices 82 750 NOK including Enova support. Break even prices for this scenario are shown in table 7.4.

With these reduced costs, the energy prices needed for a break even scenario are closer to the energy price levels on the market today. While such prices are still not available at the Norwegian market, they are not unreasonable to assume available in the future. Note that it is questionable if Enova's support will continue to exist, should such prices hit the market.

Table 7.4: Break even energy cost for different discount rates including Enova support and European price levels. Note that the cost is the average saved cost per kWh saved or produced from the PV and battery, and includes all taxes and grid tariffs.

Discount rate	**3%**	**4%**	**5%**
Break even energy price	87.2 øre/kWh	97.1 øre/kWh	107.7 øre/kWh

7.5 Battery SOC utilization

Figure 6.9 shows that no matter which grid tariff structures is being used, the EV battery SOC is never lower than 30 %, and in most cases well above 50 %. This result indicates that savings would be close to equal with an EV battery half the size of the one used in these simulations, which was 80 kWh capacity.

The figure also shows that the subscription based tariff has the highest battery use, meaning that it is charging and discharging the most throughout the year. Still, the savings provided by this tariff are the lowest overall, implying both that the tariff does not provide large saving potentials, and that that the battery has to be utilized to a larger degree in order to provide savings. The remaining three tariffs appear to have fairly equal battery usage span throughout the year, mostly staying between 70 - 100 % SOC.

The house battery is due to its smaller capacity, used to a much larger extent, SOC-wise. As previously shown, the house battery barely provides any savings when an energy based tariff is used, which is shown in figure 6.8. The power based tariff results in slightly more use of the battery, whereas the time-of-use and subscription based tariffs result in the highest battery use. Although it is high, the subscription based tariff results in less savings that the other tariffs, indicating that the high battery usage is not particularly efficient. However, the time-of-use tariff results in the highest savings, which indicates the opposite - an efficient use.

7.6 Future scenarios

While today's conditions for now do not appear to provide economic reason to invest in PV and battery installations in Norway, many things can change in the future. Some of these things are discussed in the following paragraphs.

7.6.1 PV and battery prices

The obvious and first element that comes to mind, is a price reduction of PV and batteries. As stated earlier in this thesis, the cost of PV has already dropped 75 % in the last 10 years. The market is now more consistent, however, the prices are still falling (3). Battery development shows the same story, with a price fall for batteries used in EVs. Figure 3.7 shows a price reduction of more than 70% from 2008 to 2015, with goals of reducing the price to about 10 % compared to the 2008 level by 2020. While reduction is stagnating slightly, it is reasonable to assume that battery prices will keep dropping as more and more car manufacturers decide to invest heavily into EVs, Daimler being a good example with activity in Germany (61). As previously shown in the discussion, only slight price reductions are needed to make PV and battery systems economically profitable, and there is reason to believe that these price reductions can take place.

It also has to be mentioned that EV manufacturers might change their battery guarantees if using these batteries as grid support is turning into a global trend.

7.6.2 Increasing energy prices

With low cost of coal, oil and gas, combined with high renewable energy production, spot prices from 2013 to 2015 were generally very low (25) (62). Norway's TSO, Statnett, published a report with estimates of a future power price between 45-50 euro/MWh in 2025-2030, due to higher gas prices, a CO_2 fee and lower prices of renewable energy. When oil and coal is slowly being shut down, gas prices dominate the market to a greater extent, and will determine the price to a larger degree (54).

Compared to Norway's 90 øre/kWh (incl. grid tariffs and taxes), Germany has an energy cost close to 300 øre/kWh (63). A higher energy cost results in higher profitability of a PV and battery system. Note that mainly the PV installation gains from higher power prices, whereas the battery with its balancing effect is more dependant on variations in spot price on an hourly basis. Future average prices and price variance has to be taken into account when determining what is to be invested in. However, it is a general trend that increased renewable energy production results in higher spot price variation, which is good for the simulations done in this thesis.

7.6.3 Increasing grid tariffs

Just like energy prices, grid tariffs are subject to change. The grid tariffs are decided by NVE, and is individual for the different DSOs in Norway depending on geography and customer base. The average grid tariffs since 1993 can be seen in figure 7.13.

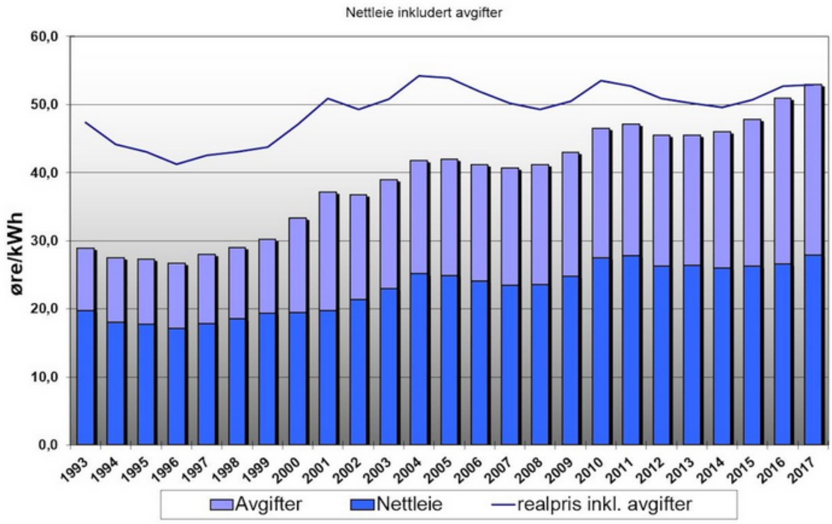


Figure 7.13: Average grid tariffs since 1993, including taxes. Dark blue represents grid tariff, light blue represents taxes and fees. Figure from NVE (17).

While the cost has slowly increased since 1993, the cost which is adjusted to inflation (shown by upper blue line), shows no significant change, with only an increase from 47.4 øre/kWh to 52.9 øre/kWh in the last 25 years, or 11.6 %. However, due to large investments (e.g. AMS) being done in the future, NVE decided to increase the grid tariffs by 5 % from 2016 to 2017. Without speculating more, it is clear that grid tariff levels are decisive for the PV and battery system's saving potential.

7.6.4 Changed energy consumption behaviour

While many household application producers are thriving to achieve high efficiency through energy savings, it is still a fact that energy consumption increases every year (6). However, with more power demanding tools, the load profiles of a residence can change drastically. The best example is the charging of an EV, which can be done with any power from 2 - 22 kW.

Other equipment such as power demanding coffee machines, water boilers and kitchen machines demand low energy amounts, but high powers. With the increase of such equipment, new peak loads could potentially appear, resulting in overloading of transformers or reduction of voltage levels. In order to avoid these outcomes, balancing elements such as a battery could provide what is often called ancillary services. In the future, such services could potentially have a market, even on residence level. Such a development would increase the economic value of a battery significantly.

7.6.5 Location

This paragraph is not meant as a future scenario, but more as a reminder of the conditions that apply in the chosen location.

The simulations performed in this thesis were done with load and irradiation data from Trondheim, Norway. With high electric load, semi low irradiation and low energy prices, it does not qualify as the most profitable location to implement a system as described in this thesis. In Kristiansand, a city far south in Norway, irradiation is 34 % higher. If Italy, France or Spain was chosen, the irradiation would be close to twice the amount (13). In addition, energy prices are in general higher in the rest of Europe compared to Norway (54), along with lower PV and battery prices (3). All these numbers added up could result in great profit if such a scenario was tried out in a different location, and is definitely an interesting research area for future studies.

7.7 Sources of error

7.7.1 Input data

Load data

All the load used in this thesis had a resolution of one hour. Resultingly, every minute-to-minute variation is not taken into account, such as heating water or using a vacuum cleaner. This means that every hour had hidden peak loads and valley loads from such short term fluctuations. In addition, load data of the apartment were rounded to the closest 100 watts, whereas the household's load data were rounded to the closest 600 watts. This gives certain insecurities to the numbers used to perform these simulations. However, for these simulations, complete precision was not required to show the potential of the proposed system. Therefore, the lack of precision is not necessarily quality decreasing of the results.

PV data

Perhaps the largest problem with the input data used were the PV data. The irradiation data used were measurements made from sensors lying horizontally. Afterwards, an inclination factor was added because irradiation increases as a function of inclination angle. With the average inclination angle of roofs in Norway, this factor was 1.2. However, when inclining PV panels, the irradiation absorbed by the panel does not only increase with a factor, but change as a function of time. This can be seen in figure 5.9, where it is shown that no irradiation takes place e.g. before 5 am and after 7 pm due to the position of the sun, whereas a horizontally lying absorber receives sunlight for a longer time. At the same time, annual production was assessed to be equal to what highly recognized reports claim. This means that the PV data used had a correct size, but a false distribution over the day and year. Daily, because more irradiation would take place during day time, and less in the morning and evening. Yearly, because more of the irradiation would be absorbed in the summer, and less in the winter, which is counterproductive to what gives saving potentials in this model (prices and loads are higher in winter). This could have been fixed with using a software such as PVSyst, which compensates for irradiation changing factors automatically. These factors are not only inclination angles, but also material composition of local surroundings. An exampe being that snow gives more indirect radiation compared to grass. All things considered, the lack of irradiation data with inclination taken into account is probably the biggest source of error in this thesis, and may possibly have given better results than what is realistic.

7.7.2 Equipment modelling

Battery model

When modelling a battery with possibility for a two way power flow, the equipment is hard to model correctly. In this thesis, only power and energy balance was taken into account, meaning that sizes such as voltage, currents and resistances were not taken into account except for in the charging efficiency model which took ohmic losses into account. However, as stated in chapter 3, a battery has different charging efficiencies as a function of both temperature and SOC (64). Due to the complications of modelling such effects, a simple efficiency curve with reduced efficiency with increased power was installed. However, this could be the contrary if charging occurs during cold weather, and charging increases temperature to a more optimal one. As internal resistance changes with SOC, different efficiencies could be experienced in lithium-ion batteries due to such affairs.

Equipment degradation

In this thesis, no degradation of either PV panels, battery efficiency, battery capacity or charger efficiency was taken into account. In reality, there will be losses and degradation in all this equipment. However, it is unsure how much, and slightly more conservative (lower) efficiencies were set to counteract untrue results.

Another perspective not taken into account is the loss of energy in the battery when it is not being used. In reality, there is a discharge coefficient which represents the energy lost from an unused battery. Optimally, both discharge coefficients and equipment degradation should be taken into account in future work.

7.7.3 EV availability model

In this thesis, very conservative numbers for the availability of the battery were assumed. The availability was set to 4pm every afternoon to 8 am the next morning, Monday to Friday. Full availability was assumed in the weekends. This was set to simulate the average car user, who uses the car to get to work and not much else. In reality there could be many deviations. One could use the car to travel, especially during weekend. One could also in theory not use the EV every day, but bike or walk to work, or work at home, which would have increased the profitability greatly. It could also be the case that a household has two cars, and that the EV is either the one being used every day, or the other way around. Different availability profiles would be very interesting to analyze in future studies. Perhaps the most interesting one would be to see what happens if an EV battery is used as house battery after the capacity is no longer eligible for transportation use. When more EVs are starting to age, there could potentially be a wave of old EV batteries used to supply private households with balancing power. The batteries used would also be significantly more powerful than the house battery used in this thesis. To summarize, many small changes could have been done with the EV availability model, both ones that influence the economic potential positively and negatively.

7.8 Choice of model

By utilizing a dynamic programming optimization algorithm, an optimal result is guaranteed. Hence, such a deterministic model is not completely, because it never will be able to represent a realistic scenario. With this in mind, results have to be considered as benchmark results - the maximum savings possible. Afterwards, stochastic models can be utilized and results can be compared to the results provided by this deterministic model. Alternatively, a rolling horizon data gathering mechanism can be utilized, using spot price, irradiation and load forecast to daily perform the dynamic programming optimization presented in this thesis. When comparing either the stochastic model, or the modified rolling horizon deterministic model to the deterministic model in this thesis, model efficiency and quality can be determined.

Chapter 8

Conclusion

The presented results show that utilization of PV as of 2017 is not economically profitable with Norwegian conditions. High investment costs, low energy prices and semi-low irradiation simply makes the investment too big compare to future savings. However, the thesis also shows that with reduced PV costs and higher energy prices, the investment is profitable over time.

In general, the EV battery proved to provide more savings than a house battery due to size and power capabilities. Because an EV battery can be considered a free investment, net present value analysis of the system show better potential compared to a stationary battery which has very high investment costs compared to the savings provided. Still, the savings potential is fairly dependant on which grid tariff structure is being used, differing from 12.0 - 19.2 % when PV is included, or 5.1 - 8.3 % when PV is not included. Results also indicate that an EV battery of approximately 50 % of the capacity used in this thesis would be sufficient to provide the same savings. In other words, the capacity could be reduced from 80 kWh to 40 kWh without saving less.

With the **energy based** tariff, there is close to no profit by utilizing a battery. However, a PV installation would save 11.1 %. The highest loads are not reduced, meaning that this structure does not solve any peak load problems for the DSO.

By utilizing a **power based** tariff, PV also saves 11.1 %, however, utilizing a house battery or EV battery increases the savings up to 13.3 and 16.6 %, respectively. While punishing high power use, the maximum loads remain equal, even rising slightly for the EV battery scenario, which implies that high loads are not ”punished” enough. However, a close look shows that the higher loads are not appearing during classic peak load hours.

The **time-of-use** tariff has a great economic potential for the customer, and provided the most savings in these simulations, which implies that it is a good structure for battery utilization. It saved 11.7 % with PV, 14.4 % for the PV and house battery scenario and 19.2 % for the PV and EV battery scenario. Also in this scenario, maximum loads rises with battery use, but again does not necessarily appear in classic high load hours.

The **subscription based** load provides the least savings, with respectively 8.2 %, 8.9 % and 12.0 % for the PV, PV + house battery and PV + EV battery scenarios. However, it restricts maximum loads to be lower, and for almost every hour restrains the residence load to be lower than the subscription limit. Due to very high price sensitivity when grid tariffs are excluded, the load duration profiles are almost completely split in two, which could cause troubles if many customers choose to use an optimization algorithm like this one.

The new developed tariffs solves some of the problems in the distribution grid by balancing power, but does not necessarily remove all of them, such as overloading or high voltage levels when PV production is high. While giving a good indication, the tariffs would have to be slightly improved to assure correct response from the optimization. Simulations show that maximum load can increase with up to 40 % with the given tariff structures, but that these maximum loads are not necessarily a problem if the optimization is not used a large enough share of the customers.

Because the simulations presented in this thesis are based on a deterministic model, this algorithm would not work in reality without modifications. The results can be used as benchmark results when testing the same scenario with stochastic or rolling horizon deterministic models.

Chapter 9

Further work

The following points are the most interesting ones to include in potential further work.

- Use software such as PVSyst to assure more realistic PV data, in order to illuminate how much the changed PV production would influence the results. In addition, it would be interesting to analyze southwest oriented PV panels compared to southeast oriented ones, to see if more production during high price late afternoon and evening hours can increase the savings even further.
- Increase the resolution of the model to 15, 10, 5 or 1 minute intervals. This way, it can be determined whether or not low resolution data influence the results.
- Model battery, PV and load with current and voltage values in order to get a more reliable model when it comes to losses. Low data resolution (time wise) might have hidden possible ”illegal” current values, which would have been detected in a high resolution model. In addition, the battery was not modelled with temperature and SOC dependant charging efficiency, and discharge coefficient, which would have reduced the efficiency of the battery.
- Compare different EV battery availability profiles in the study, to analyze how different use of the EV changes the potential profit.
- Utilize a greedy programming model instead of a dynamic programming model would be interesting in order to compare the results. This

could significantly reduce computation time, and would likely bring close to equal results.

- Introduce the given residence model to a series of residences in a neighbourhood, to see how the voltage levels load profiles change when large amounts of residences are using the same optimization algorithms. This way, new potential problems distribution grid related problems could be discovered, which would give better data basis to develop better grid tariff structures.

- Perform same simulations with better conditions, such as higher energy prices, more solar irradiation and lower installation costs. A scenario in countries like Italy or Germany would probably give more profit potential.

- Simulate equal scenarios with a stochastic model, using probability and statistics to predict future price, load and PV production. Such simulations provide more realistic results of how effective such a system potentially could be. Alternatively, create a rolling horizon data gathering model, where irradiation, data and spot price forecast is gathered daily, and therefrom utilize a dynamic programming optimization.

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Appendix A - MatLab Code

This is dynamic programming optimization algorithm. It is generic, in the sense that any series of load data, PV production data, spot price data, battery specifications and grid tariff data can be used as input. The simulations done in order to simulate the house battery had input data for a whole year (mostly 2015). Meanwhile, the simulations done in order to simulate the EV battery was more complicated, due to smaller, daily data series were used as input due to the EV battery availability. Regular load flow calculations were used for the time periods where the EV battery was not available.

optimal_charging.m

```
%%Optimal charging strategy

function [totalcost, transitioncost, path_opt, p_bat_opt, SOC_opt] = ...
optimal_charging(p_load,p_pv,spotprice_no3, spot_timetariff, structure, ...
p_bat_max,eff_ch ,eff_di ,C_bat,soc_max,soc_min,delta_soc ,year)
 %%Key parameters

%Number of possible SOCs. +1 because row 1 corresponding to SOC_min
 N_soc = 1 + (soc_max-soc_min)/delta_soc;
%Number of periods. 1 year = 8760
 N_periods = size(p_load,1)*size(p_load,2);

 %Maximum steps of change of SOC (integer)
 soc_max_change = floor(p_bat_max*eff_ch/(delta_soc*C_bat));

%%Grid tariff

 [fastledd, fastleddwithtax, energiledd, inntektsledd, ...
    energiavgift, nettavgift,fastleddstrom, spot_timetariff, ...
    grunnfaktor,powerfactor,price_overuse,powerlimit] ...
        = getNettleie(year);

 %%Initialising arrays

 %Total minimum cost to finalise to last period
 totalcost = inf(N_soc,N_periods);

 %Costs to get from SOC [1st dim] in period [2nd dim] to SOC [3rd dim]
```

```
 %in period [2nd dim + 1]
 transitioncost = inf(N_soc,N_periods,N_soc);

 %Gives which row (i.e. which SOC) that one should move to in period
 %[N_periods + 1] to min(costs)
 path_opt = zeros(N_soc,N_periods);

 %Optimum p_bat given an initial SOC.
 p_bat_opt = zeros(N_soc,N_periods);

 %Optimum SOC given an initial SOC.
SOC_opt = inf(N_soc,N_periods);
 totalcost(1,N_periods) = 0; n
 transitioncost(1,N_periods,:) = 0;

%Final state being SOC = 0.
soc_max_next = 1; %First row of SOC-array corresponding to soc_min
day = size(p_load,1); %365
hour = size(p_load,2); %24



%%Calculations

for i = 1:(N_periods-1)
    %%Decide possible SOC

    soc_max_i = min(N_soc,soc_max_next+soc_max_change);

    %%Set day and hour with respect to i

    if mod(N_periods-i,24) == 0
        hour = 24;
        day = day - 1;
    else
        hour = mod(N_periods-i,24);
    end

    %%Calculate costs

    for j = 1:soc_max_i
    %Iterates over all legal soc's in period i
    %Iterates over all legal SOC's in period i+1 which can be reached
    %from SOC j in period t

        %Lowest reachable SOC from node j in period i
```

```
soc_min_j = max(1,j-soc_max_change);
%Highest reachable SOC from node j in period i
soc_max_j = min(soc_max_next,j+soc_max_change);


for k = soc_min_j:soc_max_j
    soc_change = (k-j)*delta_soc;
    %p_bat defined positive into battery
    p_bat_temp = soc_change*C_bat;
    if p_bat_temp > 0
        p_bat_temp = p_bat_temp/eff_ch;  %eff_ch < 1
    else
        p_bat_temp = p_bat_temp*eff_di;  %eff_di < 1
    end
        p_grid = p_load(day,hour) + p_bat_temp ...
                - p_pv(day,hour);
    if p_grid > 0
        switch structure
            case 1
                %Energy structure
                transitioncost(j,N_periods-i,k) = ...
                ((spotprice_no3(day,hour) + ...
                inntektsledd) * 1.25 + nettavgift ...
                + energiledd)*p_grid;
            case 2
                %Power tariff
                transitioncost(j,N_periods-i,k) = ...
                ((spotprice_no3(day,hour) + ...
                inntektsledd) * 1.25 + nettavgift) ...
                * p_grid + ceil(p_grid) * powerfactor;
            case 3
                %Time of use, time tariff
                transitioncost(j,N_periods-i,k) = ...
                ((spotprice_no3(day,hour) + ...
                inntektsledd) * 1.25 + nettavgift) ...
                * p_grid + (spot_timetariff(day,hour)...
                * p_grid);
            case 4
                %Subscription based tariff
                if p_grid > powerlimit
                    transitioncost(j,N_periods-i,k) =
 ...
                    (p_grid - powerlimit) ...
                    * price_overuse;
                end
                transitioncost(j,N_periods-i,k) = ...
                transitioncost(j,N_periods-i,k) + ...
                (p_grid * ((spotprice_no3(day,hour)  ...
                + inntektsledd) * 1.25 + nettavgift));
```

```
                    end %switch
                else
                    transitioncost(j,N_periods-i,k) = ...
                    spotprice_no3(day,hour)*p_grid; %< 0
                end %if p_grid > 0
            end %k

    %%Calculate SOC-value and find shortest path
    %All transition costs for given period and soc
    change_cost = transitioncost(j,N_periods-i,:);
    change_cost = squeeze(change_cost);

    totalcost_temp = totalcost(:,N_periods-i+1) + change_cost;
    %Minimum cost and transition
    [min_cost, min_place] = min(totalcost_temp);
    totalcost(j, N_periods-i) = min_cost;

    path_opt(j,N_periods-i) = min_place;
    end %j
%%Preperation for new iteration
soc_max_next = soc_max_i;
end

%%Determining p_bat
for i = 1:N_soc
     soc_from = i;

    for j = 1:N_periods
        soc_to = path_opt(soc_from,j);
        p_bat_temp = (soc_to-soc_from)*C_bat*delta_soc;
            if p_bat_temp > 0
                p_bat_opt(i,j) = p_bat_temp/eff_ch;
                % eff_ch < 0
            else
                p_bat_opt(i,j) = p_bat_temp*eff_di;
                % eff_di < 0
            end
            SOC_opt(i,j) = (soc_from -1)*delta_soc;
            soc_from = soc_to;
    end
end
   p_bat_opt(:,N_periods) = 0;
end
```