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Consumption Profiles for Future Households

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Submission date: December 2015
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Problem Description

In recent years there has been a trend toward new types of loads that are energy efficient, but requires increased and more variable power than what we have seen previously, for example electric vehicles, instantaneous water heaters, large heat pumps and induction stoves. In addition, the extent of distributed generation, also for individual customers, continues to grow. Future customers within the distribution network are likely to become more segmented into different groups, some of which are active both in terms of consumption, production and storage of energy.

The goal of this master’s thesis is to describe a potential consumption profile for future households. Will there be bigger variations in the term *household customers*, in term of passive houses, zero energy buildings and energy-plus houses? How will storage of energy, charging of electric vehicles and photovoltaic production affect the consumption profiles? What measures can be done to reduce the peak load and increase the utilization time?

Abstract

Over the last few years there has been a change in energy consumption in Norwegian households. New houses are far better insulated, have high demands for efficient energy carriers and new installations that affect the electricity consumption. Today, most of the electricity in a Norwegian household is used for space heating, but this demand is expected to be reduced in the future, mainly because the need for space heating is reduced as a result of stricter demands for isolation. Electricity consumption in general will also be reduced as new appliances are becoming more energy efficient. Peak power demand caused by new installations is a challenge. The duration of and whether demand occurs simultaneously in several households is crucial for if constrains will occur and how the problems can be managed. Some appliances, such as hot fill dishwashers and washing machines have much lower energy consumption than traditional machines and can use water heated by for instance solar collectors. Local energy production, for example from sun energy, will help reduce both energy and electricity demand in a household.

To give specific examples of how consumption profiles for future households can look, a numerical analysis on a group consisting of 24 households has been completed. One of the customers was selected for further analysis, and this customer’s consumption in a given week is selected as the basis for examples of future consumption profiles. The customer has been fitted with a fictional electric vehicle, household battery and solar panel.

The analysis shows that local energy production from solar insulation often corresponds poorly with the household’s demand. The energy is mostly supplied during daytime, while the greatest demand occurs early mornings or during the afternoon. This results in customers sometimes having excess electricity production. This excess energy can be sold back to the grid if customers are prosumers, but in the way this is arranged today, customers will earn less on selling the electricity than they would have had to pay to buy it. As this prosumer scheme is not particularly attractive, the option to store energy in a battery is investigated.

The examined battery has a storage capacity of 7 kWh and a power of 3.3 kW. It turns out that during the particular week the solar panels produced more energy than the battery could store. This means that the customer cannot utilize the produced energy at any time, only for short periods at a time. Even with energy storage during daytime the panels still produce more energy than the customer’s demand at this time, so an already low consumption during daytime becomes even more reduced.

The analysis shows that using batteries to reduce demand created by an electric vehicle will contribute little to solving network problems related to peak load. The customer will not be able to earn back the large investment cost for the battery only by storing self-produced energy. This is because the power demand while charging an electric vehicle is much higher than the power the battery can deliver. A battery that will deal with high local generation and high power demand from electric vehicles would require both higher energy and power capacity than the battery that was investigated in this thesis.

The analysis showed that the battery could be useful in one scenario: When used to reduce the cost of high power demand, if new power tariffs were introduced. In general, an analysis carried out regarding new network tariffs shows that customers have great saving potentials if this is introduced. A prerequisite if the new tariffs are going to help solve the problems in the network is that they are comprehensible to customers and that the customers are aware of how their consumption affects their costs.

Sammendrag

De siste årene har man sett en endring i energibruken i norske husholdninger. Hus som blir bygd blir stadig bedre isolert, har høye krav til energieffektive energibærere og har installasjoner som påvirker elektrisitetsforbruket på nye måter. I dag går det meste av elektrisiteten i en norsk husholdning med til oppvarming, men i framtiden er det forventet at denne etterspørselen reduseres. Dette skyldes hovedsakelig at varmebehovet blir redusert som et resultat av forbedret isolasjonskrav. Elektrisitetsforbruket vil også generelt reduseres, da nye apparater blir stadig mer energieffektive. Derimot ser effekttopper forårsaket av nye installasjoner ut til å være en utfordring, men varigheten og hvorvidt de oppstår samtidig hos flere kunder er avgjørende for om problemer vil oppstå, og hvordan det eventuelt kan håndteres. Enkelte apparater som oppvask- og vaskemaskiner med varmtvannsinntak har mye lavere strømforbruk enn tradisjonelle maskiner, og kan benytte seg av vann oppvarmet av hjelp av for eksempel solvarmere. Lokal energiproduksjon for eksempel fra sol vil kunne bidra til å redusere både strøm- og energietterspørselen i et hjem.

For å gi konkrete eksempler på hvordan forbruksprofiler for framtidens husholdninger kan se ut er det gjennomført en numerisk analyse på en kundegruppe bestående av 24 husholdninger. Én av kundene er valgt ut for en nærmere analyse, og denne kundens forbruk i en gitt uke er valgt som grunnlag for eksempler på framtidens forbruksprofiler. Kunden har blitt utstyrt med fiktiv elbil og husholdningsbatteri, samt solcellepanel på taket.

Analysen viser at lokal strømproduksjon fra solceller i en husholdning ofte samsvarer dårlig med etterspørselen i huset. Strøm blir stort sett produsert på dagtid, mens den største etterspørselen er tidlig om morgenen eller utover ettermiddag og kveld. Dette resulterer i at kunder enkelte ganger produserer mer strøm enn de selv har behov for. Denne strømmen kan selges tilbake til nettet ved at kundene blir plusskunder, men slik ordningen er i dag vil kundene tjene mindre på å selge strømmen enn de hadde måttet betale for å kjøpe den. Ettersom denne plusskundeordningen ikke er særlig attraktiv per dags dato, er muligheten for å lagre energien lokalt i et batteri undersøkt.

Det batteriet som er undersøkt i denne rapporten har 7 kWh lagringskapasitet og en effekt på 3,3 kW. Det viser seg at i den aktuelle uken er strømproduksjon fra solcellene høyre enn batteriet kan lagre. Dette fører til at kunden ikke kan utnytte den produserte strømmen hele døgnet, men bare i korte perioder. Selv med energilagring på dagtid produserer fortsatt

panelene mer strøm enn kunden har behov for midt på dagen, så et allerede lavt forbruk på dagtid blir enda mer redusert.

I analysen viser det seg at å bruke batteri til å redusere effekttoppene en elbil skaper vil bidra lite til å løse problemene i nettet. Dette er fordi effektbehovet ved lading av elbil er langt høyere enn effekten batteriet kan levere. Kunden vil heller ikke kunne tjene inn den store investeringskostnaden til batteriet kun ved å lagre egenprodusert energi. Et batteri som skal kunne håndtere stor grad av lokalt produsert strøm, samt høyt effektbehov ved elbillading vil måtte ha både høyere lagringskapasitet og effekt enn batteriet som er brukt i denne analysen.

Analysen viser at batteriet kan være nyttig i et tilfelle, nemlig til å redusere kostnadene forbundet med høye effekttopper, dersom nye effekttariffer blir innført. Generelt viser en analyse gjennomført vedrørende nye tariffer at kunder har potensial til å spare mye penger dersom dette blir innført. En forutsetning for at nye tariffer vil bidra til å løse problemene i nettet er at de er forståelige for kundene, og at kundene er klar over hva slags forbruk som skaper høye utgifter.

Preface

This master's thesis is written as the final stage of the master's program Energy and Environmental Engineering, Electrical Power Engineering at the Norwegian University of Science and Technology (NTNU), fall 2015. The work is done as a continuation of the specialization project, fall 2014, with the same title.

First, I would like to thank my supervisor at NTNU, Jan Andor Foosnæs at the Department of Electrical Power Engineering and my co-supervisor Hanne Sæle at SINTEF Energy. You have always been available for questions and discussions around different topics, and your previous work regarding this subject has been an inspiration for me.

I would also like to thank NTE for providing data and documents, as well as the opportunity to let me get a head start by working there during the summer. A special thanks to Hans Wigen Finstad for giving me great advice in how to use Excel, especially the Pivot Diagram – it has been a life saver in my work.

Finally, I would also like to thank my family and friends for supporting me through these years at NTNU. A special thanks to my parents for always being interested in what I do, and to my sisters for good advice along the way and their support with the English editing and proofreading of this thesis.

Trondheim, December 2015

Marianne Blikø

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Abbreviations

AMI Advanced Metering Infrastructure

DG Distributed Generation

DHW Domestic Hot Water

DR Demand Response

DSO Distributed System Operator

FCEV Fuel Cell Electric Vehicle

EV Electric Vehicle

IoT Internet of Things

NOK Norwegian krone, currency of Norway

NTE Nord-Trøndelag Elektrisitetsverk Nett AS

NVE Norges Vassdrags- og Energidirektorat/Norwegian Water Resources and Energy Directorate

PV Photovoltaic

SOC State Of Charge

STC Standard Test Conditions

ToU Time of Use

VAT Value Added Tax

V2H Vehicle to Home

ZEB Zero Emission Building

1 Introduction

In the recent years there have been changes in the energy use in households. The work in this thesis is done as a continuation of a specialization project carried out during the fall of 2014, with the same title. The specialization project looked at the changes that have been seen in the electricity industry, until today. The report found that the total energy demand in households is stable or declining, but the power demand is increasing. This is largely caused by new power demanding appliances as well as new standards and demands in the building industry.

This thesis will look at what the electricity demand in future households will look like, with focus on consumption profiles. One new technology which is expected to greatly affect the electricity demand in the future is electric vehicles (EVs). These vehicles have a high power demand while charging, and are becoming increasingly popular. As EVs become more widespread it is important to know what challenges they expose to the distribution grid. Distributed generation (DG) for example from solar insolation will also affect consumption. Several technologies for DG are funded by Enova to make it more desirable for customers to invest in them, which causes more installations. The conditions for solar energy production in Norway are not ideal, compared to when the energy demand is at its highest. This is because the highest demand is during winter, and the highest solar energy generation is during summer. A possible solution for this is the development of battery technology for use in households. The battery will not be able to solve problems regarding different seasons, but might be an useful aid for shorter time periods. A combination of several of these technologies can generate consumption profiles that are completely different than the ones we see today. At the same time as all these new technologies become gradually more available, the building regulations get stricter. When houses get better insulated the demand for energy to space heating is reduced. Several regulations also state that only a certain amount of the energy used for space heating can be covered by electricity. All these factors are contributing to changing energy demand as we know it today.

To be able to give concrete examples of how the consumption profiles for future households will look, a numerical analysis has been completed. The basis for this analysis is the hourly electricity consumption of 24 customers situated in Steinkjer, in the county of Nord-Trøndelag. These customers were part of a field trial during a period of time in 2014, so to be able to look at consumption without the effects of this trial the consumption for the year 2013 has been used. All the customers have been given a number from 1 to 24 to be able to look at them individually. The field trial that took place in 2014 will shortly be discussed in section 8.1.1.

This thesis is divided into 11 main sections, where sections 2 and 3 describes the changes we are seeing in the electricity industry, some new appliances as well as introducing examples of what consumption looks like today. Sections 4, 5 and 6 introduce electric vehicles, distributed generation and battery technology. All these technologies are expected to affect what consumption profiles will look like in the future. In section 7 these technologies are used to give some concrete examples of what consumption profiles for future households might look like. The Norwegian water resources and energy directorate (NVE) are working on a new way for deciding tariffs in the distribution network. Section 8 will discuss this and how tariffs can be a tool to reduce peak load in the grid. Discussion, ideas for further work and conclusion are presented in sections 9, 10 and 11, respectively.

2 Transition from Energy to Power Demand

2.1 Challenges in the Distribution Grid

The high voltage distribution grid usually consists of either 11 kV or 22 kV transmission lines. The transmission lines are either overhead lines or ground cables. A distribution substation is connected to the transmission lines and transforms the voltage to the power level of the low voltage distribution grid. The voltage in the low distribution grid is 230 V or 400 V depending on what kind of network it is. From the substation the 230/400V cable goes out to the end-users in the area. These transmission lines can also be overhead lines, but in urban areas ground cables are more common. A residential area might have numerous substations to supply the end-users.

Few investments have been made in the distribution grid over the last 10 to 15 years [1], resulting in a network that is old and not equipped to handle for example distributed generation. Because of this it is expected that large investments will be done in the near future. Also, the loads in the distribution grid have changed, causing higher power demand. Because of this the grid has to endure higher flow rates than before. More power demanding equipment causes high load peaks at certain times during the day. Problems regarding transmission capacity can occur several places in the distribution system, and one example is if too many substations are connected to the 11/22 kV cable. Another problem can occur if too many houses are connected to the substation. If these houses are coupled in series, this might cause further problems.

The grid constrains in an area depends on existing infrastructure. Some areas mostly consist of old dwellings while other areas are in a development phase. Large industrial loads can be in the same network as households, or in more scattered areas and this can cause further problems.

The changes that are seen causes new challenges and makes it important for distributed system operators (DSOs) to predict what the consumption profiles will look like in the future. Approximately 37 per cent of all the energy used in Norway is used by buildings [2]. This includes commercial buildings and households. Of all the energy used in a household around 79 per cent is electricity [2]. As a relatively big part of energy consumption in households is electricity, the introduction of advanced metering infrastructure (AMI) can have a rather large influence and brings new opportunities. However, if AMI is supposed to lead to increased knowledge about electricity consumption, it is important that the technology is used right, and for more than just metering. Also, the customers need to be a part of the development.

With the introduction of AMI, the DSO will have access to significantly more data from each customer. Statnett has been entrusted by NVE to commission a national data hub for measurement values and market processes in the Norwegian power market. This data hub has been given the name Elhub, and is expected to be operational from February 2017 [3]. Elhub is supposed to contribute to a more efficient power market, where power retailers have a key role and will manage all contact with customers. Data from Elhub can supply useful information for example for design of new tariffs. New tariffs will be discussed in section 8. Also, more of the appliances and equipment households contain produce an increasing amount of data. Internet of Things (IoT) is a common term for a network of physical objects, which enables these objects to collect and exchange data. For example it enables objects to be remotely controlled, across existing network infrastructure. This makes it possible for customers to have greater overview of their consumption and to control their demand without even being present in the household.

2.2 Consumer flexibility

One way to handle the increased peak demand is to adjust customer's consumption or to reward consumer flexibility. Customers having control of their consumption is an absolute requirement if this is to become a reality. Consumer flexibility is consumers taking a more active role in their energy consumption and being able to adjust their demand. When customers change consumption as a result of incentives it is referred to as demand response (DR). In [4] DR is defined as:

> *Changes in electric usage by end-use customers from their normal consumption patterns in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized.*

Customers might not be willing to change behavior just like that, so in order for a consumer to adapt and become flexible there needs to be an advantage for the consumer. It is hard to set an accurate price on what customers consider a good price incentive for changing behavior. One example is this: a customer can save 5 NOK by not showering at 09:00 in the morning, but postponing the shower until 14:00. Is this enough to make the consumer change? Consumers probably appreciate their own flexibility more than savings in this specific area. However, if the question is postponing turning on the dishwasher for a couple of hours, the customers might be more willing. It is important to distinguish between high-grade and low-grade electricity demand. Showering, cooking and lightning might be seen as high-grade, because it is harder for a consumer to change this demand. Electricity used for example for dishwashers and washing machines can be seen as low-grade, as this demand is more flexible and can be moved without any major drawbacks for the customer. The point of DR and consumer flexibility is not necessary to reduce consumption, but to transfer it from high demand hours to low. Section 8 in this thesis looks at how changes in network tariffs can give customers incentives to change consumption, and section 6 introduces a technology to handle the same issue. Flexible customers are a useful asset to handle grid constraints. Norway has the advantage of flexible energy production with hydro power, but in countries that use other energy sources for electricity generation DR can play an important role for an efficient electricity network. One way to look at a passive customer is as a waste of resources. In order for this to change, information about DR needs to be available and motivate the customers to act.

2.3 Changes in the Building Business

As the development in the building business continues, the quality of houses built in Norway continues to increase. As [5] discusses, there is a great development in the building standards. These have become far stricter the recent years and the specific heat consumption in kWh/m^2 is reduced. TEK-15, the newest building standard, is expected to arrive soon, and here the demands most likely will be even stricter than in the current building standard, TEK-10. The regulations for total energy demand in households are now stricter than ever before. If the total area of households increases the total energy consumption is not necessary reduced.

There are several categories houses can be put into. Passive and low energy houses need to be according to the Norwegian passive house standard, NS3700, which has higher demands than TEK-10. A zero emission building (ZEB) produces enough renewable energy to compensate for the building's greenhouse gas emissions over its life span. The Research Centre on Zero Emission Buildings has defined different levels of ZEBs on how many phases of a building's lifespan are included [6]. These are listed in Table 2.1.

Table 2.1 ZEB definitions [6]

Level	Definition
ZEB – O	The building's renewable energy production compensate for greenhouse gas emissions from operation of the building.
ZEB – OM	The building's renewable energy production compensate for greenhouse gas emissions from operation and production of its building materials.
ZEB – COM	The building's renewable energy production compensate for greenhouse gas emissions from construction, operation and production of building materials.
ZEB – COMPLETE	The building's renewable energy production compensate for greenhouse gas emissions from the entire lifespan of the building. Building materials – construction – operation and demolition/recycling.

As these houses are constructed differently from ordinary houses, their consumption profile will look different. One example is that because the houses are so well-insulated, they might need cooling during the summer. In general, the energy demand for space heating is reduced and often covered by alternative energy sources and not electricity. As space heating is a great percentage of electricity consumption in households, this has huge impact on the consumption profile for a household. How the electricity consumption is distributed in a typical Norwegian household is shown in Figure 3.1, and further discussed in section 3. The demand for some houses is that the energy consumption throughout the year is zero. This can be achieved for example if the house has an abundance of produced energy during the summer, and buys some electricity from the grid during winter.

2.3.1 Skarpnes Residential Area

At Skarpnes in the south western part of Norway, outside Arendal, Skanska are working on a unique project in Norwegian scale. The original plan for the project was to make this an entire residential area consisting of only ZEBs. After about eighteen months just five houses have been sold, built and inhabited [7]. The remaining twelve houses are expected to be build according to TEK-10 standard, with an option for ZEB solution for those who want it. When the first house was inhabited in 2014, it was the first household in the Nordic region to be a private household in a ZEB [7].

Skanska provides the following information about the houses [8]: In the houses at Skarpnes all insulation, sealing, windows and exterior doors are according to the Norwegian passive house standard, NS3700. The houses are supplied with hot fill dishwasher and washing machine, as described in section 2.4. The ventilation system is also according to NS3700 and it is coupled with a geothermal heat pump for exploiting groundwater temperature to cool the intake air during summer. Solar collectors are mounted on the outer wall and connected with the geothermal system to supply the houses with hot water, both for heating and domestic hot water (DHW). All the lights in the houses are provided by LED and there are photovoltaic (PV) panels on the roof. The house is delivered with a management system that will align the technical installations as well as lighting and shading. The control unit for this control system is an iPad.

The PV panels cover the electricity demand for the fixed installations, like the ventilation system, the heat pump and lightning. The panels also deliver energy to the hot fill system [7]. The net energy demand for a house is calculated to be around 76 kWh/m^2 per year and the produced energy by the house is 38 kWh/m^2 per year [9]. Hourly energy and electricity measurements have not been provided for these houses, but because of all the installations it is expected that the consumption profile for one of these houses will look different than an ordinary household. If an entire residential area consists of buildings like these, it can have large impact on the demand in the distribution network.

If customers are ready to embrace ZEBs as an alternative to TEK-10 houses, this might be something we can see a lot of in the future. As this project shows, only five of seventeen houses have been sold, so it looks like the customers might not be ready for this kind of house yet. Good information about ZEBs as well as price, compared to non-ZEB houses, probably needs to be in place for these houses to become more popular.

2.4 New Appliances

A new trend for household appliances is that they become more energy efficient, but have a higher peak power demand. Some of the new electrical appliances that are seen on the Norwegian market are discussed in [5]. In this section concrete examples will be given on how the electricity consumption for two of these appliances is. Another technology is EVs, which are a new kind of load in the distribution network that requires high power while charging. Challenges associated with EVs will be discussed separately in section 4.

2.4.1 Instantaneous Electric Water Heaters

Today, the most widespread method for hot water heating in Norway is by using electric heating and hot water tanks. This accounts for around 15 per cent of the total electricity consumption in a typical household [10]. One example of how the electricity demand for this kind of water heater looks is shown in Figure 2.1.

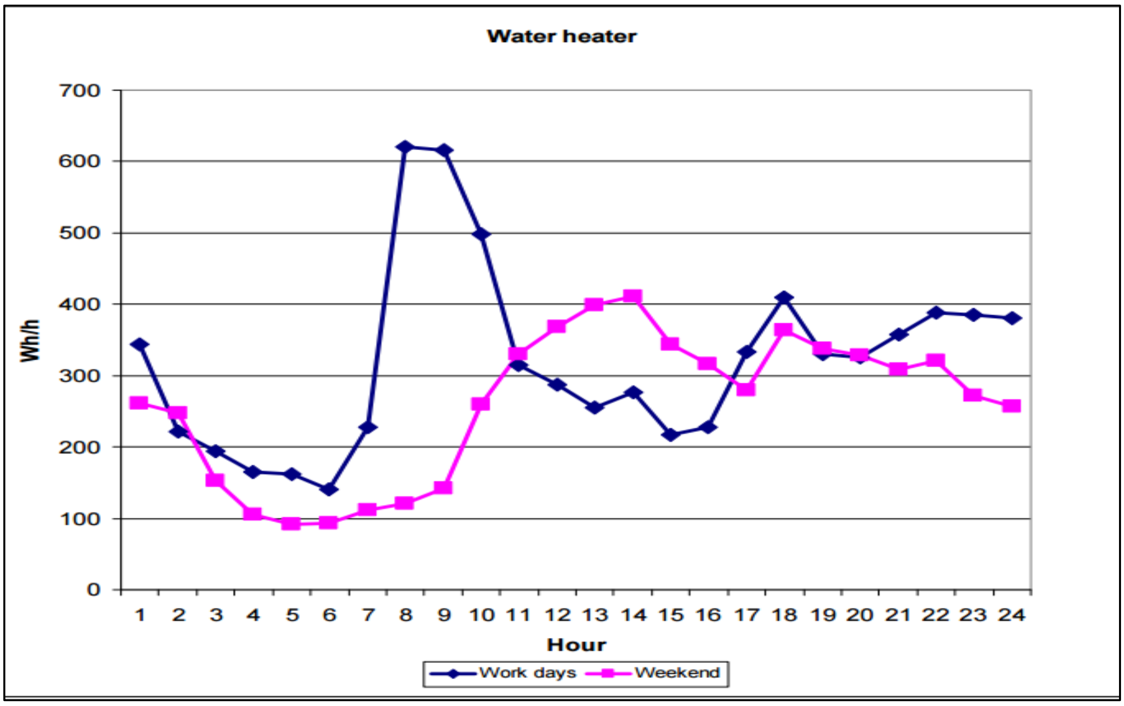

Figure 2.1 Electricity demand from a water heater [11]

A new technology that is available is the instantaneous electric water heater. The instantaneous water heater does not store hot water, but heats only the amount of water required at every time. In order to do this it has a high power demand. How high this demand is depends on the temperature difference of the cold and hot water, as well as how much water is required per minute. Unlike a hot water tank the instantaneous water heater has no energy loss while idle, and is so small it can be located near the place of use, which gives quick access to hot water. A significant energy demand in households can be avoided if the energy demand from use of hot water is served instantaneous, because the need for storing the hot water is avoided [11].

To figure out how much energy is required from an instantaneous electric water heater, formula 1 has been used.

$$P = \frac{Q \times C_j \times \Delta t}{T} \quad (1)$$

Where,

P = Power demand [kW]

Q = Amount of water [L]

C_j = Specific heat capacity of water = 4.18 $[\frac{J}{grams \times ℃}]$

Δt = Temperature difference [°C]

T = Time [seconds]

It is assumed 12 liters of water per minute and a temperature difference of Δt = 28 °C (from 10 °C to 38 °C) for T = 60 seconds (because we want kW per minute). It is assumed that 1 L of water is equivalent to 1 kg of water. This gives a power demand of 23.408 kW per minute. If the water requirement is changed from 12 L/min to 9 L/min the power demand will be 17.556 kW per minute.

If a shower with 12 L/min lasts for eight minutes the energy demand will be 3.12 kWh. This is found by taking 8 minutes × 23.408 kW/min and dividing it by 60 minutes/hour. A demand of 3.12 kWh/h is quite high, when looking at the average hourly demand in a household. This calculation only covers *one* eight minute shower, and if several people shower during this hour the power demand will be even higher. The problem with this kind of load in the distribution network occurs if several people have the same demand at the same time. For example if everyone in a neighborhood showers at the same time in the morning. If the instantaneous water heaters for example are installed in areas that highly consist of cabins, where the network is not dimensioned for the high power demand, this could cause problems.

2.4.2 Hot Fill Appliances

Hot fill appliances use pre-heated water instead of cold and both dishwashers and washing machines are available with hot fill options. Over the recent years a small number of new models that include a hot fill connection have become available within the EU market [12], but it is not very widespread yet. In a standard dishwasher, typically about 60 to 70 per cent of the energy is used to heat the water. Depending on model, a hot fill appliance saves typically 50 per cent more energy when compared to a cold connection [13]. In a washing machine hot water heating can account for as much as 90 per cent of the energy the machine uses to wash clothes and only 10 per cent goes to electricity used by the washer motor [13]. A study shows that the addition of hot fill instead of cold connection reduced the total dishwasher and washing machine electricity consumption by 38 per cent and 67 per cent, respectively [12].

Unlike some of the other appliances discussed in [5], hot fill machines does not necessary contribute to higher peak load in the distribution network. The electricity consumption for these appliances is slightly different from traditional dishwashers and washing machines, and this could contribute to changed consumption profiles in households. In Figure 2.2 and Figure 2.3 the electricity consumption profile for hot and cold fill washing machines and dishwashers are compared. Both figures show that the electricity consumption with hot fill appliances is lower than without.

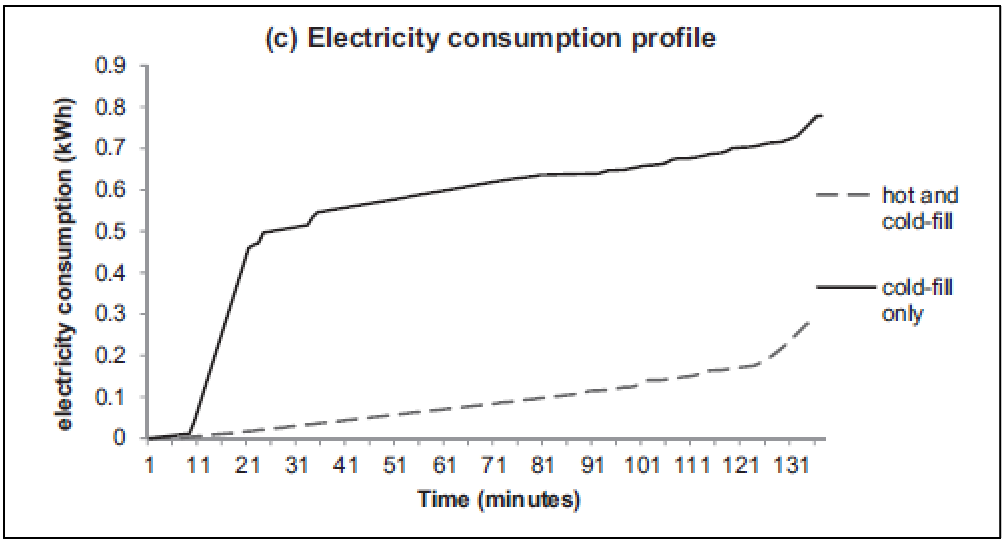

Figure 2.2 Electricity consumption with hot and cold fill washing machines on a 40 °C cotton program [12]

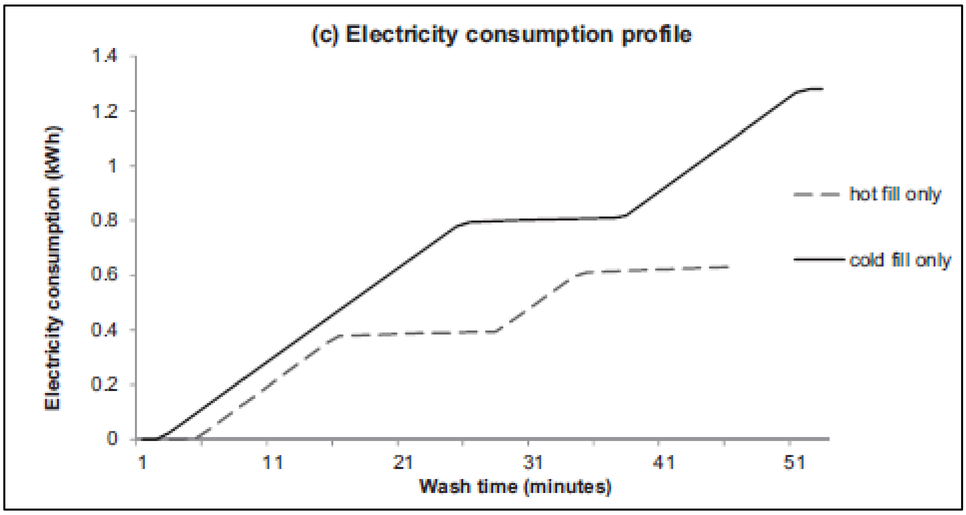

Figure 2.3 Electricity consumption with a hot and cold fill dishwasher on a 60 °C "quick and clean" program [12]

As these products have lower electricity consumption, they can be a tool to reduce peak load. The hot water will off course need to be collected from somewhere, and this system is great in combination with for example solar collectors, which will be discussed in section 5.1.1. A study of hot fill appliances also suggests that they, in addition to direct electricity reduction, can offer a method of time shifting demand away from peak periods without inconveniencing occupants' lifestyles [12].

3 What Consumption Looks Like Today

As introduced in section 2, there is a change going from energy to power demand for households. To be able to say anything about what the consumption profiles will look like in the future, it is useful to have a good picture of what the profiles look like today. The changes we have seen in consumption profiles up until today, as well as some examples of current consumption profiles are given in [5], and some of this is repeated here. This section will be a short introduction to what consumption profiles look like today and this will be used as a basis for a numerical analysis later in the thesis.

The energy consumption in Norway is quite different from the rest of Europe, as Norway tends to have a higher percentage of electricity, compared to other energy sources. One example of how the electricity consumption typically is distributed in a household is shown in Figure 3.1

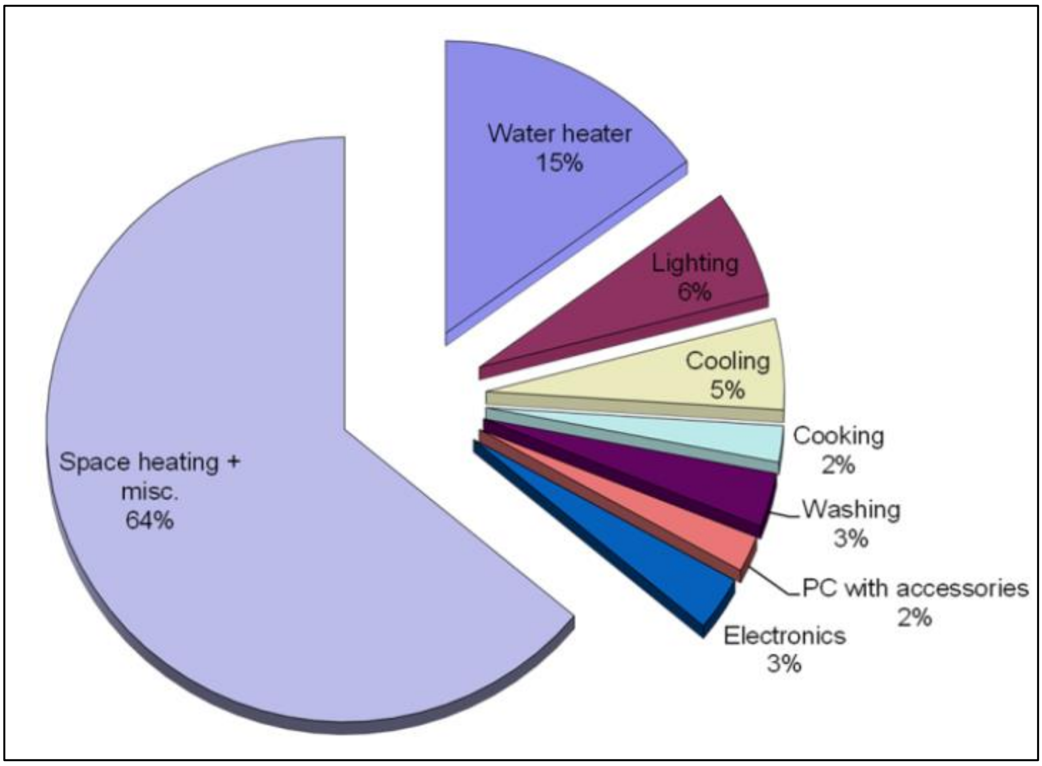

Figure 3.1 Distribution of electricity consumption in a Norwegian household [10]

As this figure shows, most of the electricity is used for space heating and water heating. Because so much electricity is used for space heating, the consumption is strongly temperature dependent. Figure 3.2 shows the total electricity consumption for each month in 2013 and the average hourly temperature. This is the average consumption for the 24 customers in the analysis in this thesis.

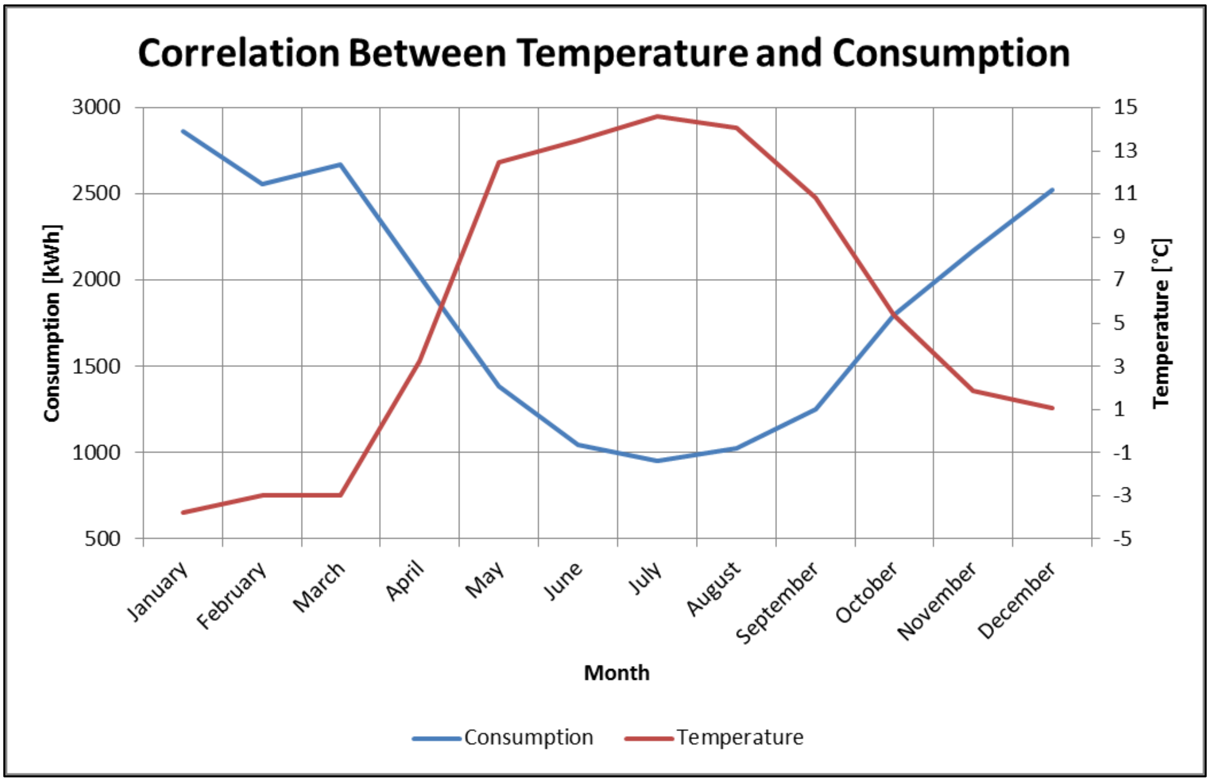

Figure 3.2 Correlation between temperature and consumption in 2013

As houses get better insulation because of the new building standards, the need for space heating is reduced. This will result in reduced electricity demand for households. Around 15 per cent of the electricity in a household is used for hot water heating [10]. This can also be significantly reduced if instantaneous water heaters, as discussed in section 2.4.1, become more common. However, as these require high power for short periods the energy demand will be replaced by short peaks in power demand.

The average consumption profile for a 24 hour period for all the customers is shown in Figure 3.3. This is the average for all the days in 2013. As the figure shows, the demand is slightly different for weekdays and weekends, because of different behavior on these days.

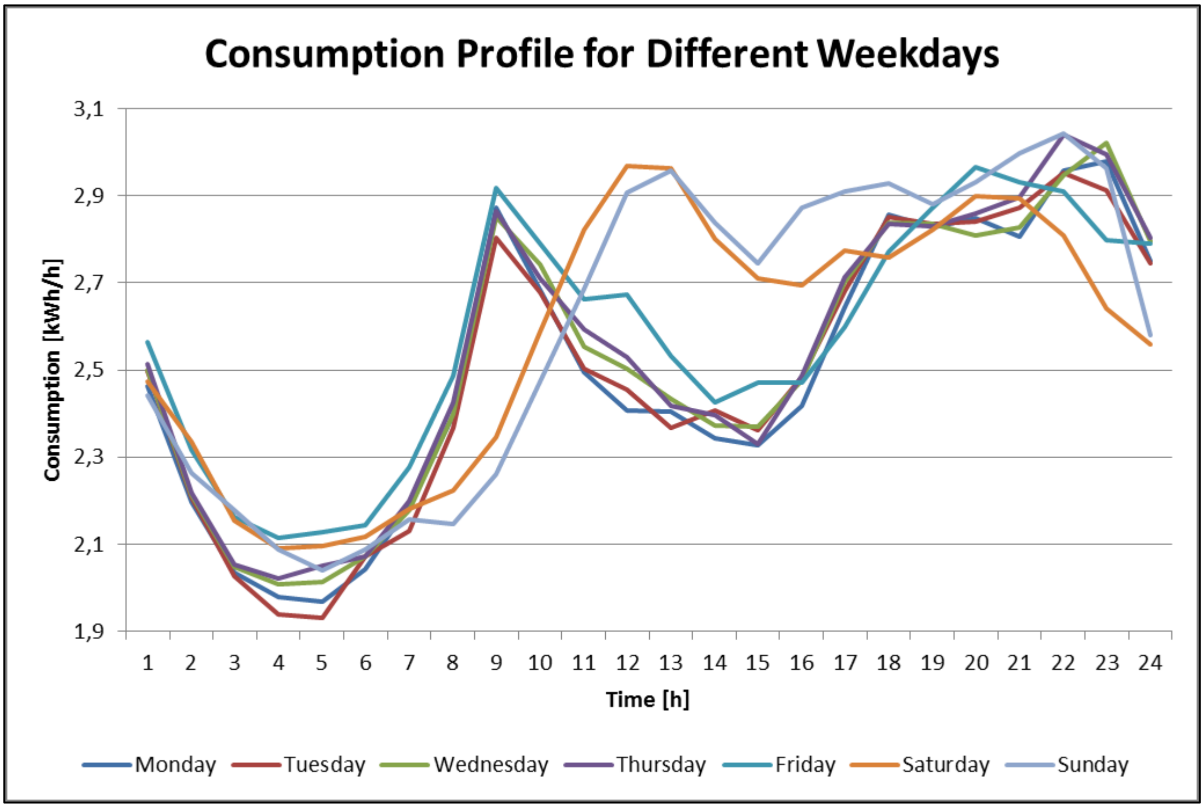

Figure 3.3 Average consumption profile in 2013 for different weekdays

Consumption also varies for different seasons. The year has been divided into four seasons, according to Table 3.1.

Table 3.1 Organization of seasons

Season	**Months**
Winter	December, January and February
Spring	March, April and May
Summer	June, July and August
Autumn	September, October and November

3.1 Customer 12

To look at more specific consumption profiles than just the average of 24 customers, one customer has been chosen for an in-depth analysis. This is customer 12, who had a yearly consumption of about 22 000 kWh in 2013.The average hourly consumption for this customer for different seasons is shown in Figure 3.4. As the figure shows, the customer has a consumption that varies a lot for the different seasons, where consumption is highest during winter and lowest during summer.

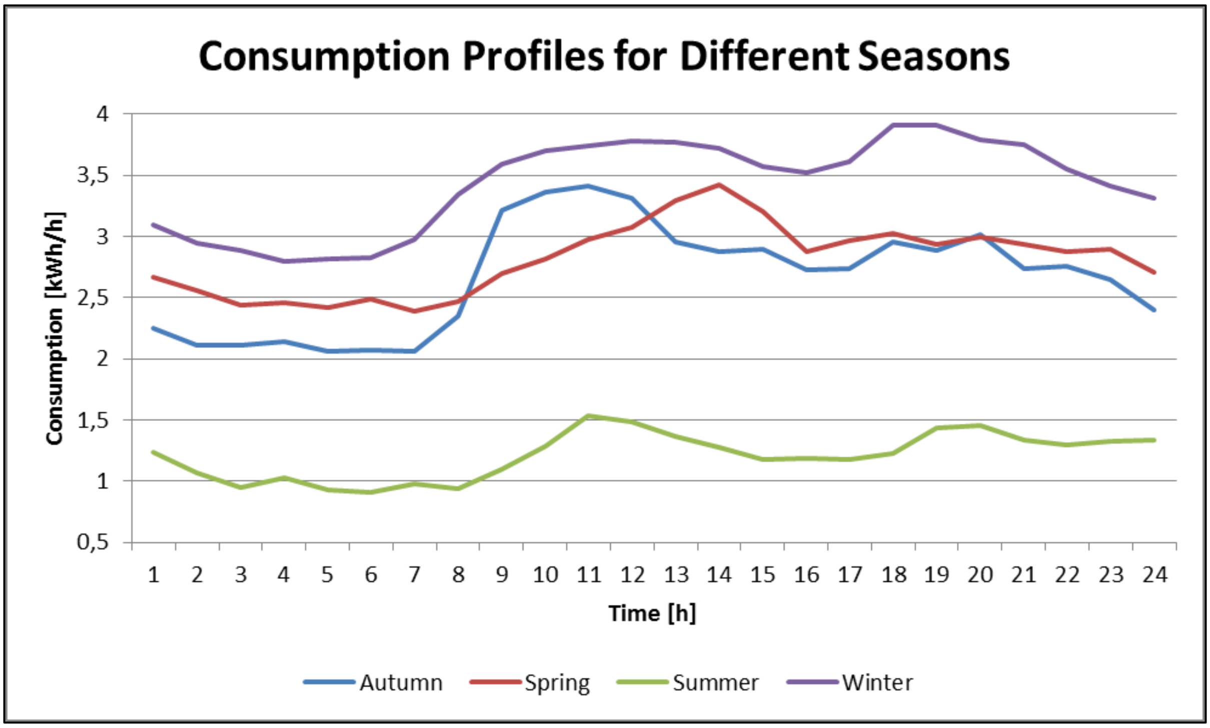

Figure 3.4 Consumption profile for customer 12 for different seasons

The average consumption profile for the entire year is shown in the figure below. This profile has similarities to the average one for all the customers, in Figure 3.3.

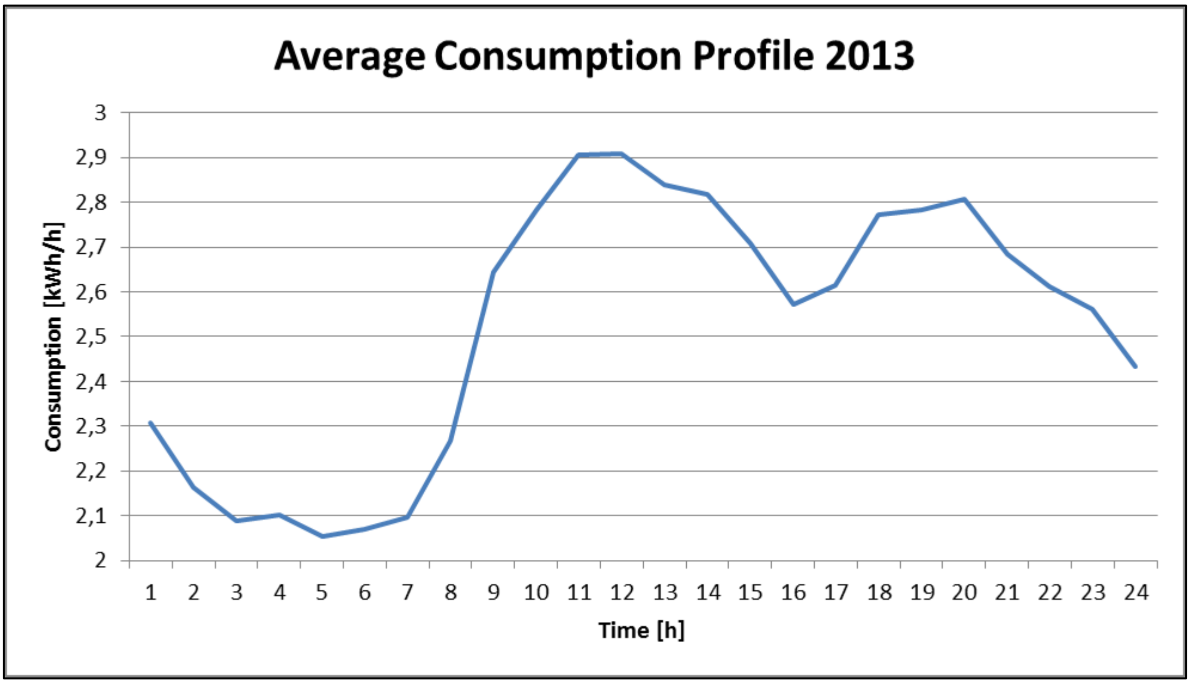

Figure 3.5 Yearly average consumption profile for customer 12 in 2013

To be able to display different future scenarios, one week has been chosen specifically. This is week 15 in 2013, which is from Monday 08.04.2013 to Sunday 14.04.2013. This week does not interfere with Easter or any other holidays. This week has been chosen because it was a week with quite a lot of solar insolation, which gives good conditions for energy production with PV.

Figure 3.6 shows the customer's consumption in week 15, 2013 and Figure 3.7 shows the average hourly consumption in the same week.

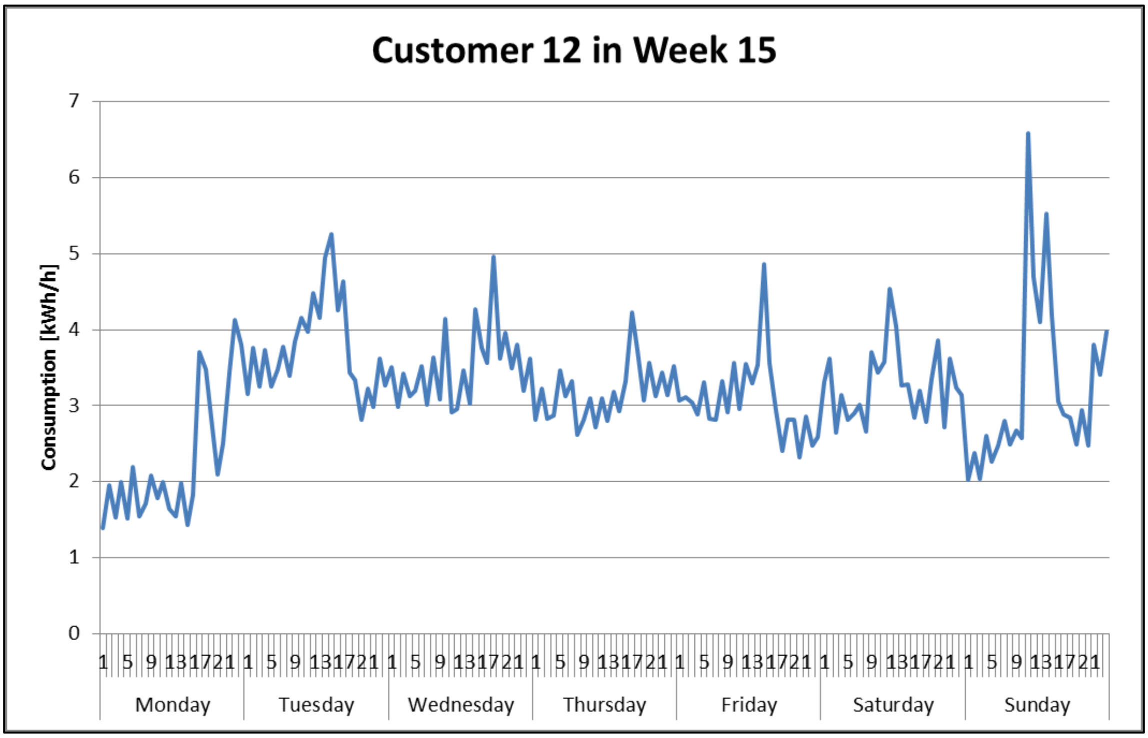

Figure 3.6 Customer 12's consumption in week 15

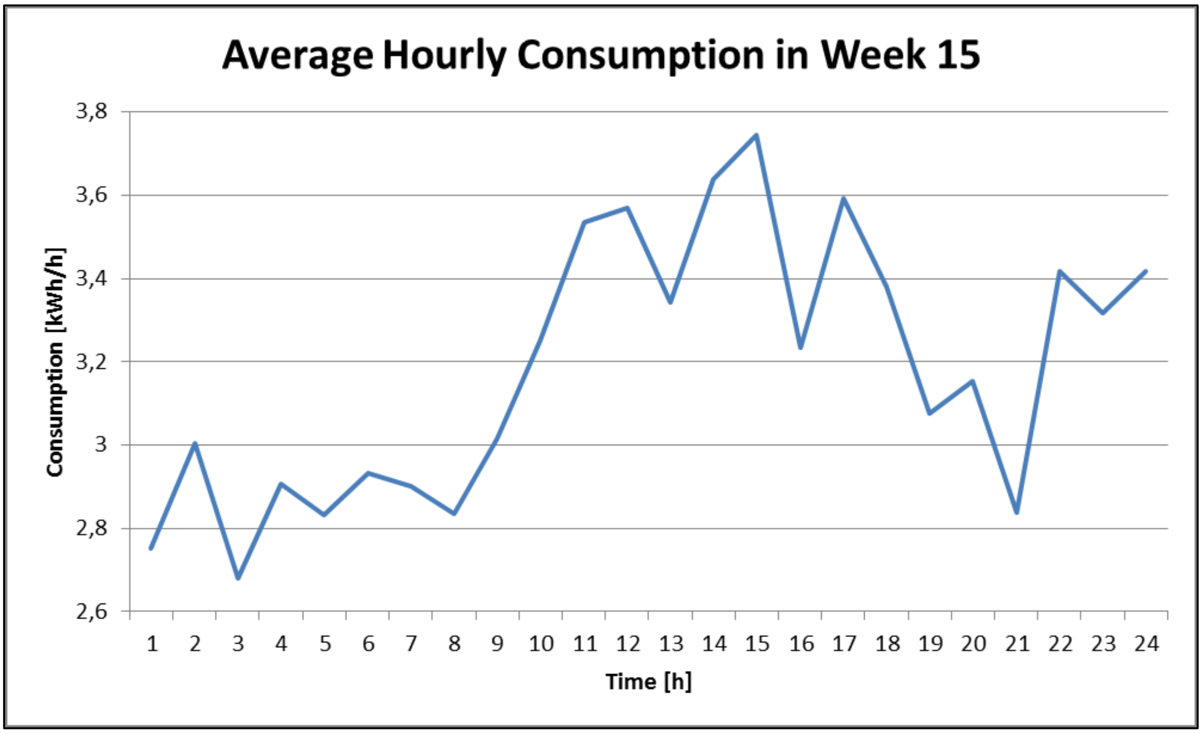

Figure 3.7 Customer 12's average hourly consumption in week 15

Comparing Figure 3.7 with Figure 3.5 shows that the customer's demand during this week was slightly higher than the yearly average.

The longer time period one looks at, the more the consumption looks like the theoretical consumption profile like in Figure 3.5, with a morning and afternoon peak. Figure 3.7 is not as smooth and this is because only seven days are used as the base.

4 Electric Vehicles

The number of EVs in Norway has increased the recent years, and many are concerned about how these new vehicles will affect the distribution network. The increase is expected to be a result of benefits and exemptions EVs have been granted by the government [5]. EVs are by many seen as an environmental-friendly alternative to traditional internal combustion engine vehicles, and they can help reduce local pollution. The energy demand for an EV can be as low as 10 per cent of the total energy demand in a household [14], but the concerns about EVs are related to the high power required while charging. Some charging options for EVs do not require more power than for example a hot water tank, but a challenge with the EV's power demand is that it is so long lasting [14]. This concern is often related to the voltage quality in the installations, if the supply to the house is weak. Different charging options for EVs will be discussed in section 4.1.

The development in battery capacity is going towards larger batteries in EVs. From the first EV that was commercially available on the market to the ones available now, there has been a great development. Having an EV does not necessary mean limitations in range, as it used to be. One of the reasons for this is the increased capacity, but also as a result of more charging stations being built. This allows people to go on longer trips with their EV. An EV with short range would normally serve as a second family car, because of the limitations. An EV with great range, as well as the access to charging stations, can work as an acceptable primary vehicle in a household.

As previously mentioned, the development of batteries for EVs has been great the recent years. The batteries get more capacity, longer lifetime and are cheaper. Figure 4.1 shows the change of prices for lithium-ion batteries, in $/kWh, and the expected development. As batteries become cheaper EVs become a more realistic alternative to traditional internal combustion engine vehicles.

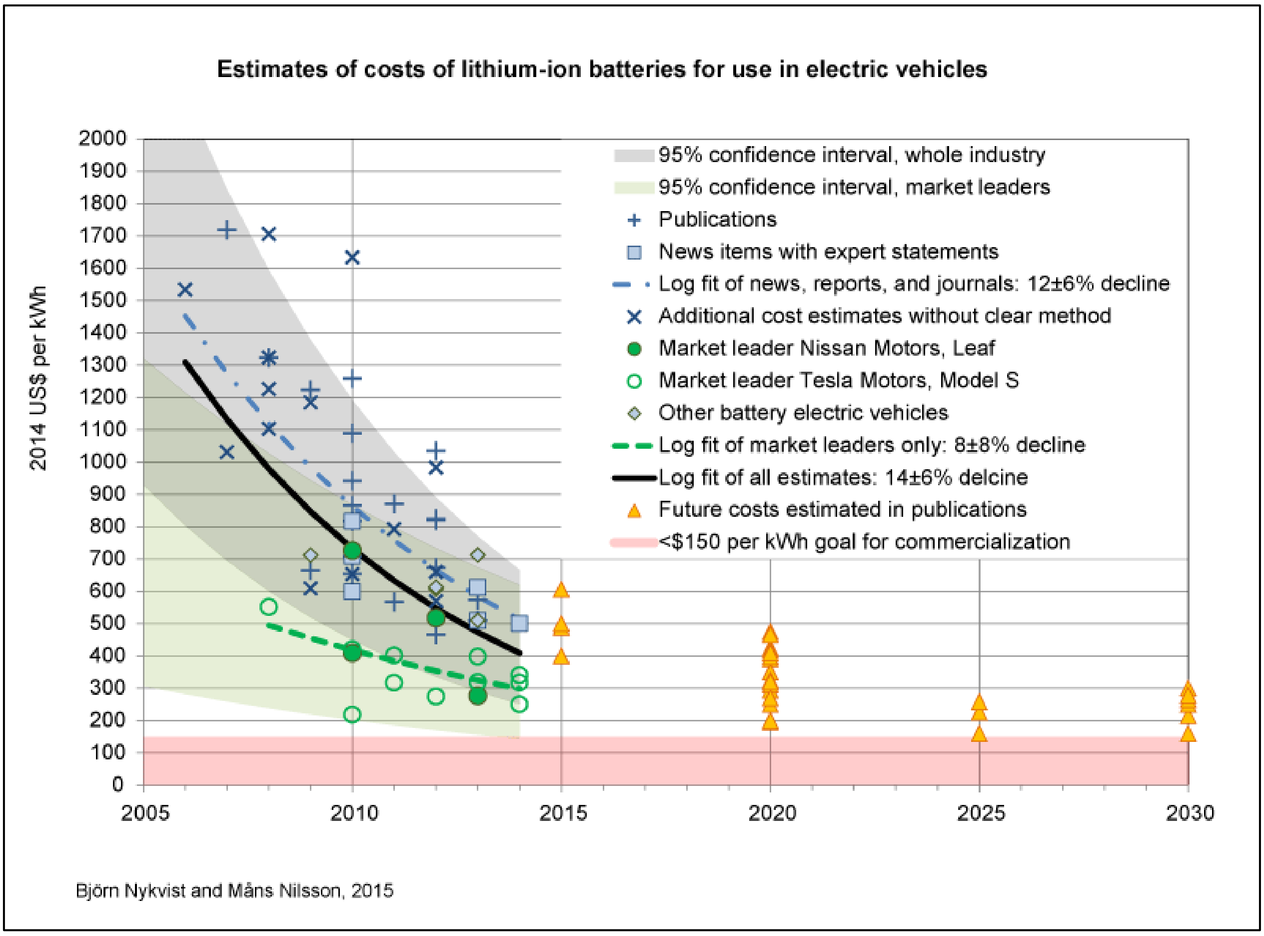

Figure 4.1 Price development for EV batteries [15]

4.1 Different Charging Profiles

Different EV models have different charging profiles. SINTEF Energy has conducted a study looking at different charging profiles for EVs [16]. Two of the models in this study are a Tesla Model S and a Nissan Leaf.

The Nissan Leaf comes in two versions, with 24 or 30 kWh battery. It can either be charged by a charging current of 10 A or 16 A. This corresponds to a power demand of 2.3 kW or 3.68 kW with a voltage level of 230 V, according to formula 2.

$$P = I \times U \tag{2}$$

Where,

P = Power [W]

I = Current [A]

U = Voltage [V]

When the EV is plugged in, the power demand is quite constant until the battery is fully charged or the vehicle is unplugged. There is a short decline in demand when the battery is close to full. Because this thesis looks at hourly measurements, this decline has been neglected. The charging profile for a Nissan Leaf with 10 A can be seen in Figure 4.2.

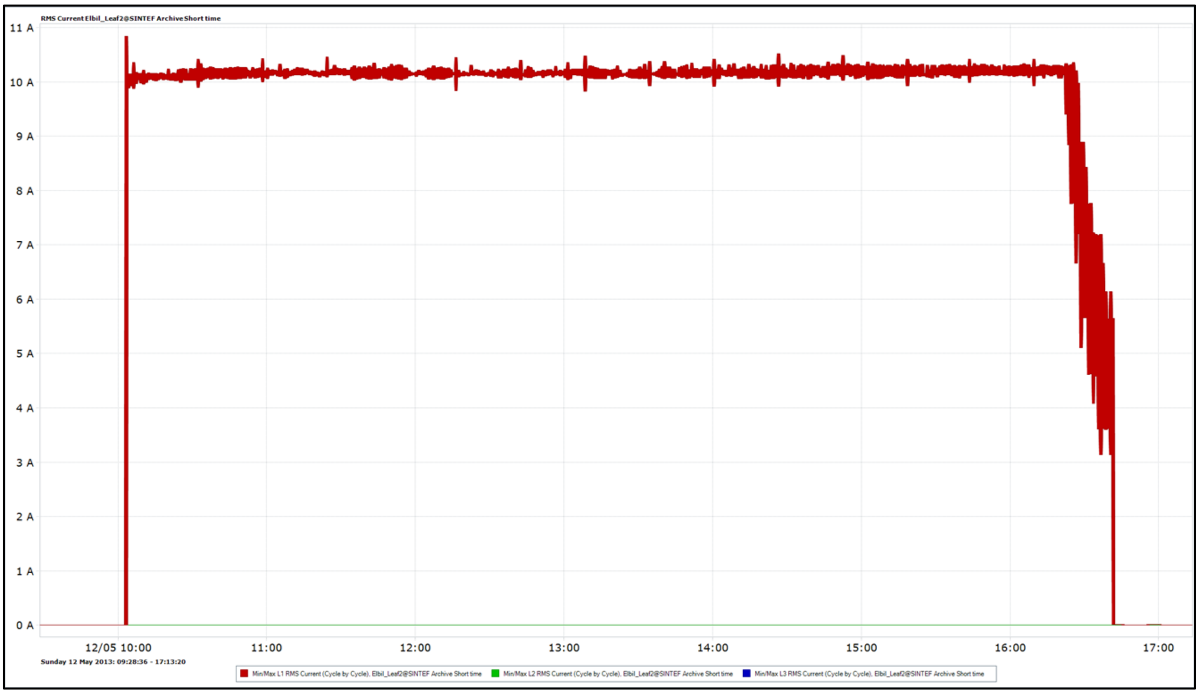

Figure 4.2 Charging profile Nissan Leaf, 10 A [16]

When flat, the 30 kWh battery in the Nissan Leaf has to be charged for approximately 13 hours with a charging current of 10 A and for 8 hours with a charging current of 16 A. How long the EV has to charge depends on the battery's state of charge (SOC[1]) when the charging starts. From Figure 4.2 it looks like this EV's battery was not completely discharged when the charging started.

The Tesla Model S has a higher battery capacity, from 60 kWh to 85 kWh, depending on model. Different charging options are available for this EV, as shown in Figure 4.3.

[1] SOC = 0 % → Battery is empty. SOC = 100 % → Battery is full

		VOLT / AMPERE	KILOWATT
	Standard plugg (Kontinental Europa)	230 V / 13 A	3,0 kW
	IEC 60309 Blått - adapter	230 V / 32 A	7,4 kW
	IEC 60309 Rødt - adapter	400 V / 16 A	11 kW
	IEC 62196 type 2	230 V / 16 A	3.7 kW
	IEC 62196 type 2	230 V / 32 A	7,4 kW
	IEC 62196 type 2	400 V / 16 A	11 kW
	IEC 62196 type 2	400 V / 32 A	22 kW*

* Kun hvis man har dobbeltlader.

Figure 4.3 Charging options for Tesla Model S [17]

The different charging options for Tesla Model S require different installations in the household. In the study conducted by SINTEF Energy the EV was charged with an average power demand of 7.2 kW, which will be used in this analysis. An 85 kWh battery which is completely discharged will need a power of 7.2 kW for approximately 12 hours to become fully charged. Figure 4.4 shows the consumption profile for a customer that has a Tesla. The charging of this household's EV starts at 16:00, lasts for about 7 hours and can be seen very clearly in the figure below.

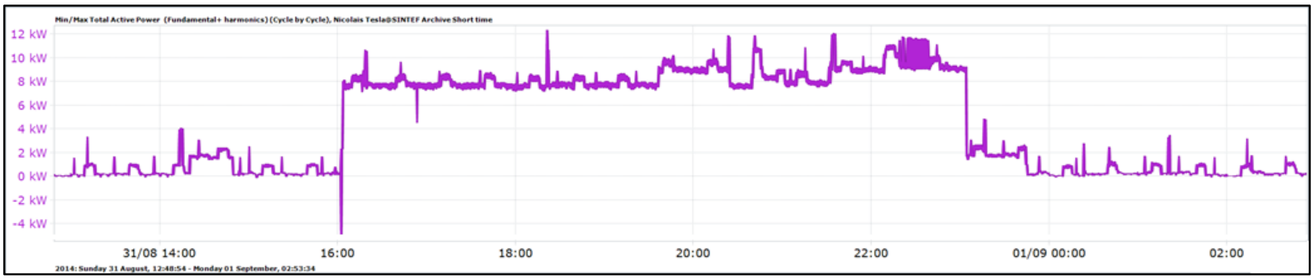

Figure 4.4 Charging profile Tesla Model S [16]

The IEC 62196 type 2 charger, at the bottom of the table in Figure 4.3 will be available on the market during the spring of 2016 [17]. This is a double charger and it can supply up to 22 kW. Charging an 85 kWh battery with this charger will take approximately 4 hours.

4.2 EV User Profile

How the charging of EVs will affect the distribution grid, depends on several factors. As presented in the previous section, the charging profiles for different EV models are different. It does not only depend on the charging current, but also the size of the battery. A Nissan with a battery of 30 kWh has to be charged more often than a Tesla with an 85 kWh battery, because the range of this vehicle is shorter. Figure 4.5 shows how a Nissan Leaf has been charged over a period of approximately two weeks.

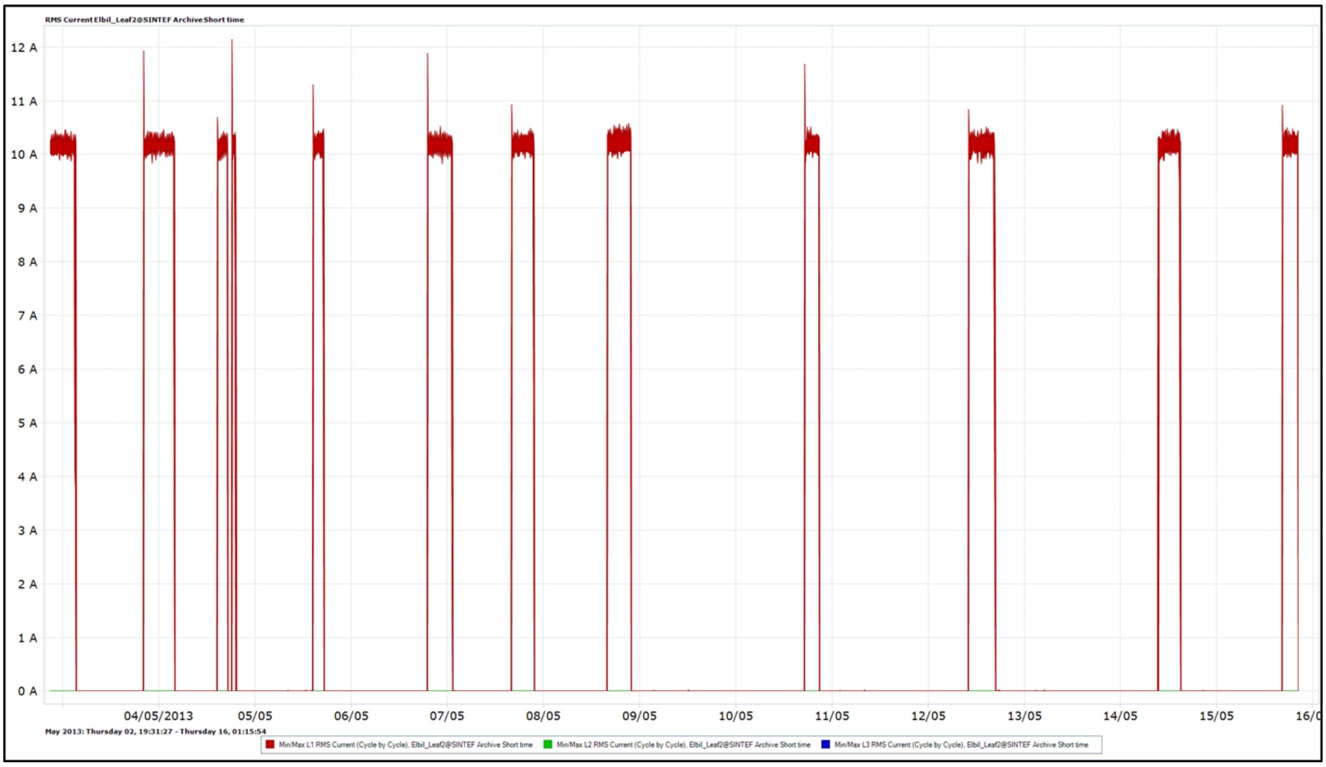

Figure 4.5 Weekly charging of a Nissan Leaf, 10A [16]

The figure shows when the EV is charging (10 A) and when it is not (0 A). Charging is typically done once a day, and most likely during the afternoon or night time. The duration of the charging depends on how much the vehicle has been used and the SOC of the battery when connected.

Today, Nissan Leaf has a larger marked share than Tesla Model S, but as previously mentioned the trends in the marked go towards bigger batteries in EVs. As the Tesla has a larger battery than the Nissan, this model has been chosen for further analysis in this thesis. This EV will also have larger impact on a household's consumption profile, as it requires higher power while charging. From here on in this thesis when numbers for EVs are used, it is always the Tesla Model S with an 85 kWh battery.

Because the Tesla has such large battery capacity, the range is longer before charging is required. It can also be seen as unnecessary for the EV owner to charge if the SOC is above 80 per cent. This implies that the vehicle does not have to be charged every day, like the Leaf. It is assumed that the vehicle should be charged when SOC reaches 30 to 40 per cent, to avoid the risk of the battery discharging completely while the EV is in use.

In order to see how the Tesla affects the consumption profile in a household, a fictitious week has been made. The owner of the EV and the time period is the same as in section 3.1. It is assumed that the customer lives in Trondheim and works at Stjørdal. The distance between Trondheim and Stjørdal is about 35 km one way and the toll fee for an ordinary passenger car is around 70 NOK each way, depending on where you live. Because EVs are exempt from toll fees, this is a highway where it can be profitable to use an EV. It is assumed that the customer drives to work from Monday to Friday, and that he does not charge the EV while at work. Some days during the week the customer uses the EV in the afternoon, while other days he does not. On Friday afternoon the customer drives to his cabin, situated 200 km away, and charges the vehicle there or on a charging station along the way. On Sunday afternoon the customer drives home from the cabin, and charges the vehicle at home. Because the customer does not want to charge his vehicle for short time periods every day, he waits until the SOC drops below 40 per cent before he charges. He charges the vehicle Sunday evening independent of the SOC, to have it ready for Monday morning. Tesla informs that the range of an 85 kWh EV is around 500 km, and it is assumed that the vehicle's energy demand is about 0.207 kWh/km when it is used [17]. Table 4.1 shows a typical week for this customer.

Table 4.1 Weekly schedule for customer with Tesla Model S

Day	Activity	Mileage [km]	Energy demand [kWh]	Energy left on battery [kWh]	SOC	Hours of charging needed	Charging activity
Monday morning				*85*	*1*		*EV is fully charged*
Monday	Work + recreation activity	80	16.6	68.4	0.81	2.3	
Tuesday	Work + recreation activity	75	15.5	52.9	0.62	4.5	
Wednesday	Work	70	14.5	38.4	0.45	6.5	
Thursday	Work + recreation activity	80	16.6	21.9	0.26	8.8	Charge EV
Friday morning				*85*	*1*		*EV is fully charged*
Friday	Work + drive to cabin	270	55.9	29.1	0.34	7.8	Charge EV at cabin
Saturday				85	1		
Sunday	Drive home from cabin	200	41.4	43.6	0.51	5.8	Charge EV

It is assumed that the customer charges the EV directly after he is finished using it. Because it was assumed that the vehicle had SOC equal to 1 on Monday morning, this customer only charges the EV two times during this week, one time on Thursday and once again on Sunday. The EV is charged for 9 hours on Thursday and for 6 hours on Sunday.

The weekly consumption profile for the customer this week will look like Figure 4.6. The blue line is the customer's demand without the EV and the red is demand with the EV.

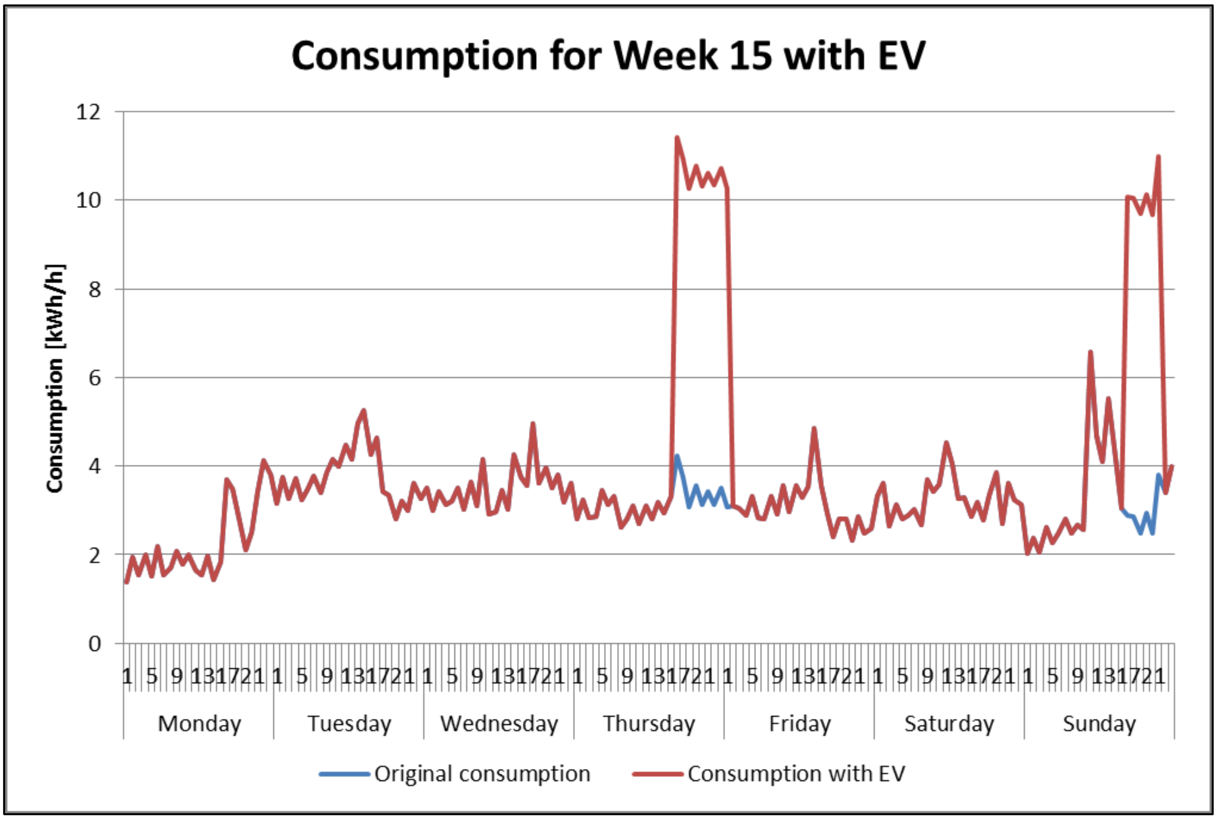

Figure 4.6 Consumption in week 15 with EV

One thing the figure immediately shows is that the assumption that the customer was at the cabin from Friday afternoon until Sunday afternoon probably is wrong. The customer has high demand during these days, and was probably at home. But as this is just an example of EV use, it is ignored in the analysis. As the figure shows the impact an EV has on the consumption profile is quite large. There are two large peaks that stand out in the consumption profile, and this is when the EV charges. The impact EVs can have on the distribution network is reinforced if many households have them and it is dependent on when these are charged. If several customers have user profiles similar to this customer, problems can occur. Figure 4.7 shows what the average consumption looks like for all the customers before this customer got the EV. As the figure shows, the average demand for all customers does not have any distinct peak demand hours, but it is usually somewhere between 2 and 4 kWh/h.

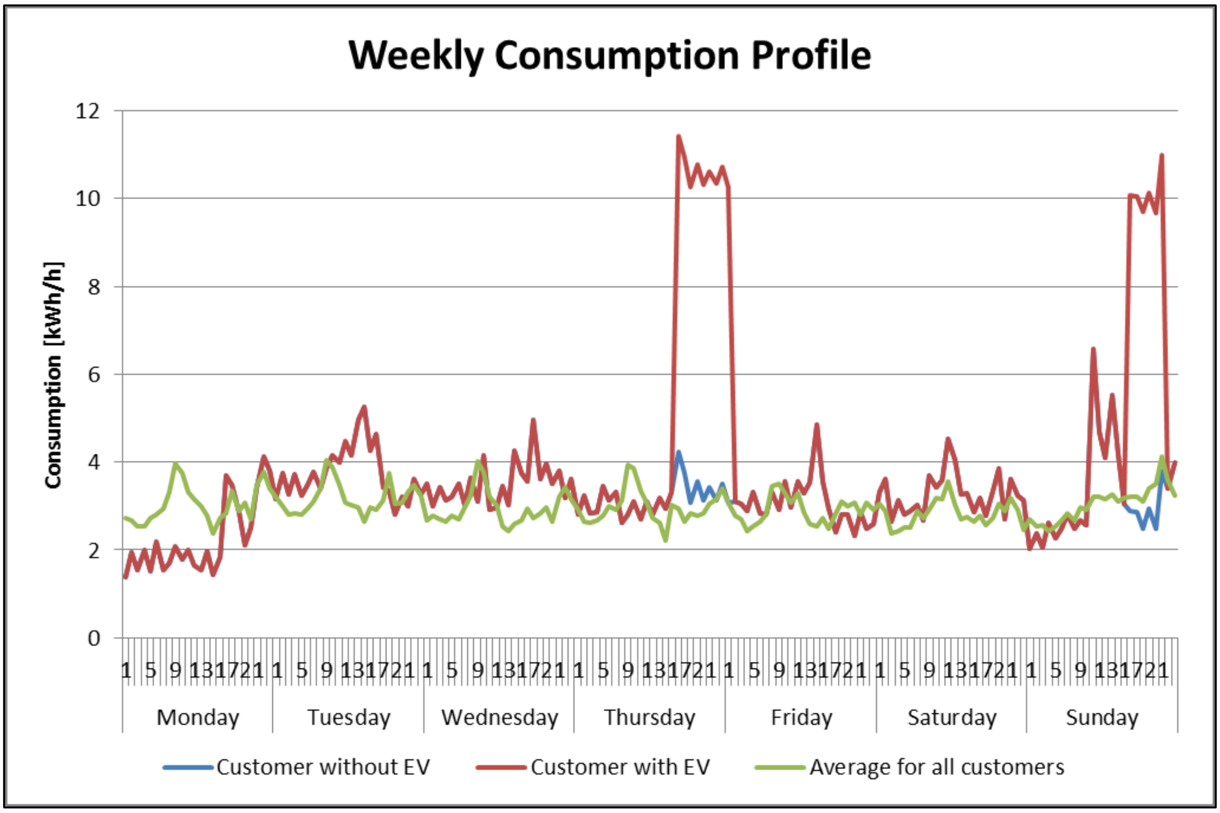

Figure 4.7 Comparison of one customer and average consumption, week 15

4.2.1 Daily EV Charging

In the example above, the EV is charged two times during the week. To see a different profile the vehicle has been charged every day in the example below. The usage of the EV is exactly the same as in Table 4.1 and the duration of the charging in this week will be according to Table 4.2.

Table 4.2 Duration of daily EV charging

Day	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
Hours of charging	2.5	2.5	2	2.5	0	0	6

The customer does not charge his EV at home during Friday and Saturday. This results in a weekly consumption profile shown in Figure 4.8.

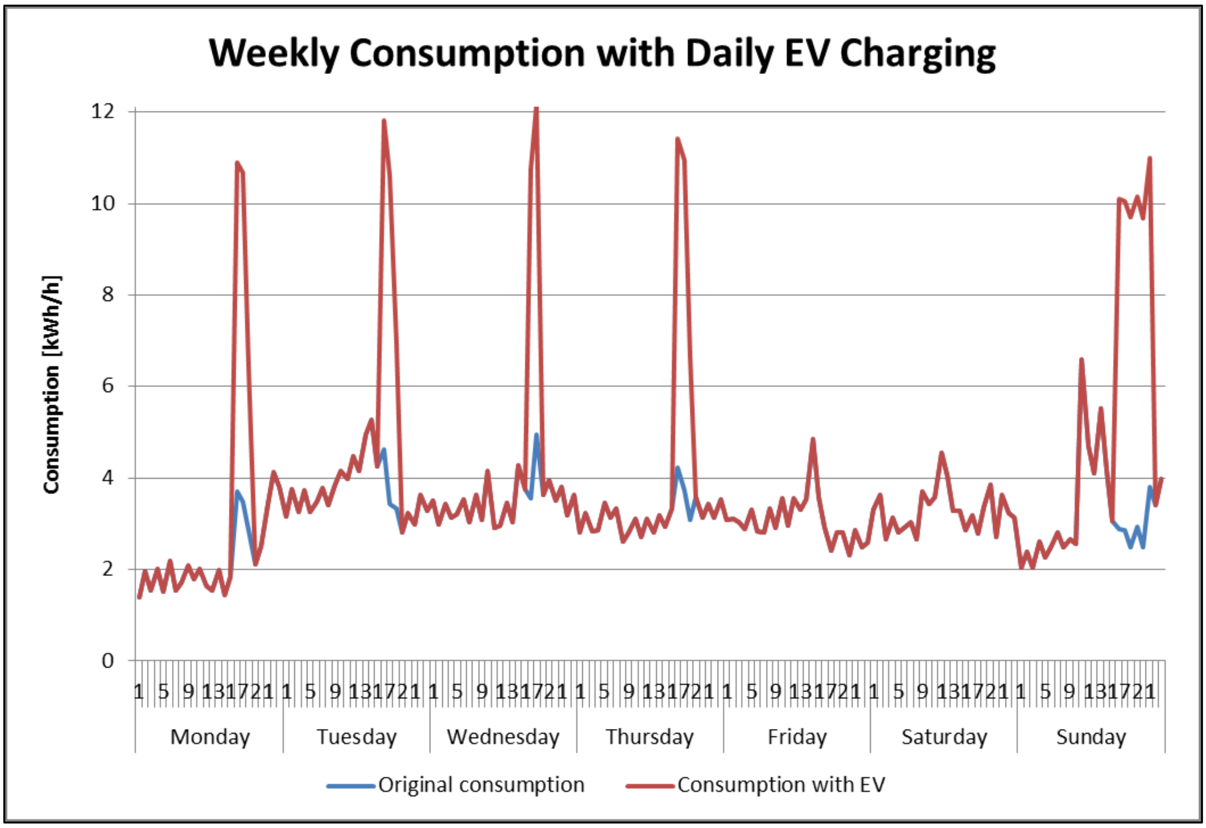

Figure 4.8 Consumption with daily EV charging, week 15

Most of the peak demand that occurs with this charging profile is shorter than the peaks that occurred when the vehicle only was charged on Thursday and Sunday, but the power demand is the same. This gives a consumption profile with different features than before. The EV's total energy demand is the same for the two scenarios. More examples of EVs effect on future consumption profiles will be given in section 7.

5 Distributed Generation

An alternative to buying electricity from a retailer is to produce it where it is used, by distributed generation. Customers that are both producing and consuming electricity are often referred to as prosumers. By producing electricity that is used in a household locally, the network may be spared of some strain because demand is reduced. In this section, several available technologies for local energy generation are presented.

Customers with local energy generation want to earn the most on their production, compared to buying electricity from the grid. The price in NOK/kWh for locally produced energy versus the cost of buying it from the grid is a good motivation for customers. For further deployment of distributed generation it is a prerequisite that the cost matches, or is lower than obtaining it from the grid.

Electricity produced by households that is self-consumed is often exempted from grid costs and other system charges [18]. As the electricity is locally produced and consumed, it does not utilize the distribution grid, and the exemption is reasonable. However, unless the generated electricity is consumed during peak load in the grid, the DSO’s costs will not be reduced. This is because the DSO’s costs are driven by the peak capacity in the network. A large-scale deployment of self-consumption could impact the profitability for the DSOs, especially in countries with high volumetric grid tariffs.

DG has the ability to change household’s consumption profiles, even when the production is small. The household might *use* energy in exactly the same way as before, but because they produce some of the electricity themselves the demand in the grid will look different. This is dependent on what kind of energy the household produces, and whether or not the household has opportunities for energy storage.

5.1 Solar Energy

Solar energy is a widespread solution for local energy production. The energy from The Sun is most commonly utilized by solar collectors or PV panels. The solar insolation is variable across the globe and varies throughout the year, see Appendix A and B. In this thesis the focus will be on solar insolation in the region of Trøndelag, as the customers that are considered live in this area.

Steinkjer is located approximately at latitude 64°. Because this is rather far north, the access to sunlight varies throughout the year, as shown in Figure 5.1. In the figure, sun hours represent the number of hours between sunrise and sunset.

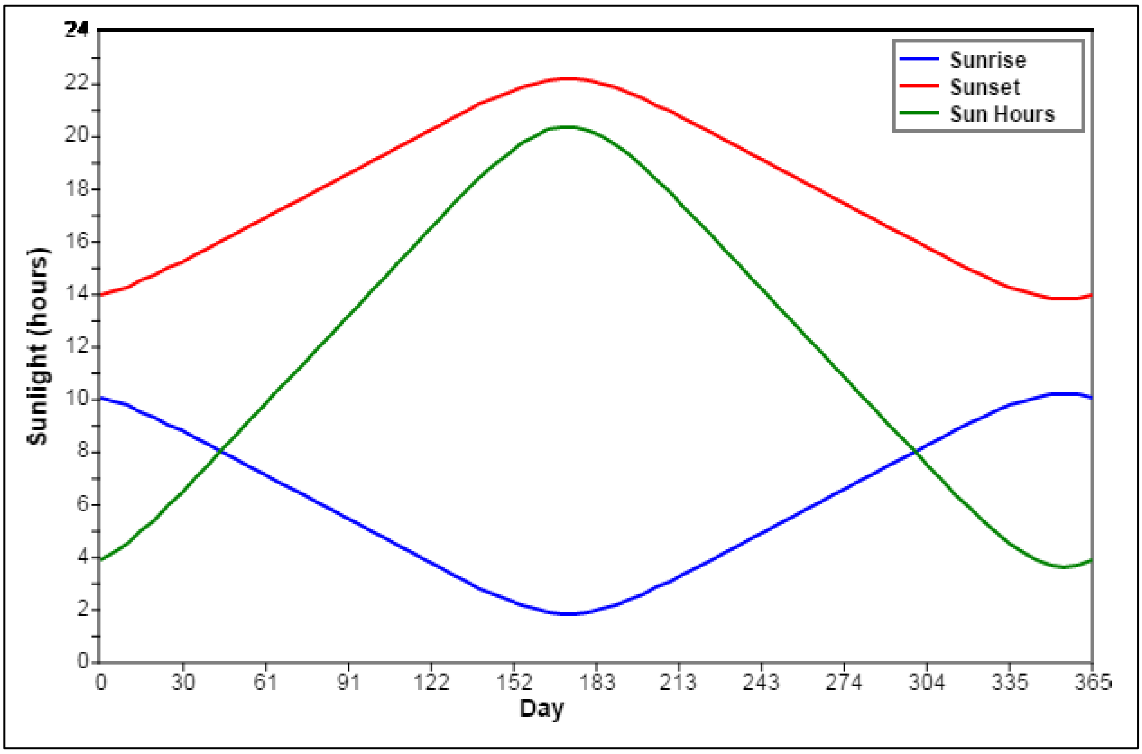

Figure 5.1 The number of hours The Sun is shining each day in Steinkjer [19]

As the figure shows, the number of sun hours can be as low as 4 during the winter and during the summer it can be as high as 20. This will influence the theoretical possible energy that can be utilized. Because most of the energy consumption in Norwegian households is during winter months, the coherence between supply and demand is not optimal. Solar energy might be seen as favorable in places where electricity is used for example for cooling systems during daytime.

Figure 5.1 shows the average radiation on a horizontal surface during a day for four seasons in 2013 at Mære station in Nord-Trøndelag. The figure shows that the variations are large for each season.

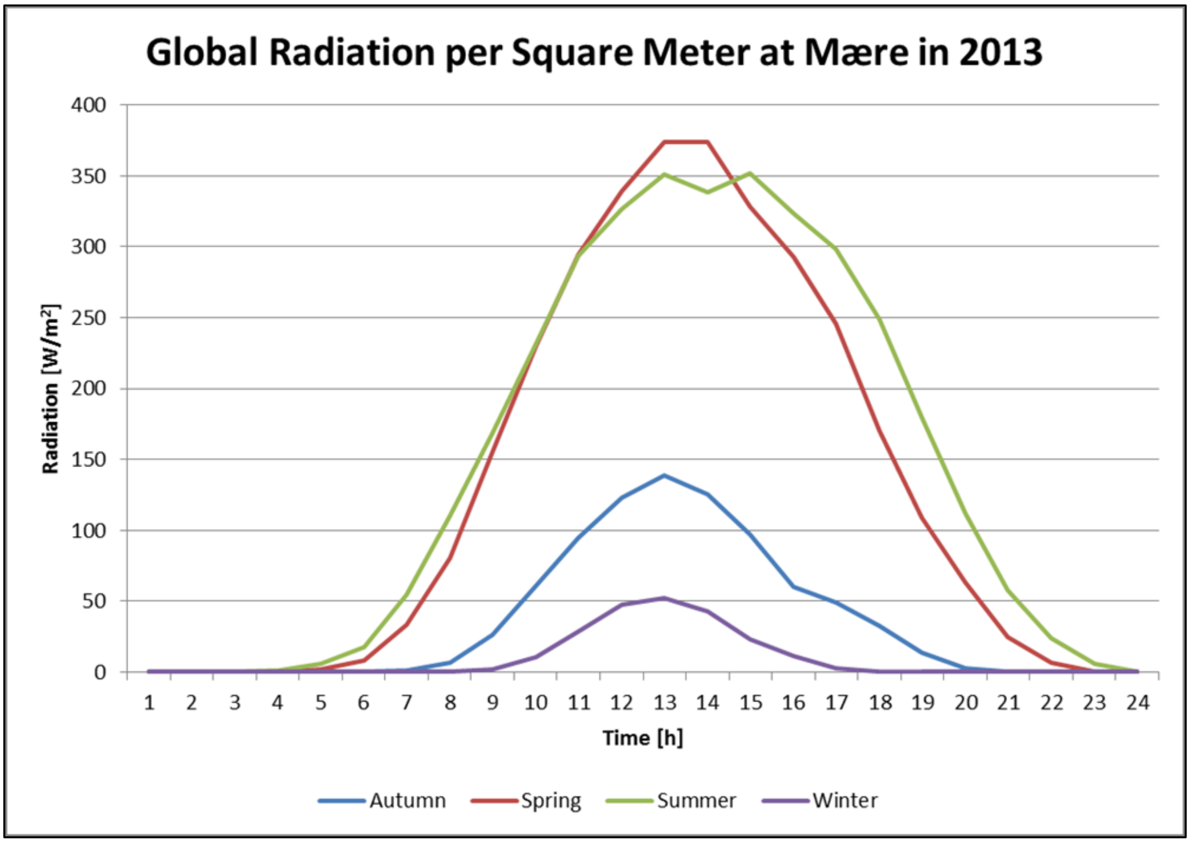

Figure 5.2 Global radiation during 2013 [20]

This figure confirms that the radiation is significantly lower during wintertime. The weather station at Mære is located 59 meters above sea level at latitude 63.94244° and longitude 11.42527°. Global radiation is the sum of direct and diffuse radiation from The Sun. It is measured by a pyranometer, which measures the radiation incident on a horizontal surface [20]. More information about The Sun's movement in the sky throughout the year can be found in Appendix A. The numbers in Figure 5.2 represent one year, and weather variations in this particular year can make a major impact on the measurements.

The two main technologies for exploiting solar energy, solar collectors and PV panels, will be discussed below.

5.1.1 Solar Collectors

Solar collectors are used to generate heat by absorbing sunlight. The heat is usually utilized to produce hot water. Different solar collector technologies are available and the hot water produced can be used directly for hot fill washing appliances, hydronic heating systems or for DHW use, such as for showering. This section will briefly discuss how having solar collectors can affect the consumption profiles in households.

There are quite large differences in how much electricity consumption profiles will change, depending on what kind of system is installed. A system that heats water which can be used for showering etc. will reduce the energy demand for regular DHW. In Norway the most common way to heat water is by using electricity and a hot water tank, as presented in section 2.4.1. Figure 5.3 shows an example of how the electricity consumption in a typical Norwegian household is distributed for a 24 hour period. As this figure shows, the electricity used for hot water heating is quite evenly distributed during the day. The highest consumption is during the night, but there are small peaks in the morning and afternoon as well. By using solar collectors for hot water, the demand during daytime can be reduced. If the hot water is used in hot fill appliances, the category including "other" can also be reduced.

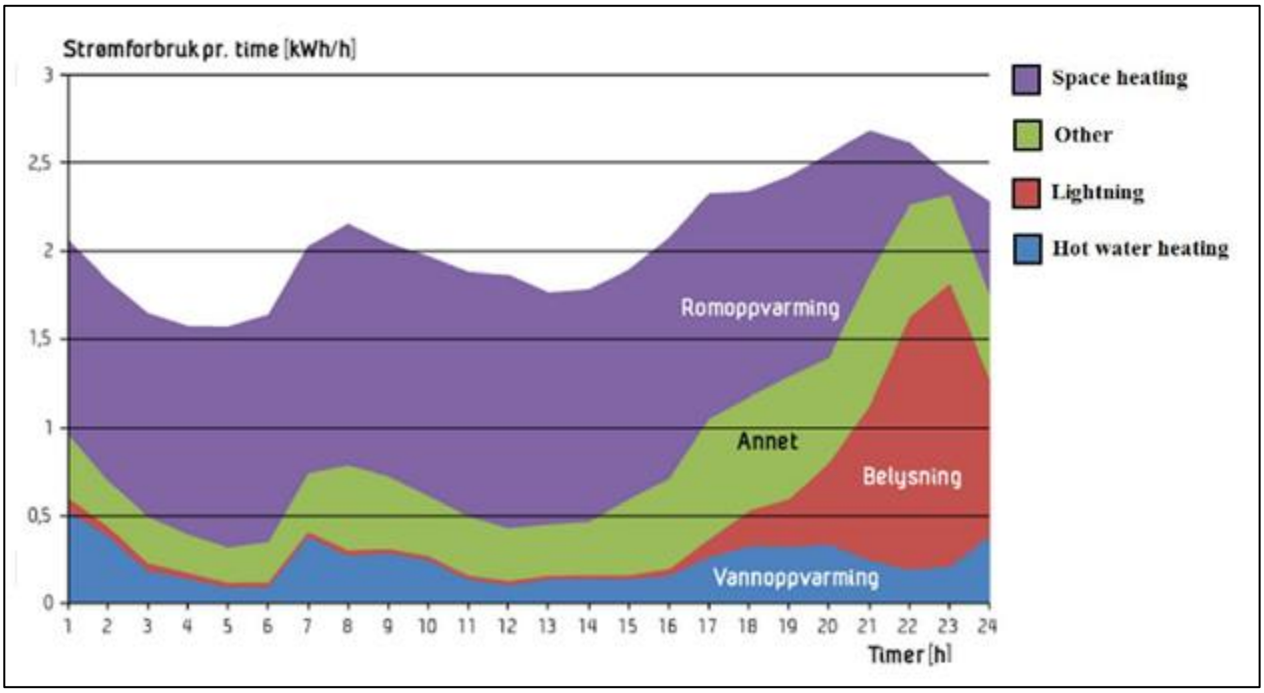

Figure 5.3 Electricity consumption for a typical Norwegian household [21]

By having a 7 m^2 solar collector facing south with an angle of 45°, Enova [22] estimates that the benefit will be 2 290 kWh per year if the system is located in Trondheim. This is calculated with a hot water usage of 5 000 kWh per year. These benefits will vary depending on where in the country the system is located.

The other system solution with solar collectors is a combination of hot water heating and a hydronic heating system. This system can further reduce the electricity demand in a household. Figure 5.4 shows an example of how this system can look. The solar collectors on the roof provide energy for hot water, as well as space heating in the house.

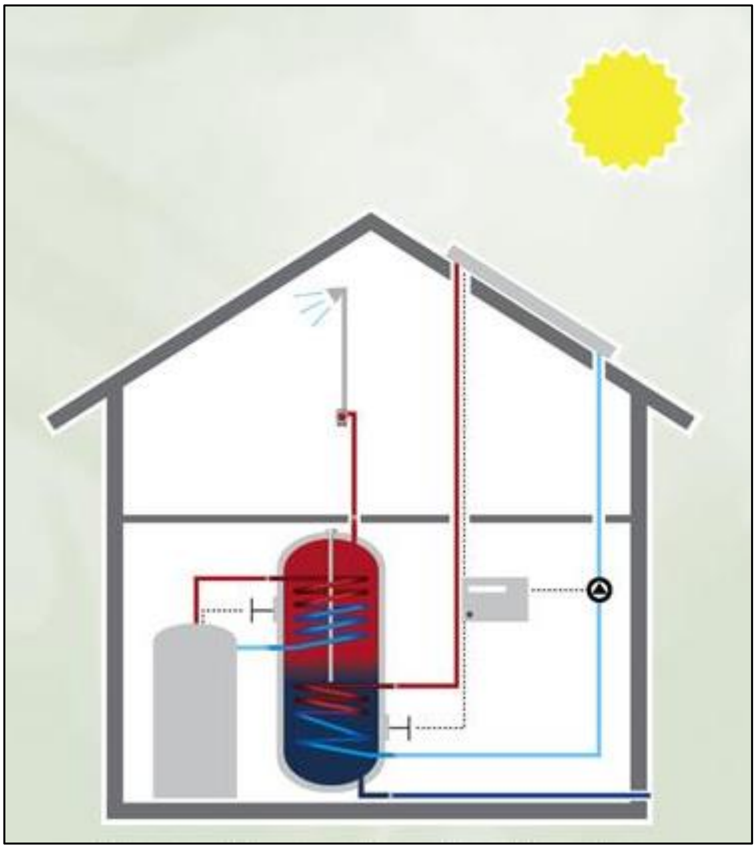

Figure 5.4 Combined solar collector system [22]

Using a solar collector-system that has a hydronic heating system in addition to DHW can in some households cover up to 50 per cent of the total heat demand [22]. As Figure 5.3 shows, most of the consumed electricity in the household is used for space heating. With the combined solar system, this electricity demand can be significantly reduced. A 25 m^2 solar collector system facing south with an angle of 60°, can reduce the electricity consumption in a household by 6 500 kWh per year [22], assumed hot water use is 6 000 kWh per year and space heating is 10 500 kWh per year. The tilt of the panels in this example is most likely set so high to take full advantage of solar irradiation during winter. The systems are usually designed to cover up to 50 per cent of the hot water demand and 30 per cent of the space heating [22].

Both the solution without, and the system with the hydronic heating system, will reduce the electricity consumption in households. This is because energy demand that previously was covered by electricity now will be covered by solar energy. The systems can also be combined with other energy sources such as a heat pump or bio boiler, which can keep the system running when The Sun does not provide enough energy.

The area of installed thermal solar energy systems in Norway has increased the recent years, as shown in Figure 5.5.

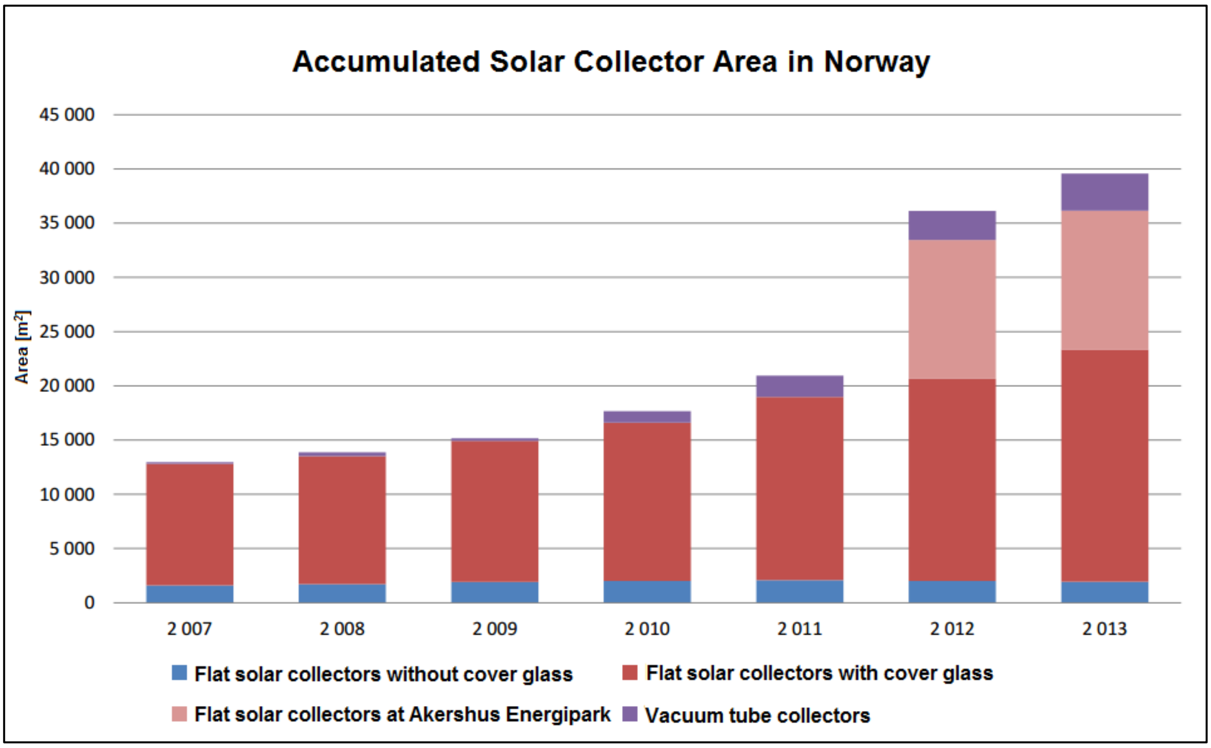

Figure 5.5 Historic development of installed solar collector capacity in Norway [23]

As the figure shows, the trend is that the installed capacity increases every year. The massive increase from 2011 to 2012 was the construction of Norway's first large scale solar thermal facility, Akershus Energipark. The plant consists of 13 000 m^2 solar collector panels and it is connected to the district heating system at Lillestrøm [24].

One important factor that determines if households decide to install solar collectors is price. Enova [22] estimates that the installation price of a system for DHW is around 30 000 NOK and up, depending on the dimensioning, design and operation. For a solar collector/heat pump system the price will be from 100 000 NOK and up. The annual savings for the DHW system mentioned above is calculated to be around 2 290 NOK per year in Trondheim and the combined DHW and hydronic heating system can give savings of around 6 500 NOK per year. This is calculated with an alternative energy price of 1 NOK per kWh [22]. Enova has a funding scheme for households who want to make an effort for the climate. Households that have installed solar collectors can get 25 per cent back on documented total costs, including value added tax (VAT). The refund has an upper limit of 10 000 NOK repayment, plus 200 NOK per square meter of collectors limited to 25 m^2 [25].

5.1.2 PV panels

The other common technology for utilizing energy from The Sun is PV panels. Unlike solar collectors that produce heat, PV panels generate electricity which is considered a high quality energy source. As most of the energy consumption in Norwegian households is electricity [2], the use of PV panels can have large influence on the consumption profiles. In households, PV panels are recommended to be placed on rooftops facing south. This gives the most radiation, and if the panels have a tilt, the radiation can be even more exploited compared to horizontal surfaces. As previously mentioned, the number of sun hours and The Sun's height varies throughout the year. During winter The Sun can be very low in the sky at northern latitudes, and to benefit most of the energy, other technologies needs to be utilized. One of the best solutions for this is to use moving panels. The panels can be attached to single- or dual-axis tracking systems. These systems follow The Sun's movement throughout the day and increase direct radiation. This technology will also allow more utilization of The Sun during summer. When The Sun is shining 24 hours, or close to this, it will at some point of the day appear on the rear of a fixed tilted panel. By using tracking systems, the panel follows it's movement and more radiation to the panel is achieved. Figures showing the potential using solar tracking systems are found in Appendix B. However, tracking systems are more expensive than fixed rooftop panels, and in this thesis the main focus will be on fixed systems.

Solar panel ratings are often given in kW_p. This is the theoretical power during standard test conditions (STC), which is at a temperature of 25 °C, radiation of 1 000 W/m^2 and atmospheric density at 1.5. The rated efficiency of PV panels varies, and the theoretical value usually is a lot higher than the actual. The use of PV panels in Norway has certain advantages and the efficiency can increase in low temperatures. Therefore, delivered power from a module can be very high during a sunny day in March, even though this is considered to be slightly off season for production in Norway. Also, the panels do not need direct sunlight to produce electricity, but it is sufficient with daylight. Rain can also be advantageous, as this cleans the panels. During winter, the snow on the ground can give reflections and increase irradiance on the panels. Snow on the panels is not desirable, but as the panels often are mounted at an angle and retain some warmth, a little snowfall should melt and slide off rather quickly. This is off course dependent on the amount of snow.

The price of solar panels have decreased during the last decade and become far more available [5]. Price, efficiency and performance varies a lot from manufacturer to manufacturer. The module that is investigated in this thesis is a REC255PE module delivered by REC, a

Norwegian company that supplies solar panels and installations. Data for this module is given in Table 5.1.

Table 5.1 Data sheet REC255PE module [26]

Electrical data @ STC	**REC255PE**
Peak Power Watts - P_{max} [W_p]	255
Watt Class Sorting [W]	0/+5
Maximum Power Voltage - V_{mpp} [V]	30.5
Maximum Power Current - I_{mpp} [A]	8.42
Open Circuit Voltage - V_{oc} [V]	37.6
Short Circuit Current - I_{sc} [A]	8.95
Panel Efficiency [%]	15.5

At low irradiance of 200 W/m² (Air mass 1.5 and cell temperature 25 °C) at least 95.5 per cent of the STC module efficiency will be achieved for this panel [26]. A drawing of one panel with measurements in millimeters is given in Figure 5.6.

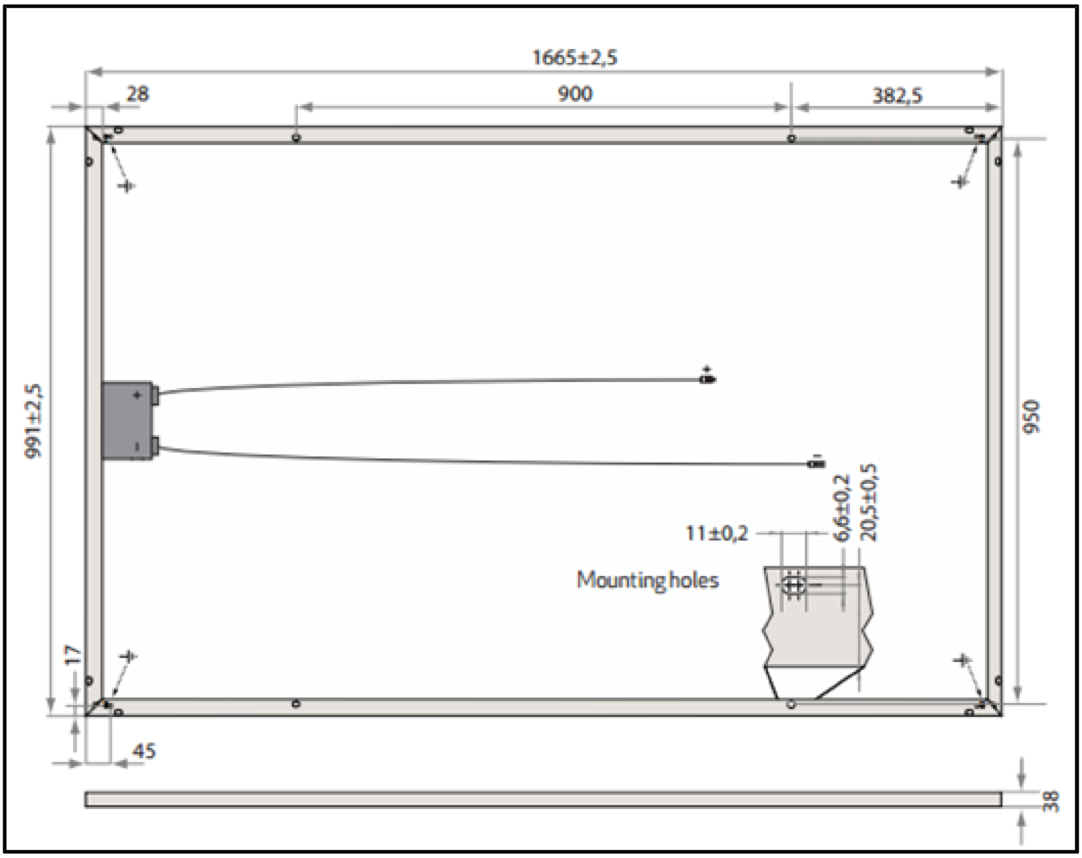

Figure 5.6 REC255PE panel [26]

In this analysis the PV module consists of 12 panels, which gives an area of approximately 20 m^2. The REC255PE panel and this module size are selected on the basis of one customer. The customer has this exact module, as well as measurements on production and demand covered by gird connection. The customer has worked as a control test, to see if the numbers used in the analysis are realistic. The customer is not one of the 24 who are a part of the original analysis. The customer informs that the efficiency of the inverter is 94.4 per cent, and this is used in the analysis as well. Figure 5.7 shows this customer's consumption profile on Sunday 05.06.2015. The red line shows the power generated by the PV module, measured on the inverter, and the blue line shows the customer's power demand from the distribution grid. As the figure shows, with the PV panel the customer exports energy back to the grid during midday.

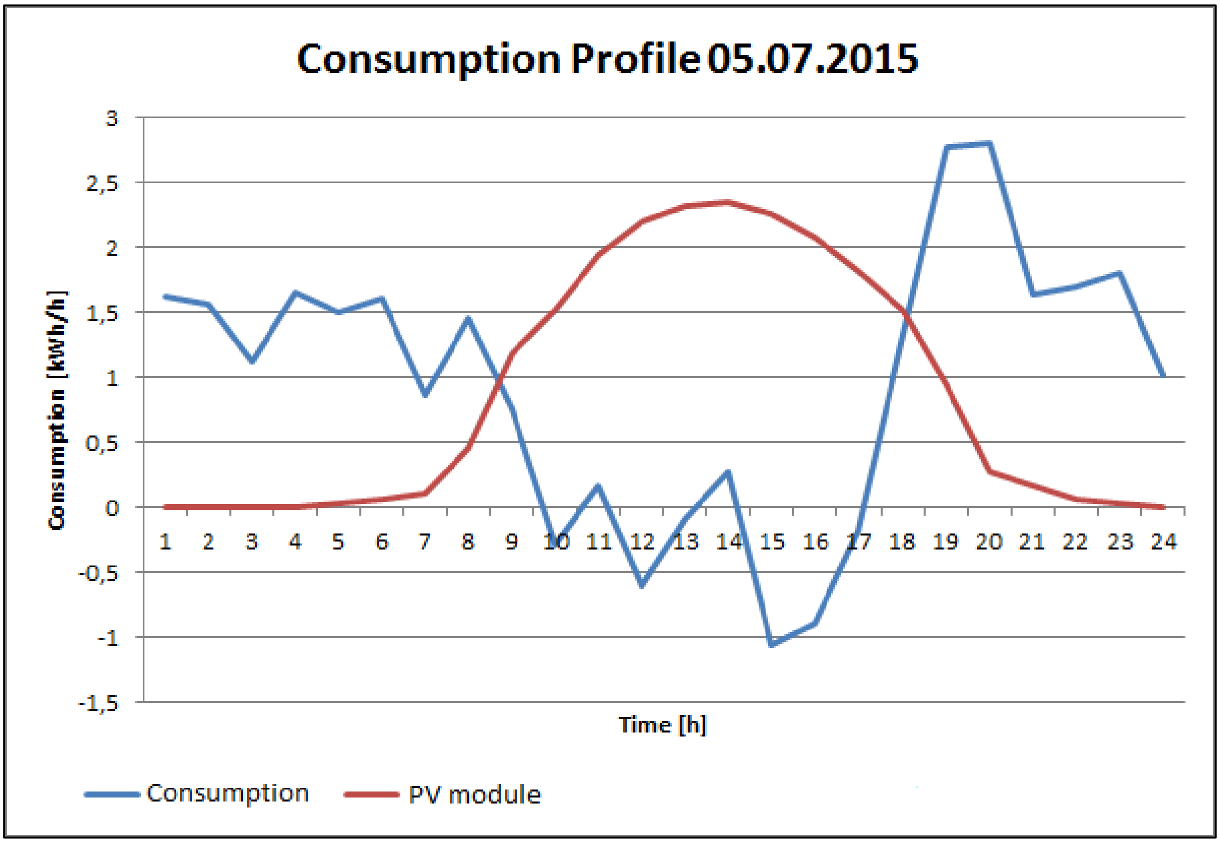

Figure 5.7 Consumption profile for test customer

In this analysis, the panels will be on rooftops, facing south with an angle of 30°, as further explained in Appendix A. The data provided by Agrometeorology Norway [20] is used as a basis to calculate theoretical production for the panels. The yearly production for each of the customers with this PV module is calculated using formula 3.

$$\sum_{t=1}^{8760} S_{M,t} \times A_{module} \times \eta_{inverter} \times \eta_{PV} \tag{3}$$

Where,

$S_{M,t}$ = Solar radiation perpendicular on a panel with a tilt of 30° in hour t [kWh/m^2]

A_{module} = The total area of the PV module [m^2]

$\eta_{inverter}$ = Efficiency of the inverter = 94.4 [%]

η_{PV} = Efficiency of the PV panels = 15.5 [%]

With the insolation in 2013, the 20 m^2 module will produce approximately 3 363 kWh this year. Figure 5.8 shows how the supplied energy is distributed throughout the year. As expected, the production is higher during the spring and summer months.

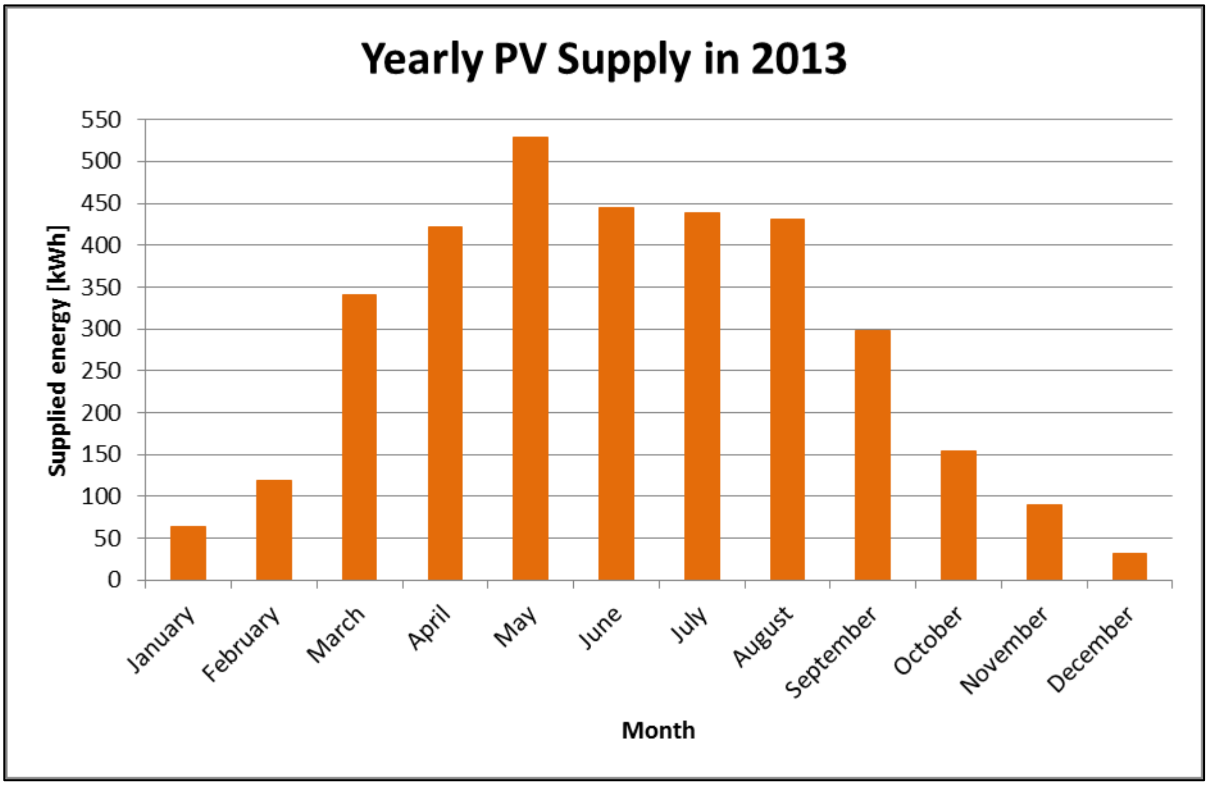

Figure 5.8 Yearly supplied energy by PV module in 2013

In a real life installation of PV panels for the 24 customers, it might not be realistic that all the customers have the same module size, as consumption is very variable for all the households. Some of the customers should perhaps have smaller modules, and some bigger. All the households are considered to have the same module size in this analysis, to show the potential for utilization of solar energy. One possibility is also that an entire neighborhood invests in a shared PV module with higher capacity. This will shortly be discussed in section 5.4.

As Figure 5.8 shows, the produced energy varies throughout the year. A more detailed picture of the production is shown in Figure 5.9. This figure shows the average hourly production for each season.

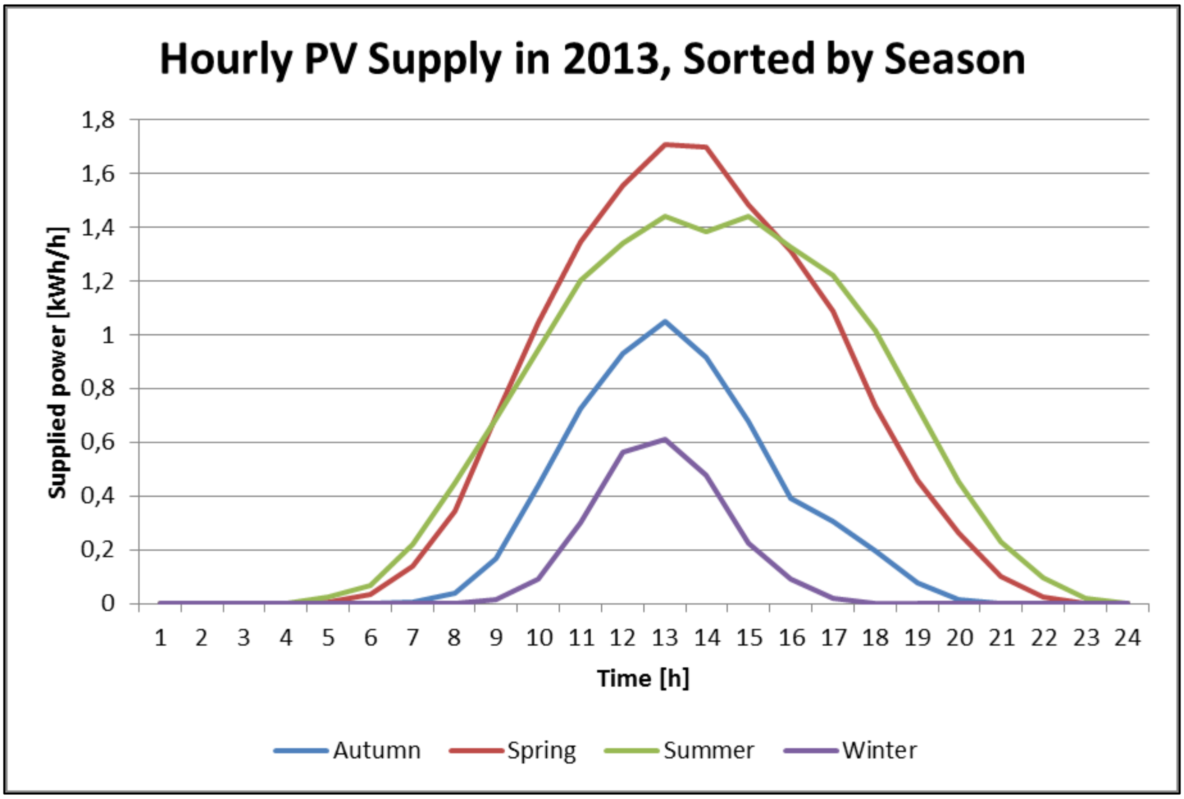

Figure 5.9 Hourly PV supply in 2013

Comparing Figure 5.9 with Figure 5.2, which displayed global radiation on a horizontal surface, shows the importance of tilt angle for the PV modules. As The Sun is lower on the sky during winter months, the solar radiation can be exploited better if the panels have optimal tilt angle. The tilt angle also enables increased production during spring and autumn.

Because PV panels produce electricity, not just heat, the impact on the electricity consumption profile for a house can be rather big. The consumption that will be affected to the greatest extent is the consumption during daytime. From Figure 5.3, showing the distribution of consumption in a house, one can see that the only category that might not be affected by PV panels is lightning. In general, having PV will reduce electricity demand during daytime. Excess energy produced by the PV module can be fed back into the grid, which will be discussed in section 5.3.

In order to see how PV supply can change electricity consumption profiles in households, the year 2013 has been used as a case. In Figure 5.10 to Figure 5.13, the blue line shows the average electricity demand profile for one season. This is the actual consumer demands in 2013. The red line is the combined demand and PV production. If the PV panel produces more than the demand during one hour, the consumption profile will be negative. This means that the customer exports electricity back to the grid.

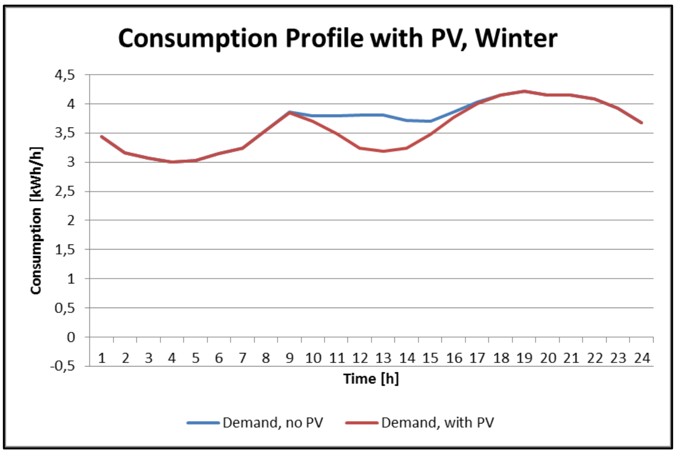

Figure 5.10 Consumption profile with PV, winter

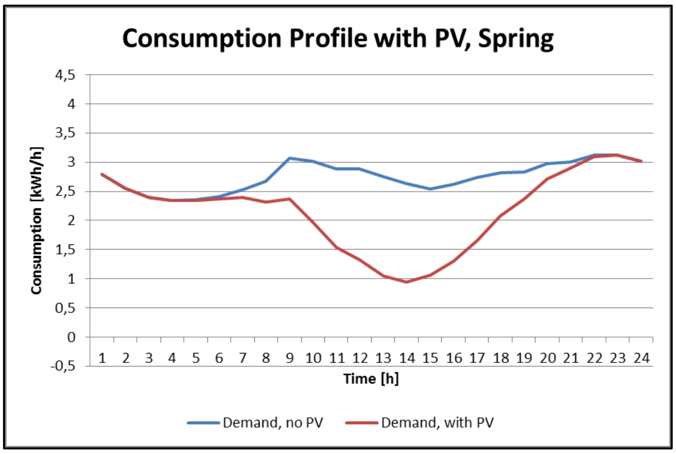

Figure 5.11 Consumption profile with PV, spring

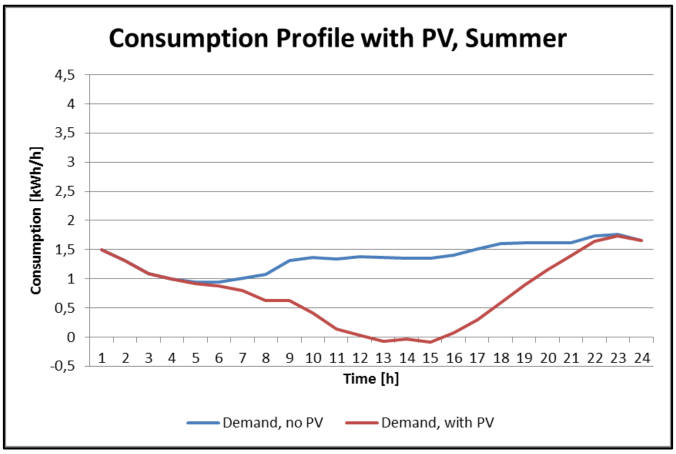

Figure 5.12 Consumption profile with PV, summer

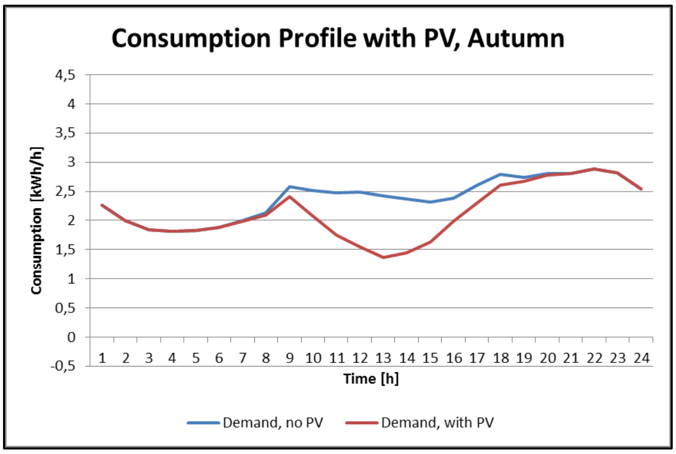

Figure 5.13 Consumption profile with PV, autumn

As the figures show, the season with the smallest change in demand is winter. This is because the electricity production from PV is lower in this season. Even though production is low during the winter, PV can have benefits in this period. Because most of the electricity used in households is for space heating, it is very temperature dependent and cold temperatures can cause peak load in the grid. Figure 5.14 shows the consumption profile for one of the customers on a Saturday in February 2013. For this customer the consumption is different on weekdays and weekends. On weekends the demand is higher during daytime, and the morning peaks are not as distinct as on working weekdays. This specific day was quite cold, as the green line in the figure shows.

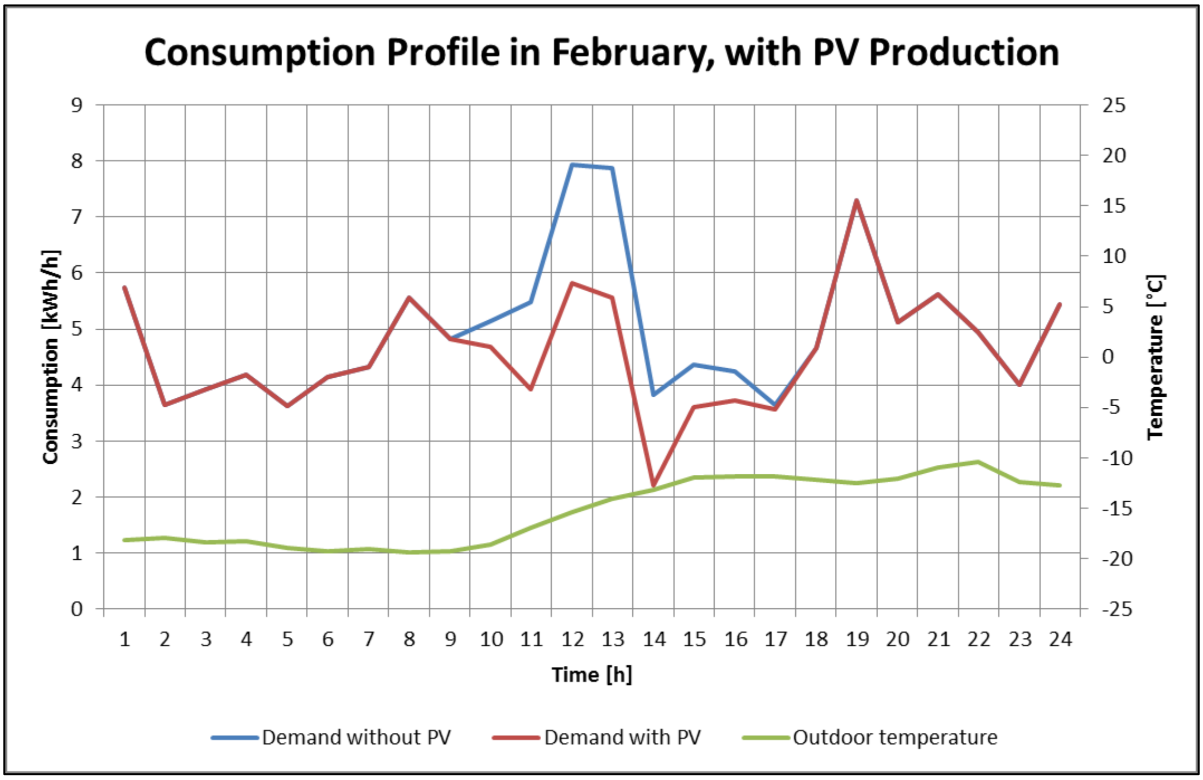

Figure 5.14 Consumption profile for customer in February

The blue line represents the customer's actual consumption, and for the red line the PV supply is subtracted from the demand. By having the PV module on the roof, this customer avoids a large peak demand between the hours of 11 and 13. On this specific day the peak demand is reduced from 7.97 kWh/h to 5.83 kWh/h. A reduction of peak demand is great news for the DSO, but in the future this can also be a great way for the customer to save money on the electricity bill. This will be discussed in section 8, "Tariffs to Reduce Peak Load and Increase Utilization Time".

Figure 5.15 shows the energy generated and supplied by the PV panel during week 15 in 2013. As the figure shows the supply is quite stable through the week, but a little lower on Sunday.

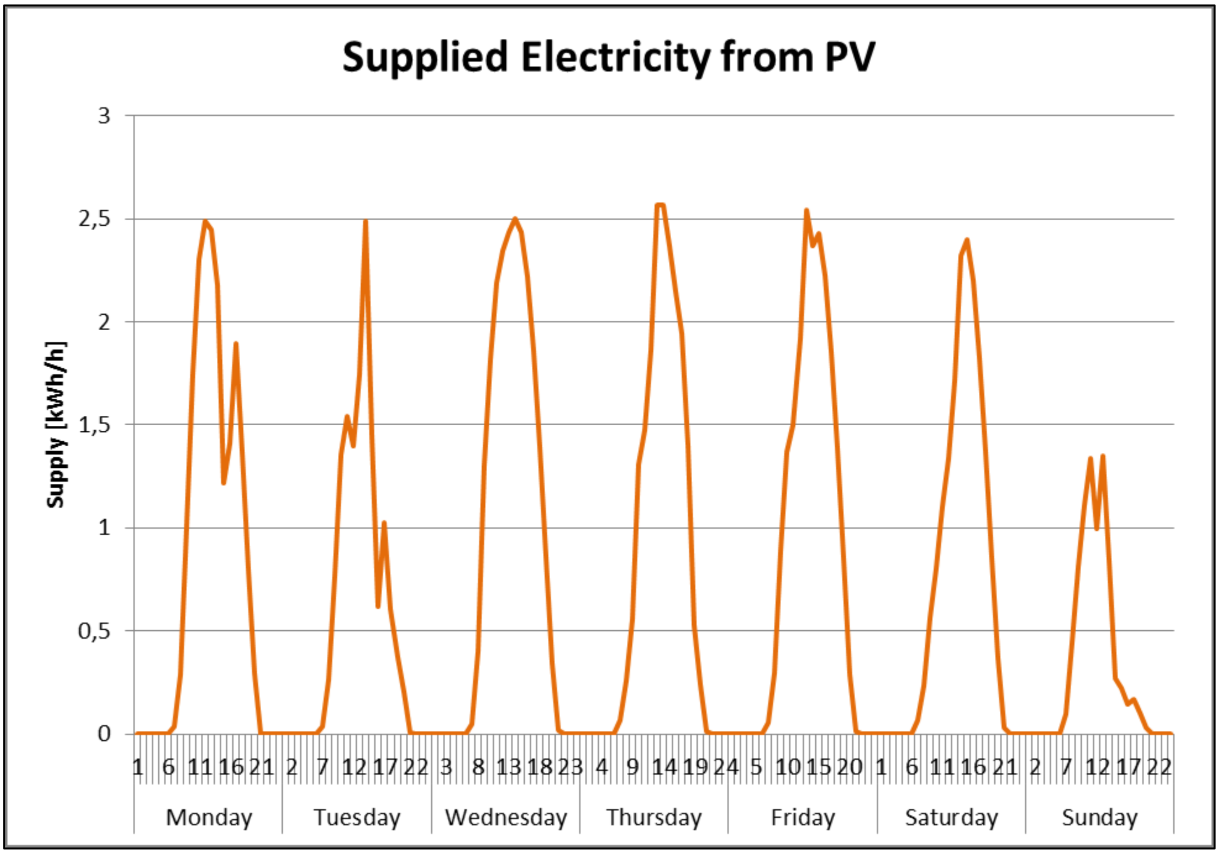

Figure 5.15 Supplied electricity by PV panels in week 15

The total energy supplied every day is listed in Table 5.2. The total production this week was 120 kWh.

Table 5.2 Energy production by PV panel in week 15

Day	**Monday**	**Tuesday**	**Wednesday**	**Thursday**	**Friday**	**Saturday**	**Sunday**
Energy	19.5 kWh	13.9 kWh	22.2 kWh	19.3 kWh	20 kWh	17.2 kWh	7.9 kWh

Figure 5.16 shows what the consumption for the customer from section 3.1 will look like in the selected week, with this particular PV module. The electricity supplied by the PV module has been subtracted from the customer's ordinary demand. As the figure shows, this customer has higher production than demand during Monday and therefore exports electricity to the grid. On Sunday the PV supply was low, so the consumption profile does not change much for this day.

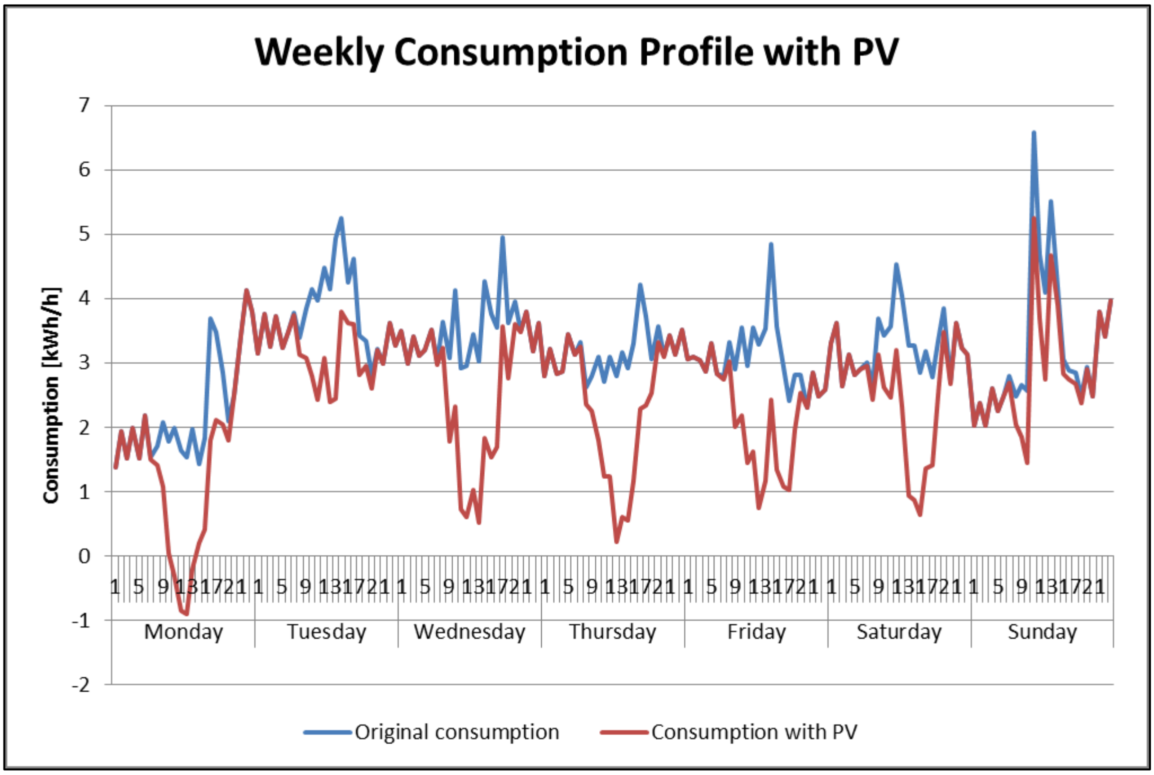

Figure 5.16 Weekly consumption with PV in week 15

Installation of PV has become more popular the recent years. Figure 5.17 shows the total installed capacity in Norway from 2004 to 2014.

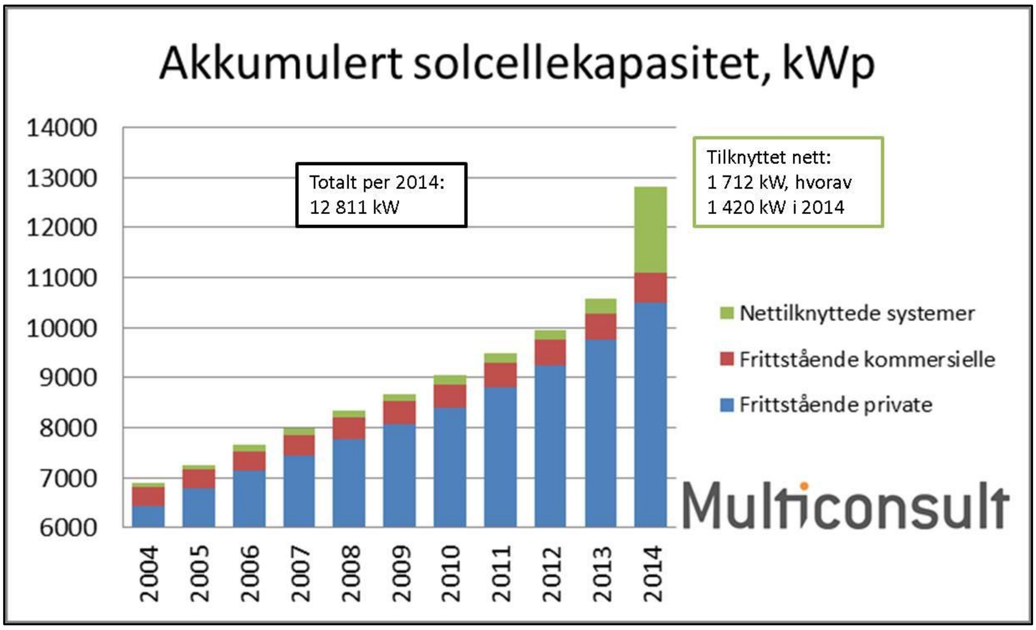

Figure 5.17 PV capacity in Norway, 2004-2014 [27]

In this figure the blue area represents stand-alone private systems, the red is stand-alone commercial systems and the green represents grid connected systems. The total installed capacity in 2014 was 12 811 kW. Many of the systems are stand-alone systems for example used on cabins and lighthouses [27].

Customers can reduce electricity demand from the grid by installing PV in their household. Despite a decline in PV prices the recent years, the investment cost is still quite high. The installation of a PV system is quite expensive, but the expected lifetime is long. Just like for solar collectors, Enova has a funding scheme for electricity production from renewable sources like wind or solar energy. Households that have installed PV modules can get 35 per cent back of documented total costs, including VAT. The refund has an upper limit of 10 000 NOK repayment, plus 1 250 NOK per kW installed power up to 15 kW [28].

5.2 Alternative Energy Sources

There are alternative energy sources for distributed generation. Some will be briefly discussed below, but the main focus in this thesis will be on solar energy.

5.2.1 Fuel Cells

One technology for local generation is the use of fuel cells. The most common fuel for this technology is hydrogen, but there are also fuel cells that can utilize for example natural gas, methanol or gasoline. The technology draws energy from the chemical reaction that occurs when hydrogen combines with oxygen to form water [29] and is used to produce electricity. The excess heat from the process can be used to heat water for DHW. Hydrogen can for example be prepared from natural gas or electrolysis of water [30]. As the fuel cells have no moving parts they are very quiet, compared to for example a diesel powered aggregate. The system also has shorter start-up time and lower maintenance costs [30].

Fuel cells can work as a back-up power source or as a contributor to reduction of electricity demand. The system can work as long-term storage of energy, but requires space to store hydrogen. Fuel cells are also more robust and offer extended backup time compared to for instance batteries.

The fuel cell technology is really popular in Japan. In larger cities in Japan most households are connected to the gas network, as this is a common energy source in households. This makes the investment costs lower for installing fuel cells, since hydrogen can be prepared from natural gas. In 2013 more than 30 000 fuel cells were installed in Japanese households [30]. The fuel cell is about the size of a suitcase and can for example sit just outside the door [29]. The Japanese government has earmarked $309 million USD a year for fuel cell development. The government plans for 10 million homes to be powered by fuel cells by 2020, which represent about one-fourth of all Japanese households [29].

This technology can also be used in the transport sector. A fuel cell electric vehicle (FCEV) is an alternative to an electric vehicle or a traditional vehicle. A fuel cell is about twice as efficient as an internal combustion engine when used in a conventional car [30]. As the only waste material from this car is water, the cars can make a big difference for the local environment.

5.2.2 Wind Energy

Small wind turbines can be an alternative for local energy generation. Solar energy varies a lot throughout the day and is only available when The Sun is in the sky. Wind is an energy source that is available and not depending on the time of day, but only on weather conditions. Because of this, a small-scale wind turbine mounted on a customer's house might be a useful supplement when The Sun is absent. The kinetic energy that can be recovered by a wind turbine is given in formula 4.

$$P_{turbine} = \frac{1}{2} \times A \times \rho \times v^3 \tag{4}$$

Where,

A = Area of the turbine [m^2]

ρ = Air density = 1.23 [kg/m^3]

v = Wind speed [m/s]

The most important factor in this formula is the wind speed, v. The wind speed is usually measured at 80 meters height, because it is more stable there. In the case of local generation for a household, a wind turbine of much lower height is more applicable. To get a stable wind speed the turbines are recommended to be in areas without agglomerations. Wind turbines might also cause noise and aesthetic problems and is probably a better alternative for rural areas above cities. Price and installation for small scale wind power is expensive, and not profitable with today's power prices.

5.3 Prosumers

One alternative for customers having distributed generation is to sell the electricity back to the network. A customer with this option is referred to as a prosumer. A prosumer is an end user with consumption and production behind the connection point to the network, where input production at the connection point at no time exceed 100 kW [31]. In recent years, NVE have put in place a scheme for prosumers that allows for normal household customers and businesses to install distributed generation with simplified requirements for concession [31]. Another requirement is that production mainly is used to cover own consumption, so the scheme is not intended for facilities that generate significantly more energy than it consumes. The prosumers also need to have a contract with a power retailer to sell their production, not with a DSO as it was before. In order to receive support from Enova, the customer needs to be connected to the network.

Customers who decide to sell their excess electricity production sell it with a negative variable cost in NOK/kWh back to the grid. How big this variable cost is, is decided by formula 5.

$$VC = E \times S \times M \quad (5)$$

Where,

E = Excess energy [kWh]

S = Spot price [NOK/kWh]

M = Marginal loss rate [%]

The customers get less money for their electricity than they have to pay to buy it from the power retailer. This is because the customers have to pay consumer tax and a fee to the energy fund when buying, but not when selling. If customers feel they get too little for their electricity, an alternative can be to store the energy in batteries. This will be discussed in section 6.

5.4 Microgrids

For a group of customers who have a great amount of distributed generation and storage options when needed, a microgrid can be the solution. A microgrid is defined by the U.S. Department of Energy [32] as:

> *A group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. A microgrid can connect and disconnect from the grid to enable it to operate in both grid-connected or island-mode.*

As the definition implies, the microgrid is different from a system that is totally isolated from the grid, because it can operate both connected to the grid and not. If households are connected to microgrids this can have huge impact on the consumption profiles, seen from the grid. It will cause demand to vary for different periods, depending on whether the microgrid is operating in grid-connected or island-mode. There are several advantages with microgrids being interconnected with the grid; like for example excess electricity produced by the microgrid can be exported back to the grid and in case of a fault in the grid the microgrid can continue operation in island-mode.

A solution for electricity production in a microgrid can be that several customers unite and invest in a shared facility, like for example PV. This might be a better solution compared to all the customers having their own unit, because demand can vary. If the unit is shared, a customer with high demand is not limited by the size of his private module. Likewise, the excess production for a customer with low demand can be utilized by someone else. If production is higher than the combined demand from all the customers, the excess energy can be stored in battery facilities.

Microgrids can, especially in urban areas, contribute to sustainability through reduced need for power transmission and distribution and thus reduce the need for transmission capacity in the main grid and distribution network [33]. In rural areas a solution can be to create microgrids that are not connected to the main grid, but it has the option to be connected later. A higher percentage of people that today live without access to electricity can get this with microgrids.

6 Battery Technology

One technology for utilizing distributed generation is batteries. Batteries are a technology that works as a buffer, where locally produced electricity can be stored and used at a later time. The battery can also be charged form the electricity grid, and in places with varying prices the customer can benefit from this by charging the battery when prices are low and discharging when prices are high.

In this thesis one of the batteries available on the market will be used as an example. This is the Powerwall, delivered by Tesla Motors [34]. The Powerwall is a home battery that comes in two sizes: a 7 kWh for daily cycle applications, and a 10 kWh for backup applications. In this thesis the focus will be on the 7 kWh model. The Specs for this battery are listed in Table 6.1.

Table 6.1 Specs for Powerwall [34]

Technology	Wall mounted rechargeable lithium ion battery with liquid thermal control.
Warranty	10 years
Efficiency	92 % round-trip DC efficiency
Power	3.3 kW
Voltage	350 – 450 volts
Current	9.5 amp
Compatibility	Single phase and three phase utility grid compatible
Operating Temperature	- 20 °C to 43 °C
Enclosure	Rated for indoor and outdoor installation.
Installation	Requires installation by a trained electrician. DC-AC inverter not included.
Weight	100 kg
Dimensions	1 300 mm x 860 mm x 180 mm
Price	$3 000

Tesla describes their home battery as follows [34]:

> *Powerwall is a home battery that charges using electricity generated from solar panels, or when utility rates are low, and powers your home in the evening. It also fortifies your home against power outages by providing a backup electricity supply. Automated, compact and simple to install, Powerwall offers independence from the utility grid and the security of an emergency backup.*

Delivery and installation of the first Powerwalls in Norway is expected to be in early 2016. A picture of what the battery looks like is shown below, in Figure 6.1.

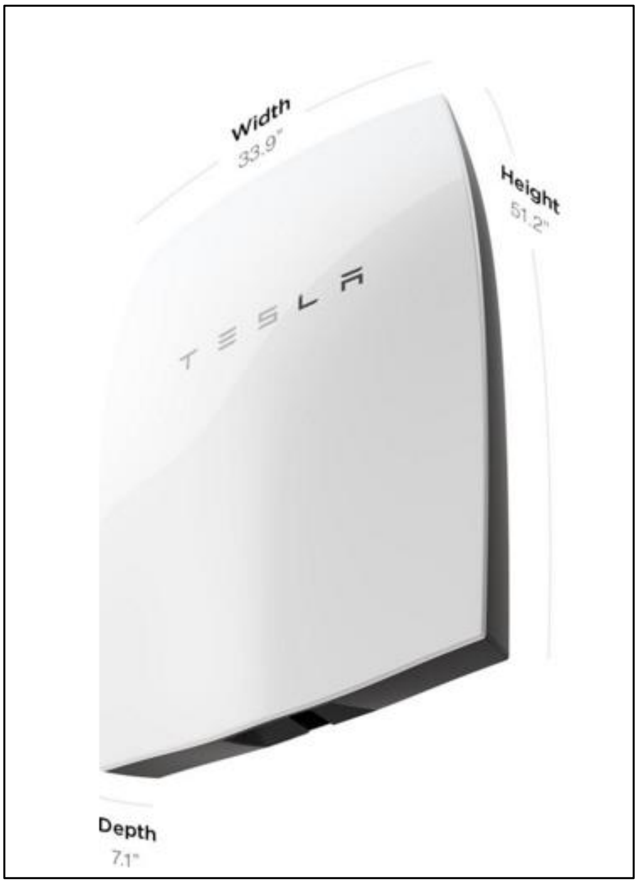

Figure 6.1 Tesla Powerwall [34]

Several Powerwalls can be interconnected to achieve higher capacity. The battery has an operating temperature that starts at -20 °C. This means that on cold days during the winter in Norway, the battery might not work as intended. This is an unfortunate coincidence, considering that the demand often is highest during cold winter days.

The technical specifications of the battery in this analysis have been simplified, and only one example of a possible application is given. The analysis does not consider for example C-rate.

6.1 Example of Battery in a Household

Using a battery in a household may lead to changed consumption profiles for electricity. In this thesis the focus will be on two different scenarios and ways to utilize battery technology in households. The first is to see if it is possible to even out electricity demand from the grid, to avoid high peak load. The other scenario is to see if it is possible to be self-powered by local generation, like for example PV. This will be discussed in section 7.2.

As Table 6.1 shows, the battery has a capacity of 7 kWh, and a power of 3.3 kW. This means that the battery can deliver 3.3 KW for approximately 2 hours during maximum demand, given that the battery is fully charged. In this analysis the goal has been to even out the electricity consumption from the grid. The battery has been charged when demand is low, and discharged to avoid high peaks. Customer 12 in week 15 has been used in this scenario. It is assumed that the battery has 0 kWh on Monday morning and 0 kWh again at the end of Sunday evening. The analysis has been performed manually in Excel, and a more advanced program would perhaps give a better utilization of the battery. The use of the battery during this week is only meant to show an example, and is considered to be an acceptable estimate of how a battery can be used. Figure 6.2 shows what the average hourly consumption looked like in this week with, and without the Powerwall battery.

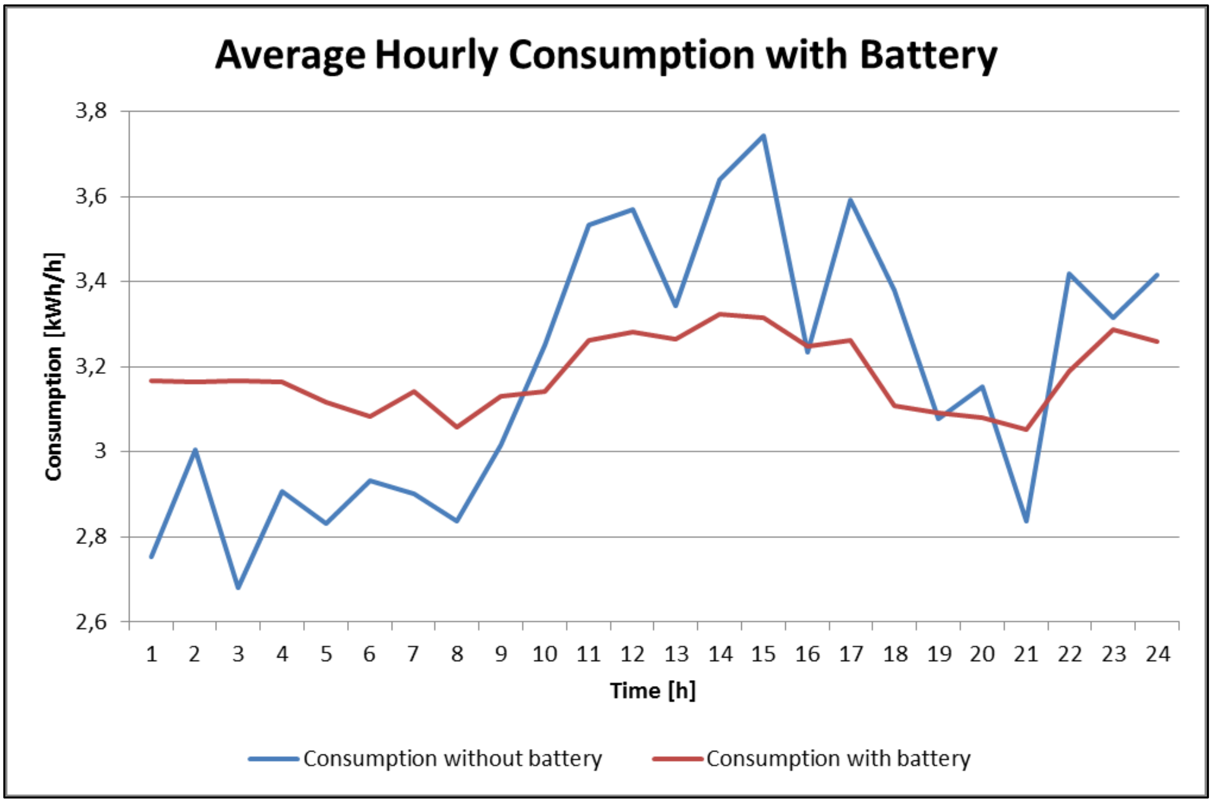

Figure 6.2 Average hourly consumption with battery in week 15

As the figures shows, consumption has been increased in periods that previously had low demand and decreased during peak load. Figure 6.3 shows what the battery's demand looked like. The figure shows that the battery usually charges early in the morning and discharges during day time and in the afternoon. This goes well together with how the demand profile in the grid looks, as shown for example in Figure 3.3.

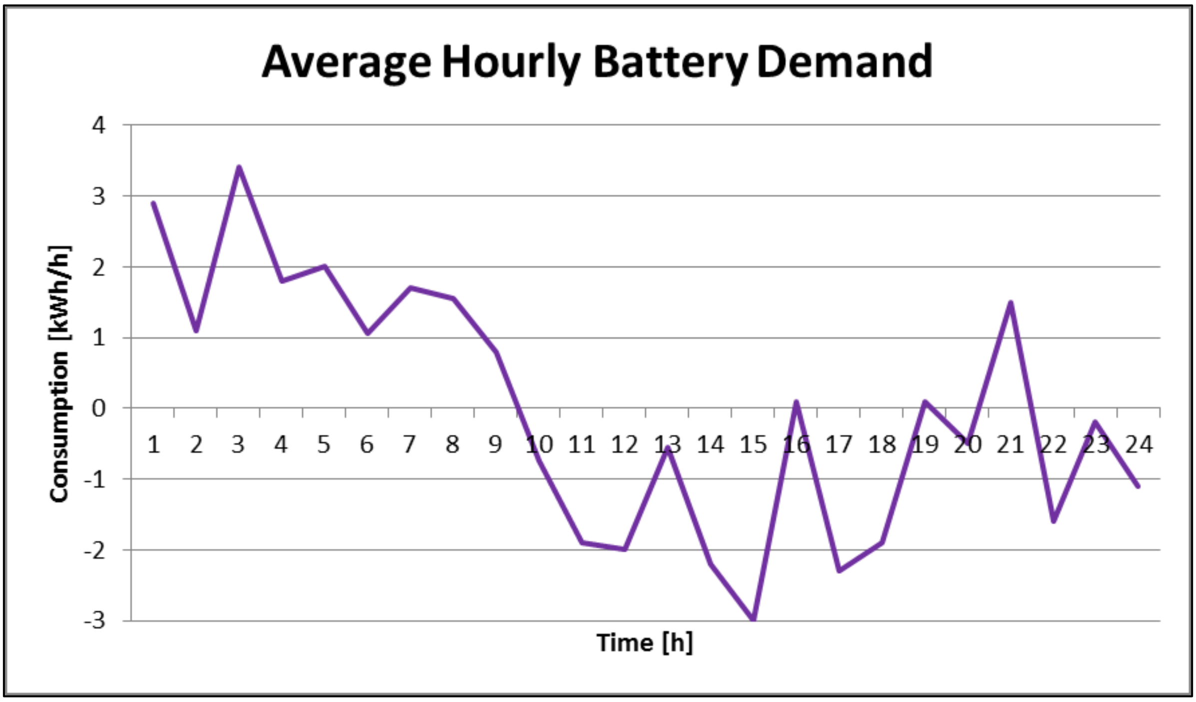

Figure 6.3 Average hourly battery demand in week 15

Figure 6.4 shows the consumption for the whole week. This figure demonstrates that the power peaks are reduced because of the battery.

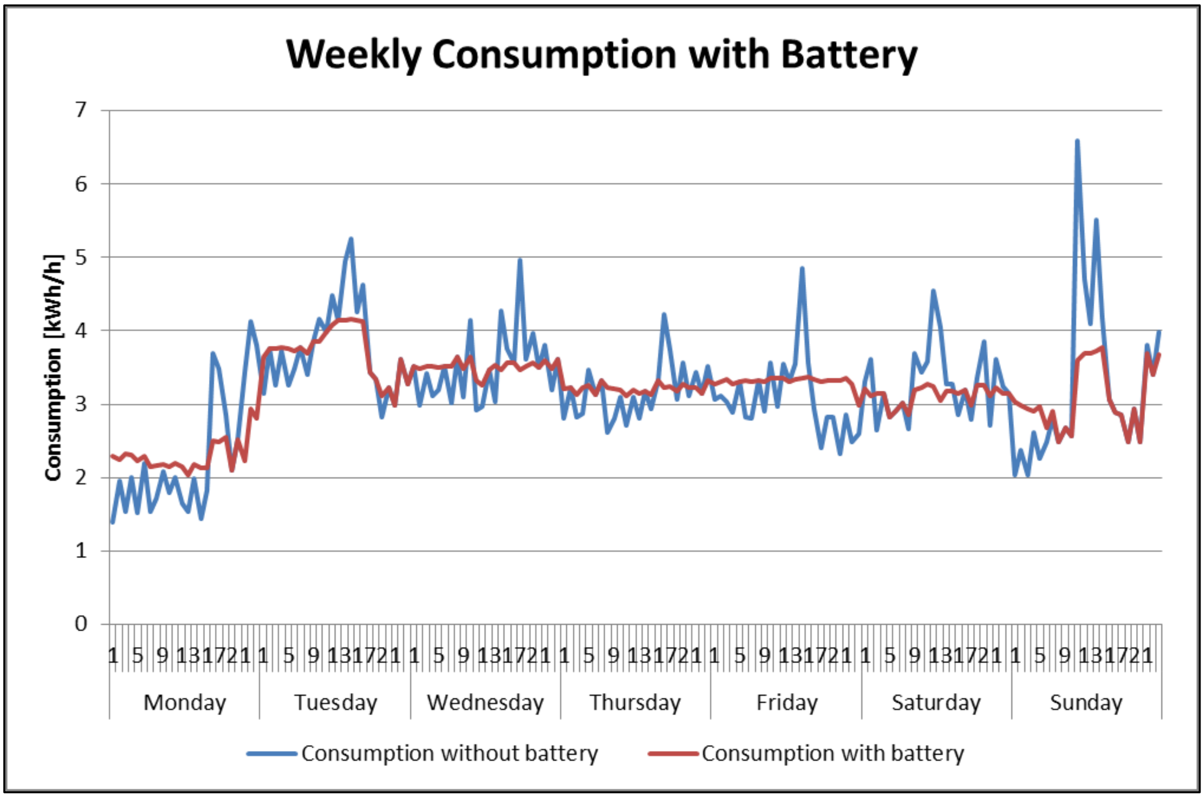

Figure 6.4 Weekly consumption with battery in week 15

If the battery had greater capacity than 7 kWh it would have been possible to level out the demand even more. As Figure 6.4 shows, the peaks are significantly reduced compared to how they were without the battery. This is despite that the Powerwall only can deliver 3.3 kWh/h. Figure 6.5 shows the battery's demand during this week. Positive numbers occur when the battery is charging from the grid and negative when it discharges. The figure shows that the battery rarely charges or discharges more than 1 kWh/h at any time during this week. If this analysis was performed for several customers, and for longer time periods, the demand graphs in Figure 6.3 and Figure 6.5 would probably be more evened out. All these figures also show that the battery can work both as a load and a generator in the grid.

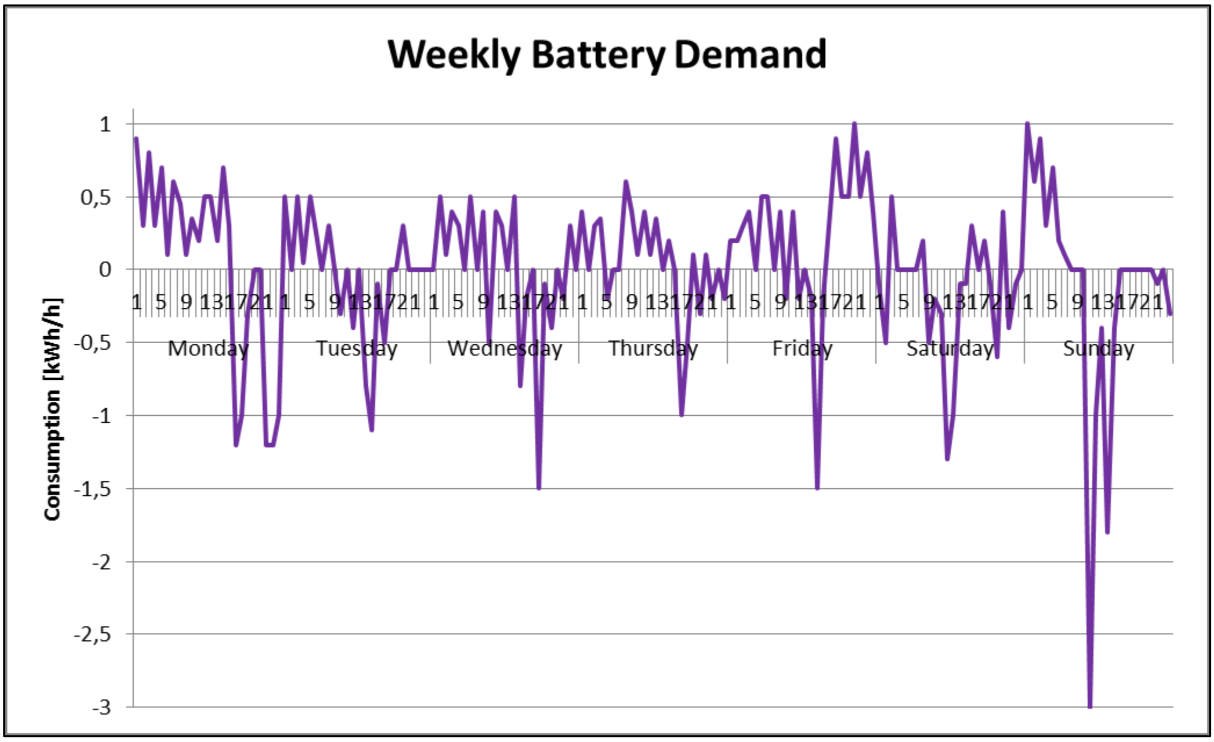

Figure 6.5 Weekly battery demand in week 15

Household batteries are not a widespread technology that is used in Norway. The main reason for this might be that this type of battery is considered to be expensive. Prices are going down [15], and this is likely the key factor to whether or not household batteries will become more common. As discussed in section 5.3, customers get less money from selling electricity back to the grid than they pay for selling it. This is perhaps the main reason why battery technology in combination with distributed generation can be profitable.

Looking at a household with the PV module from section 5.1.2, the profitability of installing a Powerwall is evaluated. The PV module produced about 3 300 kWh during 2013. Assuming that the household uses half of this energy, about 1 600 kWh is excess energy that can be sold back to the grid or stored in a battery. The value of the electricity is about 0.8 NOK/kWh, which is the price the customer has to pay to buy the electricity [35]. This includes the actual price of the electricity, network tariffs and surcharges. If the customer sells the electricity to the grid he only gets payed the electricity price, which is around 0.25 NOK/kWh [35]. The actual value of the electricity for the customer is then 0.55 NOK/kWh. The customer can potentially save 0.55 NOK/kWh × 1 600 kWh = 880 NOK per year. With a lifespan of 10 years this gives 8 800 NOK. Considering that the price of the Powerwall is around 26 000 NOK[2] this does not seem like a profitable investment.

As section 4 presented, the Tesla Model S has a battery of 85 kWh. The Powerwall is small in relation to this. The possibility for vehicle-to-home (V2H) exploitation of EV batteries could mean interesting things for future consumption profiles. This will only be discussed briefly in this thesis, in section 7.2. It could especially be interesting in situations with long blackouts, due to for instance extreme weather.

In section 7 the Powerwall will be used to predict future scenarios for consumption profiles. Just like in this section it will only be an example of how the battery can be used. The full utilization with this technology will be better obtained by using a better analyzing tool or different program than Excel.

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[2] 1 USD = 8.65 NOK (02.12.2015)

7 Possible Future Scenarios

In this section the different technologies discussed in section 4 to 6 will be used to present possible scenarios for consumption profiles for future households. The main focus will be on three technologies: PV, batteries and electric vehicles and different combinations of these. The customer from section 3.1 will be used as an example, and the week that is investigated is still week 15.

7.1 PV and EV

Section 4 looked at what the consumption profile for customer 12 would look like in week 15 if this customer had a Tesla Model S, which was charged according to the fictional activities during the week. In this analysis the customer also has the PV module from section 5.1.2. The PV supply is subtracted from the customer's demand. Figure 7.1 shows the weekly consumption profile with an EV, both with and without the PV module.

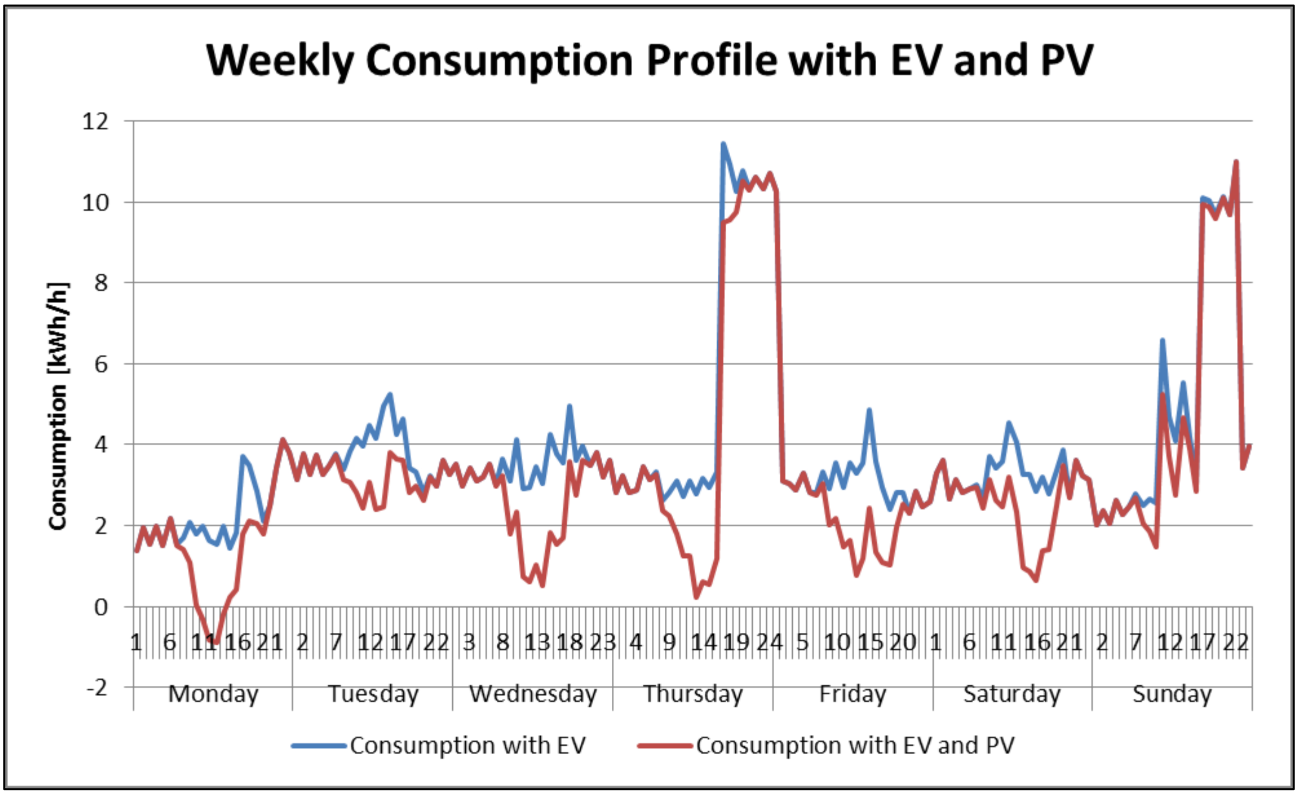

Figure 7.1 Consumption with EV and PV in week 15

The only difference in the customer's demand when having PV and an EV compared to not, is when the vehicle charges on Thursday and Sunday afternoon. The EV charges in the afternoon and the PV supply is small or absent during these hours. Therefore, having a PV panel will not affect the consumption profile for a household with an EV significantly. If the

EV was charged during daytime when solar insolation is at its highest, the profile would look different. If the EV was charged with a lower power, like the Nissan Leaf, the PV would contribute more if the vehicle was charged while the PV supplied electricity.

One way to solve the problems that occur regarding timing is to use a battery to store the solar energy. This will be discussed in the next section. Having both a battery, PV and an EV will be discussed in section 7.4.

7.2 PV and battery

The PV system is this section will be the same as in the previous, and the customer's battery will be the Powerwall from section 6. The goal for the analysis was to use all the electricity produced by the PV module in the battery, so that the battery never charges from the grid. The total energy supply from the PV module was 120 kWh for this week, which gives an average of more than 17 kWh per day. The capacity of the battery is 7 kWh and as the figures below will show, the supply was during daytime sometimes more than the battery could store. This caused very low demand during daytime for some days. If the customer had a bigger battery this electricity could have been stored and used later in the day. Nevertheless, the battery can maximize the usefulness of PV panels, as it allows a more smooth consumption profile than only having PV. This is because produced electricity from PV can be evened out over the day, and not only used when The Sun shines. Figure 7.2 shows what the demand during the week looked like with the 7 kWh battery and Figure 7.3 shows the average hourly demand in the same week.

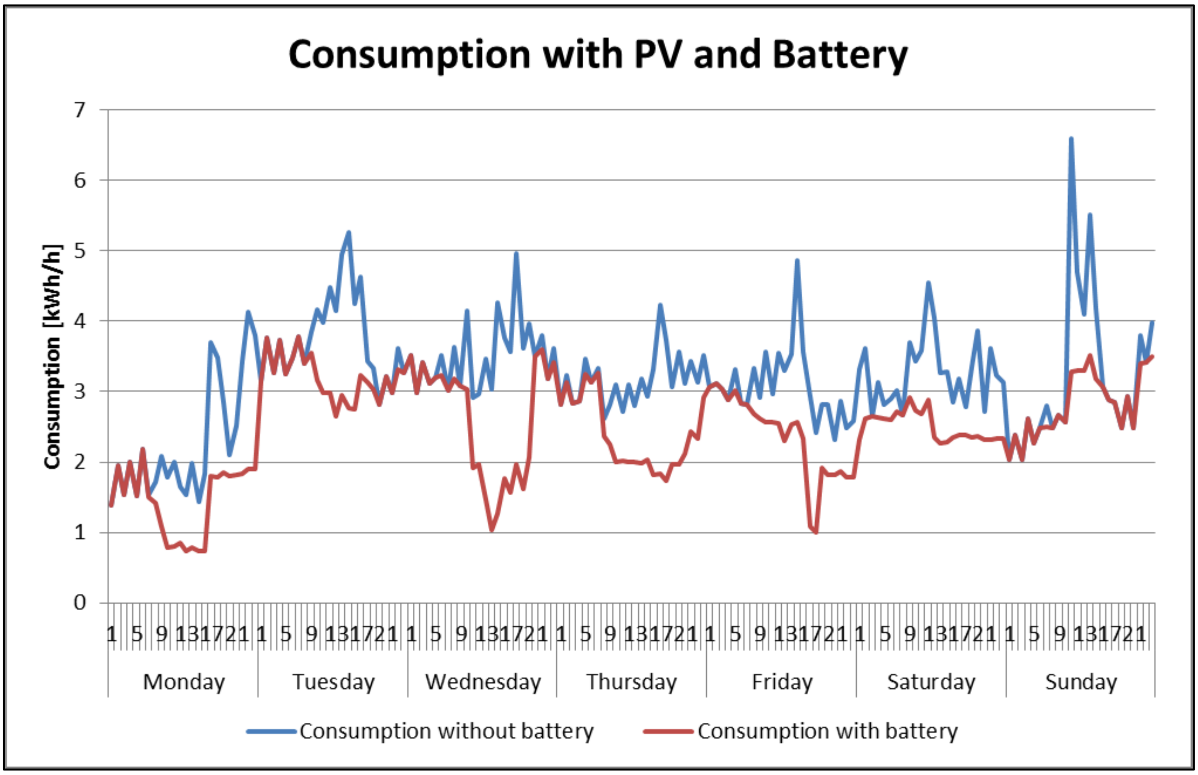

Figure 7.2 Consumption with PV and battery in week 15

Figure 7.2 shows that the peak demand can be considerably reduced with the use of PV and battery technology. The battery was only charged by the PV supply, so the total energy demand from the grid was reduced by 120 kWh during this week. With the battery this customer does not export electricity to the grid on Monday like before.

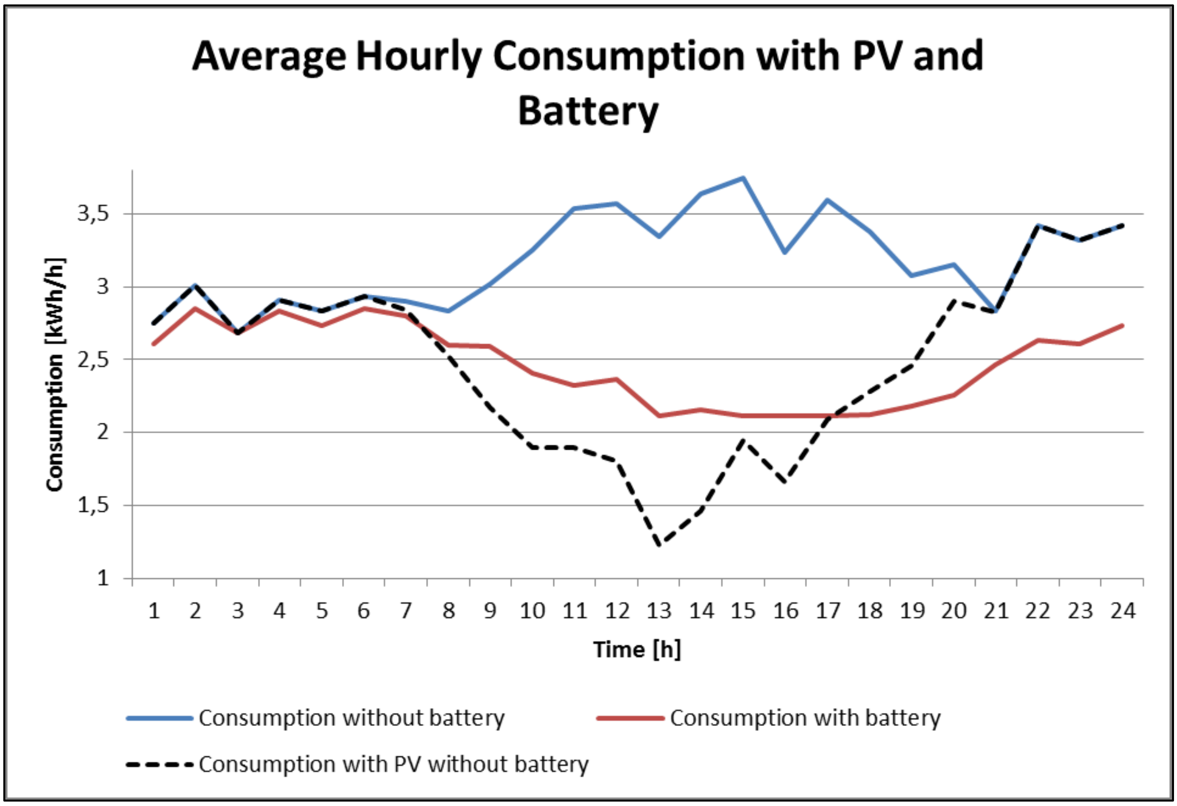

Figure 7.3 Average hourly consumption with PV and battery in week 15

As Figure 7.3 shows, the average hourly demand in this week has changed a lot. The black line shows what consumption with PV looked like before the battery was installed, when the production from the PV was subtracted from the demand. Without the battery the PV only contributes to the consumption profile when there is access to sunlight, but with the battery the energy can be utilized during the evening or early morning. The biggest problem with the system in this analysis was that the PV production during daytime was too high, compared to the storage capacity in the battery.

To compare opportunities, Figure 7.4 shows the consumption profile for the same week, but with a battery of 85 kWh. It was assumed that the SOC Monday morning was 0.5 i.e. 42.5 kWh. The power for this battery is also set to 3.3 kW, like the Powerwall.

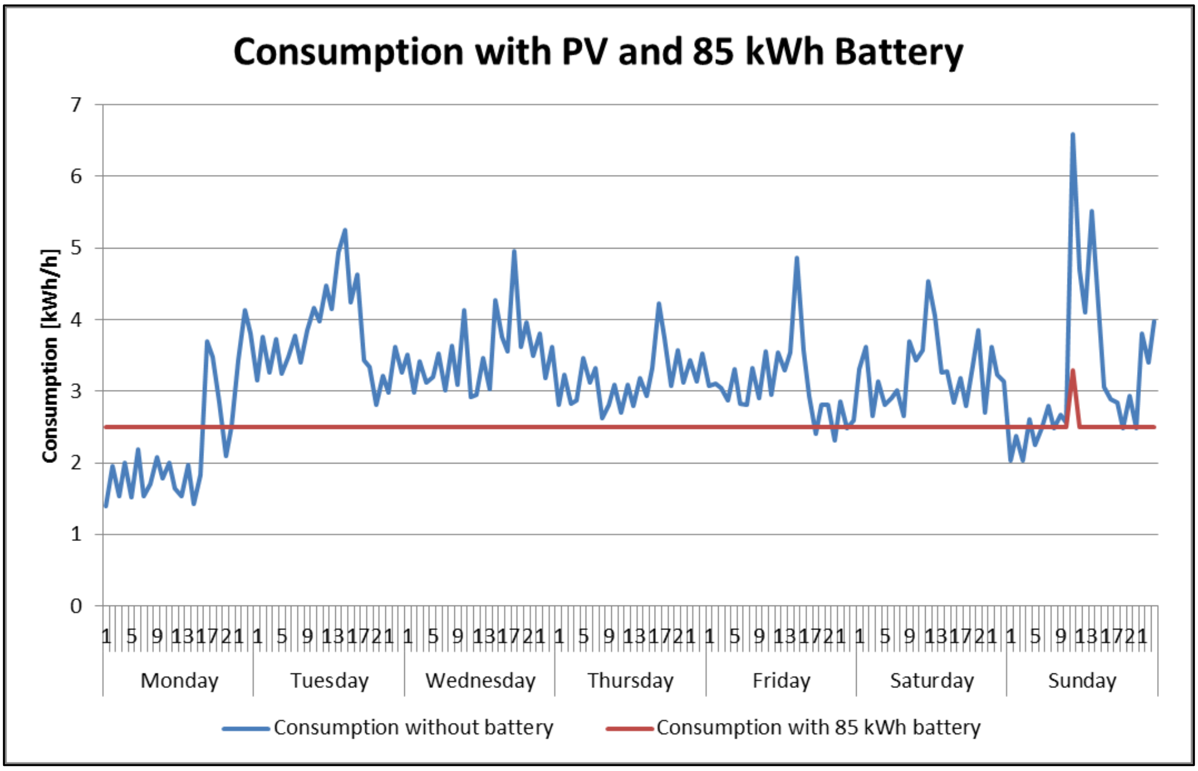

Figure 7.4 Consumption with PV and an 85 kWh battery in week 15

As this figure shows, the potential for load leveling is great through a battery with big capacity. The average demand during this week was 2.5 kWh/h, except for one hour on Sunday when the demand was 3.29 kWh/h. This small peak could have been avoided with higher power on the battery. The total energy demand during this week was 114 kWh lower than the customer's original consumption without PV or battery. The capacity of the battery was 47.5 kWh on Sunday evening, so the customer ends the week with more capacity in the battery than on Monday morning.

The Tesla Model S has a battery capacity of 85 kWh, and is the basis for this analysis. In this example the vehicle has not been used for driving, but only as a home battery in a V2H solution. V2H is not a widespread technology, but as the figure shows it could have great potential. The battery of the Tesla Model S is more than ten times the size of the Powerwall. In case of a blackout this battery would be able to keep the house operating for a longer time, compared to the 7 kWh battery. It would also keep peak demand low, which would be interesting regarding new tariffs, which will be discussed in section 8.

This section was also supposed to investigate the possibility to be self-powered with local generation by using the Powerwall. As the total demand during this week was 535 kWh and the production from the PV was 120 kWh, this is not possible. If the goal is to get this household self-powered by local energy production, two things need to be in place; the house needs to produce more energy and it needs to reduce demand. This can be done by installing different energy sources, such as solar collectors or a heat pump. Demand, especially from space heating, can be reduced by isolating the house, or change to better windows.

7.3 EV and battery

This section takes a look at what consumption will look like for a household that has an EV and a battery. The EV is a Tesla Model S and the battery is a Powerwall. The EV is used in the same way as it was in section 4.2 and the battery is used to try to reduce peak demand as much as possible. The result is shown in Figure 7.5.

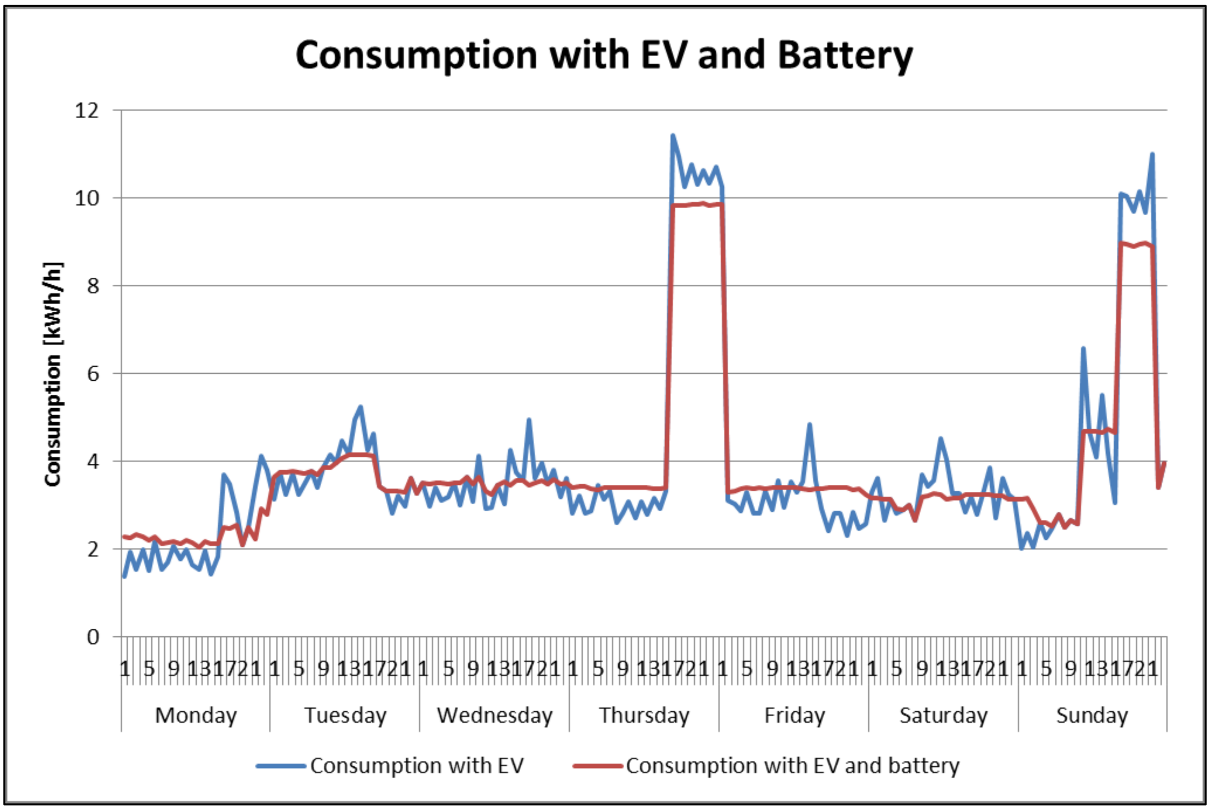

Figure 7.5 Consumption with EV and battery in week 15

The consumption is quite similar to what was seen in Figure 6.4 in section 6.1, when the customer only had a battery. The difference is on Thursday and Sunday evening, when the EV charges. The goal was to have the battery fully charged when the EV was plugged in, to maximize the effect of having a battery. As the figure shows, the battery does not have enough capacity to really reduce the peak load. The peaks are slightly reduced, but not enough to make a great difference. In general, the consumption was more leveled out and short peak demand for some hours was avoided.

The battery demand during the week can be seen in Figure 7.6.

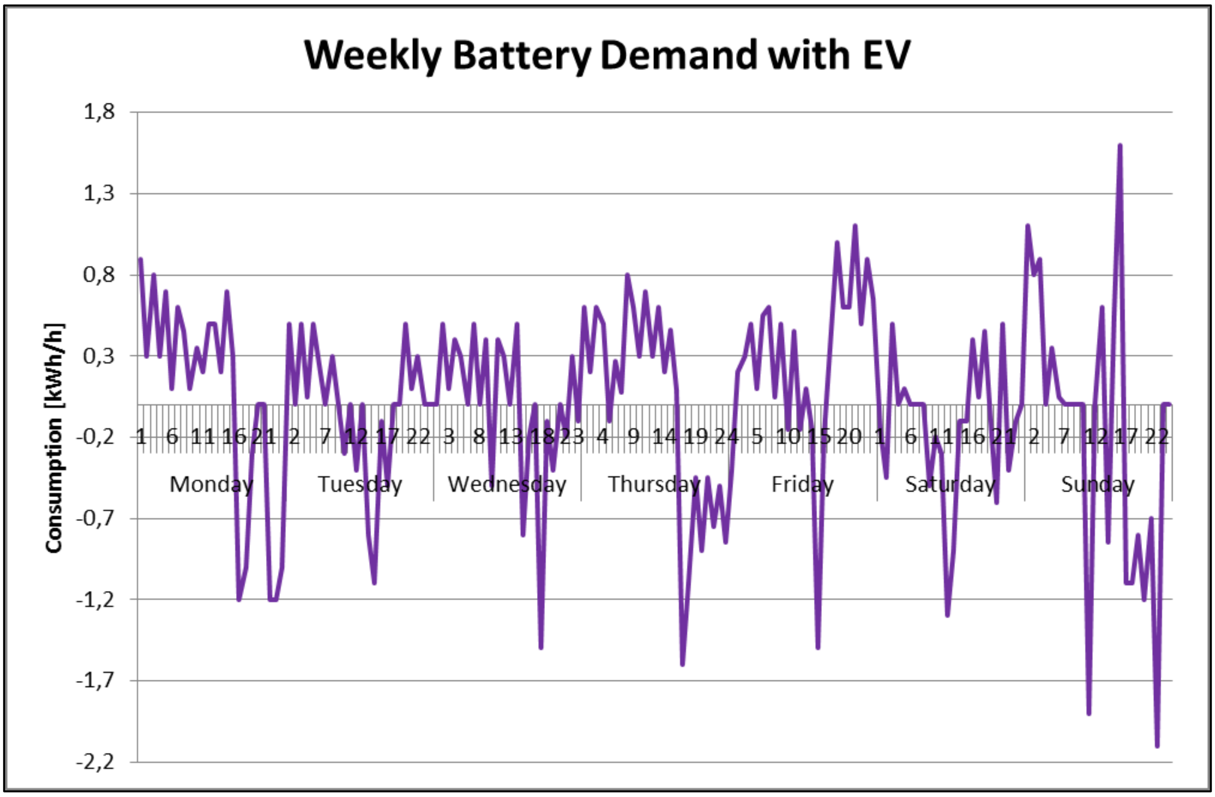

Figure 7.6 Weekly battery demand with EV in week 15

As the figure shows, the battery demand when having an EV is quite similar to not having an EV, except for some extra use of the battery while the EV charges on Thursday and Sunday. The battery demand without an EV is shown in Figure 6.5.

7.4 PV, EV and battery

In this section the customer will have an EV, a battery and PV modules on the roof. The weekly consumption profile is shown in Figure 7.7.

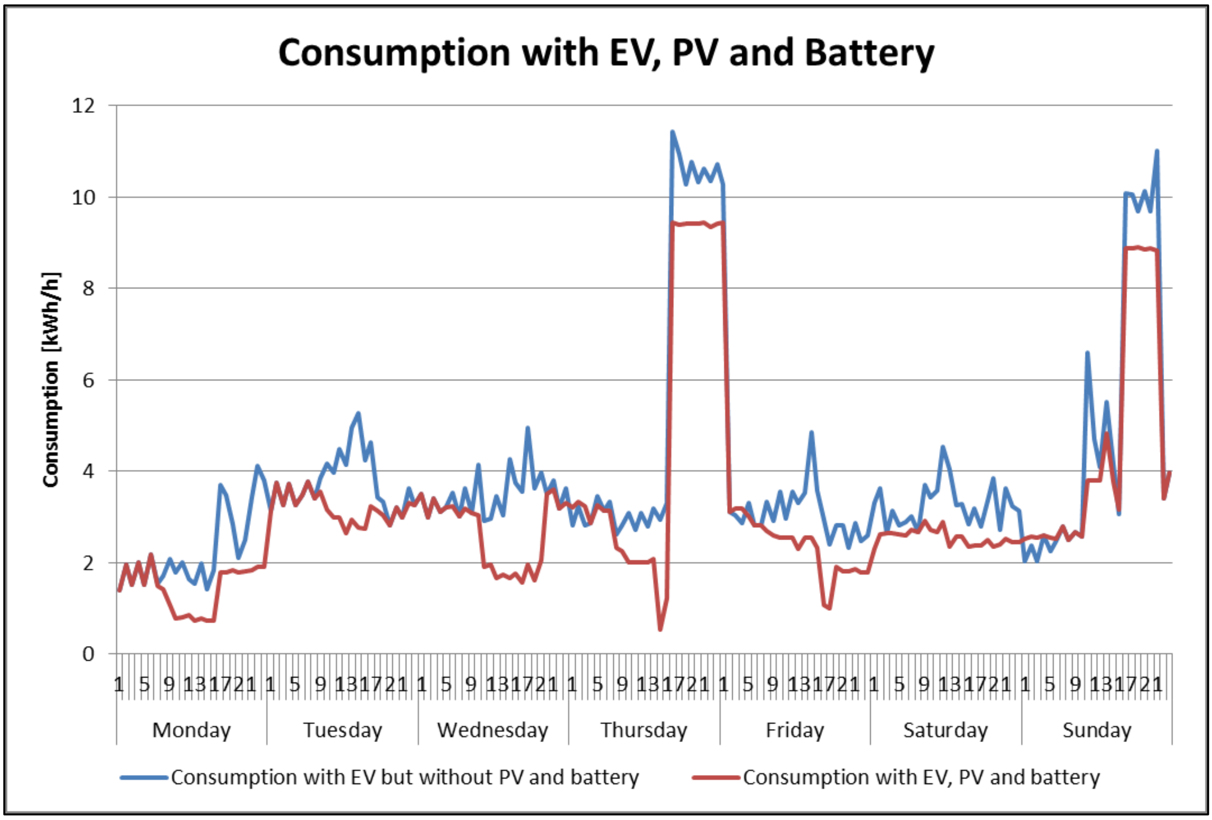

Figure 7.7 Consumption with EV, PV and battery in week 15

This figure is quite similar to Figure 7.5, which showed consumption for a household with an EV and a battery, but without the PV. The only major difference is that demand is reduced during daytime because of the PV. The peak demand on Thursday is also slightly reduced, compared to a system without PV. The peak demand because of EV charging is still high, compared to the demand for the rest of the week. There are two main reasons why it is hard to reduce these peaks. First of all, the demand is at hours when there is little solar insolation and hence little PV supply. This energy could be set aside by a battery that saves energy and discharges when it is needed. Yet, the second problem is that the battery has too little capacity, compared to the demand. It also needs to have greater power, to be able to handle the peak load from charging a Tesla Model S.

In section 7.2 the battery was only charged by PV. To be able to utilize the maximum effect of having a battery, the battery in this section is also charged from the grid when it is needed. Figure 7.8 shows the battery's demand during the week.

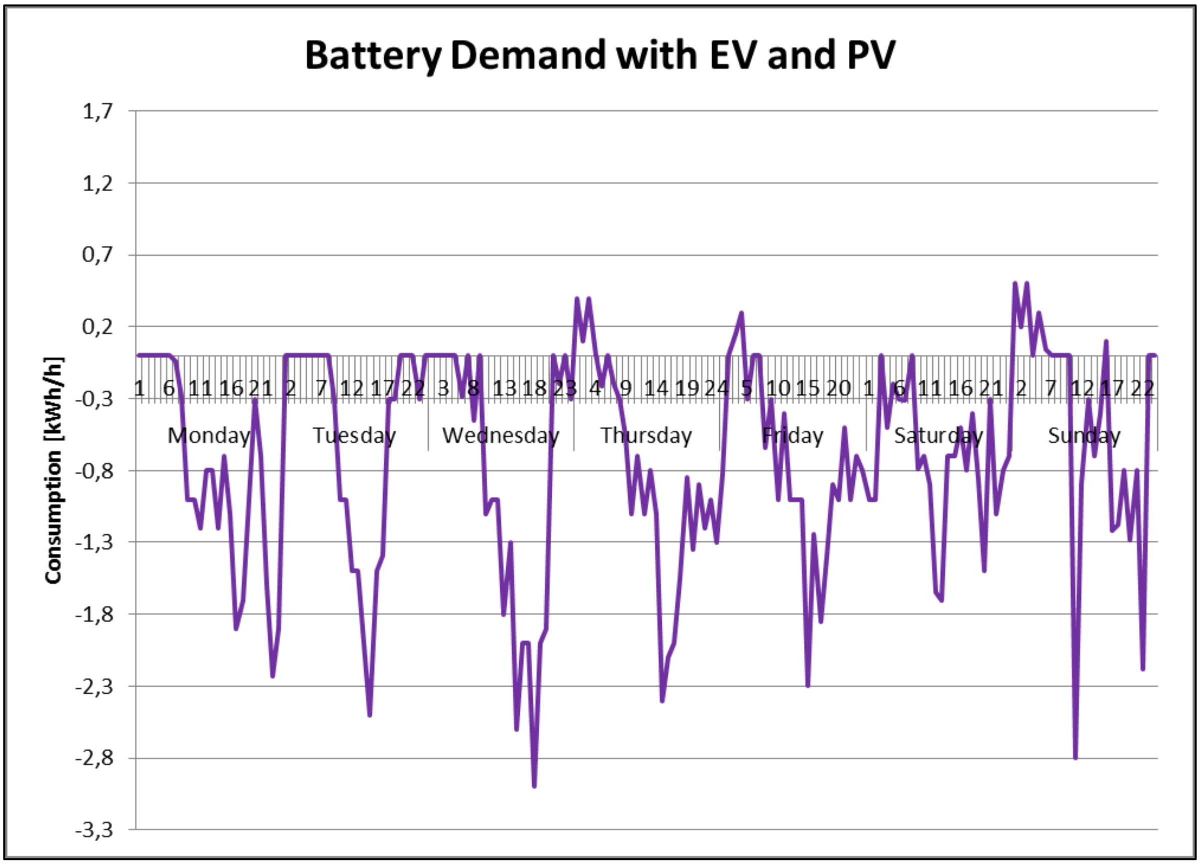

Figure 7.8 Battery demand with EV and PV in week 15

As the figure shows, the battery barely charges from the grid and the demand is never more than 0.5 kWh/h. This is because the battery usually is charged by PV supply. The battery never discharges more than 3 kWh/h despite that the rated power is 3.3 kWh/h. This is because the capacity of the battery only is 7 kWh. If the battery discharged 3.3 kWh/h the capacity would only last for about two hours. Since the power demand while charging the EV lasts for 6 and 9 hours the goal has been to reduce the average peak demand for these hours as much as possible.

7.4.1 Daily EV Charging with PV and Battery

When using the scenario from section 4.2.1, when the EV charges every day, the weekly consumption profile looks a little different. The consumption in week 15 with PV and a battery is shown in Figure 7.9.

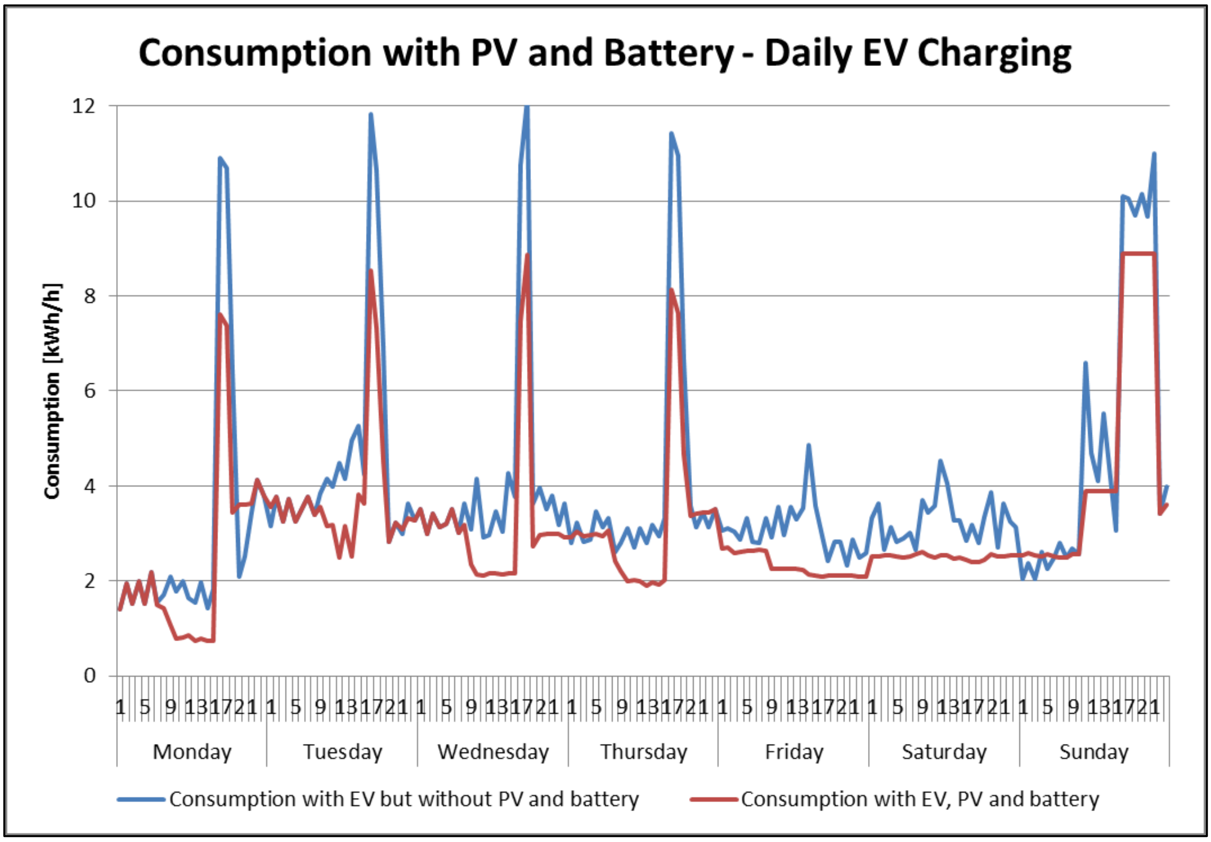

Figure 7.9 Weekly consumption profile with daily EV charging, PV and battery

The high demand only lasts for a short while. Because of this, the battery is able to deliver 3.3 kWh/h for the entire charging period. This reduces the peaks more than when the EV was charged only two times during the week, like in Figure 7.7. When charging the EV daily, the battery is charged slightly more from the grid. The battery demand can be seen in Figure 7.10.

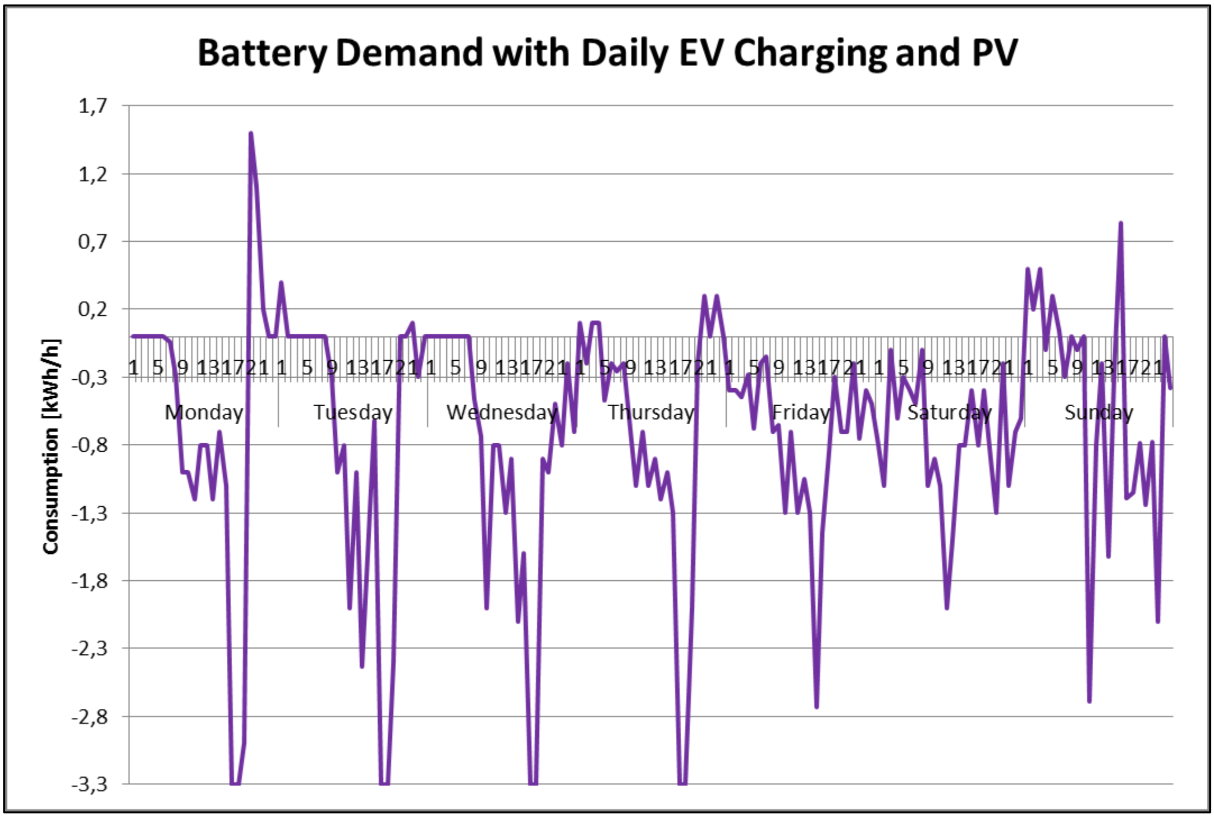

Figure 7.10 Battery demand with daily EV charging and PV in week 15

As Figure 7.10 shows, the power capacity of the battery is more utilized, compared to what it was in Figure 7.8. Now the battery discharges at maximum power of 3.3 kWh/h several times. This helps reduce the peak load.

8 Tariffs to Reduce Peak Load and Increase Utilization Time

One measure to reduce peak load and increase utilization time can be to change a customer's grid related costs by changing network owner tariffs. NVE has published a hearing regarding tariffs for withdrawals in the distribution network [36]. The goal of this hearing has been to get a more cost-efficient allocation of the grid related costs. The tariffs should contribute to efficient exploitation of the already existing grid and contribute to the right investments in the electricity grid, consumption, production and alternative energy sources [36]. The hearing suggests and shortly evaluates several proposals for new tariffs for customers in the distribution network. Some of the proposals in the hearing, in addition to some new, are evaluated in section 8.1 to 8.4 of this thesis. The new tariffs are compared with today's arrangement to see how the various tariff structures provide different incentives for electricity consumers.

The Norwegian power system is deregulated, so the DSO and the power retailer are two separate entities. As a result of this, customers need two separate contracts; the network tariff to pay for their use of the grid and another contract for their energy use [37]. This contract is between the customer and a power retailer which is free of choice. The power retailers can offer a set of different contracts for the customers, such as spot price contracts or fixed price for given time periods. This section only takes the network tariff into consideration.

All customers connected to the distribution grid are bound to the local network owner, the DSO. The customers pay a fee to the DSO, henceforth referred to as network tariff. The revenue for each company is regulated by NVE and the tariffs are set to cover the costs. The DSO's costs are driven by the installed grid capacity, which is the maximum amount of electricity flow that the distribution grid needs to deal with, and not by variations in the distributed volumes of electricity [18]. There are some variations in how the network tariff is composed for the different DSOs, due to regional differences such as population density and topography. A DSO in an area with high population density usually has lower costs than a company operating in an area with scattered population, due to cable costs for large distances. The most common tariff design is a volumetric tariff. It has a fixed yearly cost and a variable cost associated with the volume of consumed energy. The variable cost can be different for winter and summer season, or constant throughout the year and it is meant to reflect the costs of using the grid. Heat is developed as electricity is transferred, which causes losses in the grid. In the existing tariff, the variable energy cost is higher than the actual loss expense. This might cause electricity to be compared unfortunate to alternative energy sources. The high variable cost also implies that customers using energy efficient but power demanding equipment contribute less to the grid related expenses. Table 8.1 shows the average network tariff in 2015 for all the counties in Norway, including VAT.

Table 8.1 Tariffs in 2015 sorted by county [38]

County	Fixed cost [NOK/year]	Variable cost [NOK/kWh]
Østfold	1 801	0.388
Akershus	8 98	0.395
Oslo	750	0.401
Hedmark	3 682	0.364
Oppland	3 868	0.341
Buskerud	1 801	0.418
Vestfold	2 500	0.334
Telemark	2 816	0.388
Aust-Agder	1 438	0.464
Vest-Agder	1 438	0.464
Rogaland	1 935	0.355
Hordaland	1 882	0.378
Sogn og Fjordane	2 665	0.537
Møre og Romsdal	2 515	0.398
Sør-Trøndelag	1 908	0.437
Nord-Trøndelag	2 500	0.428
Nordland	2 816	0.331
Troms	1 380	0.308
Finnmark	2 891	0.214
National average	1 968	0.385

Later in this section, the new tariff proposals will be compared with the current tariff model. As all the examined customers are situated in Nord-Trøndelag, the price from this county is used. In Nord-Trøndelag, the network owner is Nord-Trøndelag Elektrisitetsverk Nett AS (NTE). NTE's tariff for household customers in the distribution network is called NH4. For 2015 NH4 has a fixed cost, C, of 2 500 NOK/year and a variable cost, β, of 0.4281 NOK/kWh. The variable cost includes consumer tax of 0.1706 NOK/kWh and a fee to the energy fund of 0.0125 NOK/kWh [39]. Formula 6 is used to calculate a consumer's yearly total cost with the NH4 tariff.

$$TC_{NH4} = C + \sum_{i=1}^{12} \beta \times W_i \tag{6}$$

Where,

C = Fixed yearly cost [NOK/year]

β = Variable energy cost [NOK/kWh]

W_i = Consumed energy in month i [kWh]

For a customer with a yearly consumption of 20 000 kWh the network tariff will be:

$$TC_{NH4} = C + \sum_{i=1}^{12} \beta \times W_i = 2\ 500\ NOK + 0.4281 \frac{NOK}{kWh} \times 20\ 000\ kWh = 11\ 062\ NOK$$

This gives an average monthly cost of about 922 NOK.

In the numerical analysis below, the hourly consumption during 2013 for the 24 customers is examined. The total electricity consumption for each of the households during 2013 is shown in Figure 8.1.

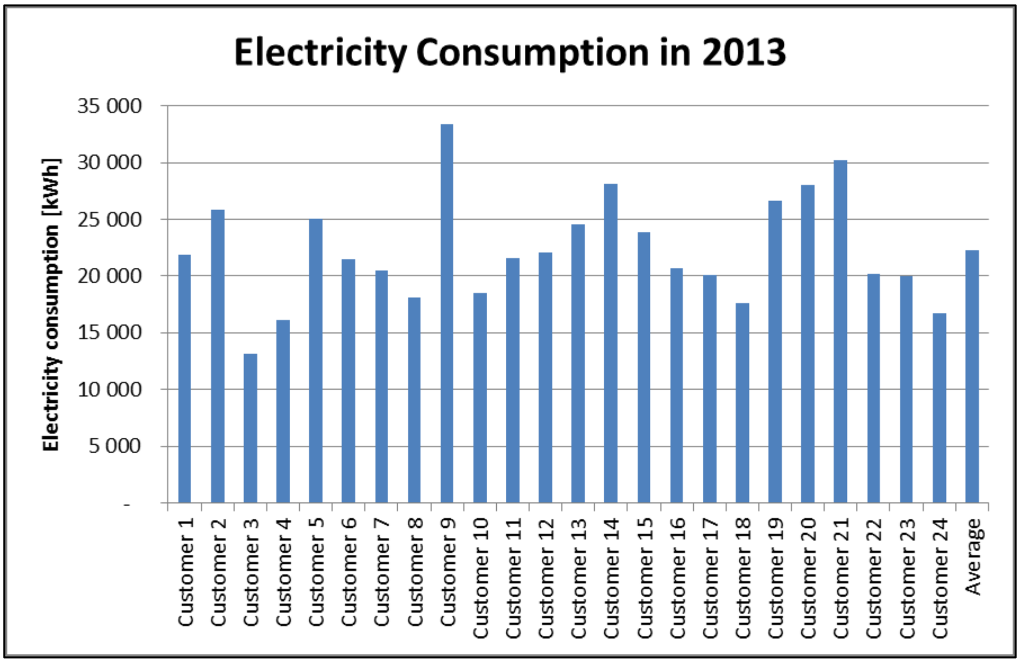

Figure 8.1 Customer electricity consumption in 2013

The customer with the lowest consumption is customer 3, with a yearly consumption of 13 130 kWh. The customer with the highest consumption is customer 9, with 33 344 kWh. Using formula 6, this energy consumption results in a yearly network tariff for 2013 as shown in Figure 8.2.

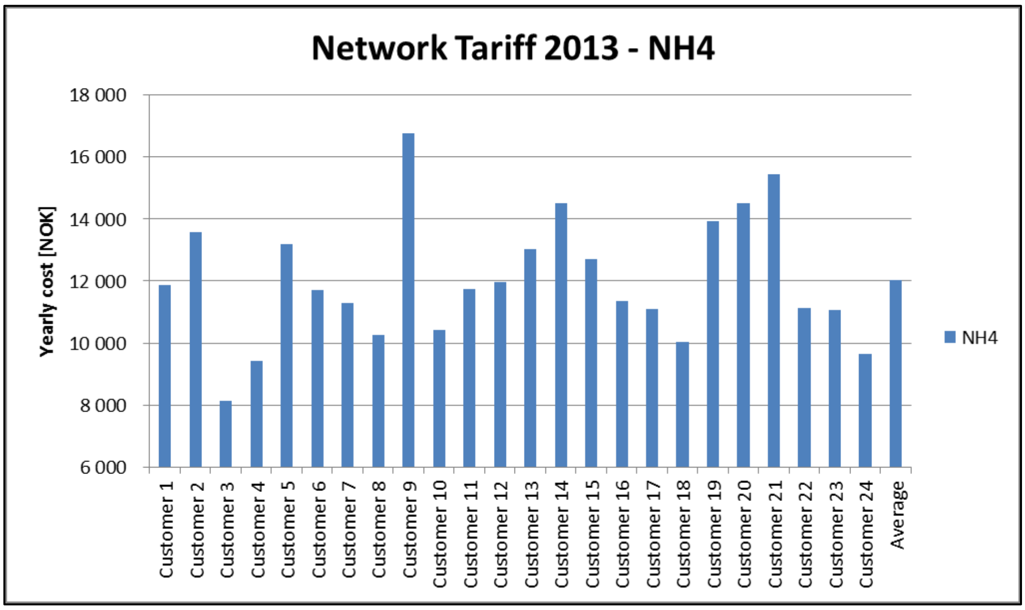

Figure 8.2 Customer network tariffs in 2013

As Formula 6, Figure 8.1 and Figure 8.2 shows, NH4 gives a cost that is directly related to energy consumption. This is clear as both the figures have exactly the same shape. This is not necessary the case for the new tariffs that will be discussed.

In each of the new suggested tariffs, the goal has been to minimize the difference in the DSO's income from the old and the new tariff, and to allocate the costs where they belong. In other words: the prices are calculated to give the average customer the same costs if this customer does not change consumption pattern. The different prices have been found by looking at the DSO's total income from all the 24 customers. The shown prices are examples of how the tariffs can be designed, and are only based on consumption during 2013. In order to find more accurate prices, more data and information will have to be examined. The consumption can vary from year to year, and to find more correct prices, additional customers and data from several years will have to form the basis for the prices. However, these examples are considered to give a good picture of how the tariffs can be designed and show differences between the various suggested tariffs.

Table 8.2 New suggested network tariffs

Code	Name
NT1	Subscribed Power Tariff
NT2	Peak Demand Tariff
NT3	Peak Demand in the Grid Tariff
NT4	Coincidence Factor Tariff

All the new tariffs have some similarities to each other and to NH4. All the tariffs have a fixed cost, *C*, similar to NH4, of 2 500 NOK/year. *C* is supposed to cover at least customer specific costs. All the tariffs also have a variable energy segment, β. This segment is meant to cover at least the marginal costs for network losses. Included in β is consumer tax of 0.1706 NOK/kWh and a fee to the energy fund of 0.0125 NOK/kWh. In addition, the expenses the network owners experience by transporting the energy is included. This is found by a very simple estimate: The average energy price in 2013 for area NO3 in NordPool was 303.43 NOK/MWh [40]. It is assumed a loss of 10 per cent during transportation, which gives a marginal loss cost of 0.030343 NOK/kWh. All these elements combined give an energy segment β of 0.2135 NOK/kWh.

The hearing published by NVE also includes tariffs that are not discussed in this thesis. One of the tariffs discussed is a tariff based on fuse size. This tariff is based on customers paying for a given fuse size, which would physically limit the power demand in a household. This could possibly create dangerous situations, as people reduce their fuse size to minimize expenses. It would also require that the DSO at all times has information about fuse sizes for all the customers. This would be time consuming, considering that this information is not readily available. Another tariff is the Time of Use (ToU) tariff. This tariff has predefined peak load periods when constraints in the network and hence high prices are expected. These time periods are usually during the morning and afternoon and the customers have to pay more for their demand during these hours. This can help shift demand from peak load to periods with low demand. Other tariffs could also have been included in the analysis, but the main point of the analysis has been to look at what incentives and price signals changed network tariffs can do to change future consumption profiles. The four chosen tariffs are considered to give a good picture of this.

8.1 NT1 – Subscribed Power Tariff

NT1 or subscribed power is a tariff that is individual for each customer. All customers must find a power limit that represents their necessary peak power demand. If customers at any time have a higher power demand than their subscribed power demand, they have to pay an overconsumption fee for the excess energy. The customer pays two fixed costs: C and a charge, λ, per subscribed kW power demand. The variable costs are divided into two: the energy segment β per kWh and the overconsumption segment δ per kWh of consumption above the subscribed power. The yearly costs are calculated using formula 7.

$$TC_{NT1} = C + \lambda \times E_{\lambda} + \sum_{i=1}^{12} (\delta \times O_i + \beta \times W_i) \tag{7}$$

Where,

C = Fixed costs [NOK/year]

λ = Cost for subscribed power [NOK/kW]

E_{λ} = Subscribed power [kW]

δ = Cost for overconsumption [NOK/kWh]

O_i = Overconsumption in month i [kWh]

β = Energy segment [NOK/kWh]

W_i = Consumed energy in month i [kWh]

The goal is to keep the network owner's revenue constant. The following prices are used and they give the network owner decreased revenue of 12 NOK/year for the relevant year:

C = 2 500 NOK/year

λ = 610 NOK/kW

δ = 6.67 NOK/kWh/h

β = 0.2135 NOK/kWh

The subscribed power demand for each of the customers in this analysis is set to be the same as in a field trial of this tariff during 2014, as shown in Figure 8.3. This study is briefly discussed in section 8.1.1.

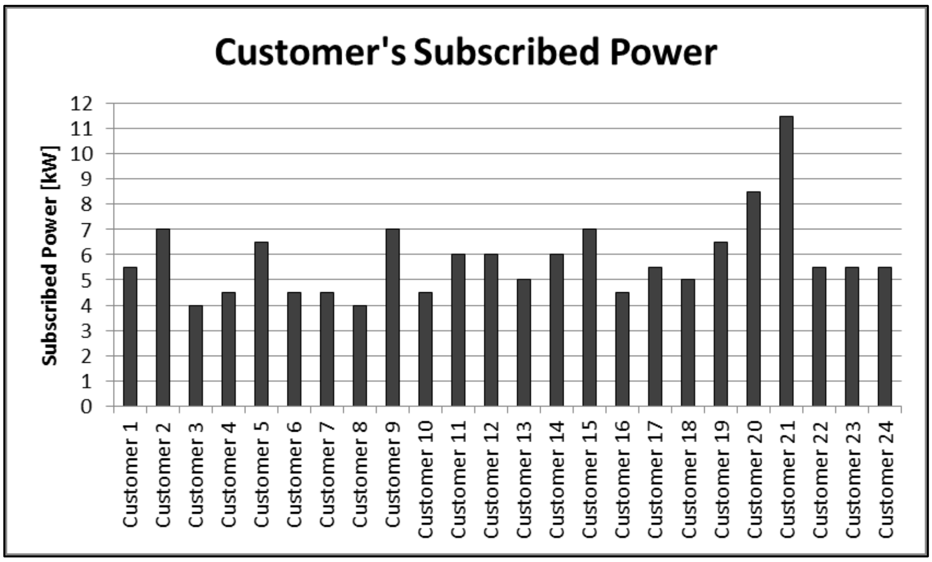

Figure 8.3 Customer's subscribed power for NT1

Figure 8.4 shows the expected yearly network tariff for each customer using NT1. The blue line shows the original tariff, NH4.

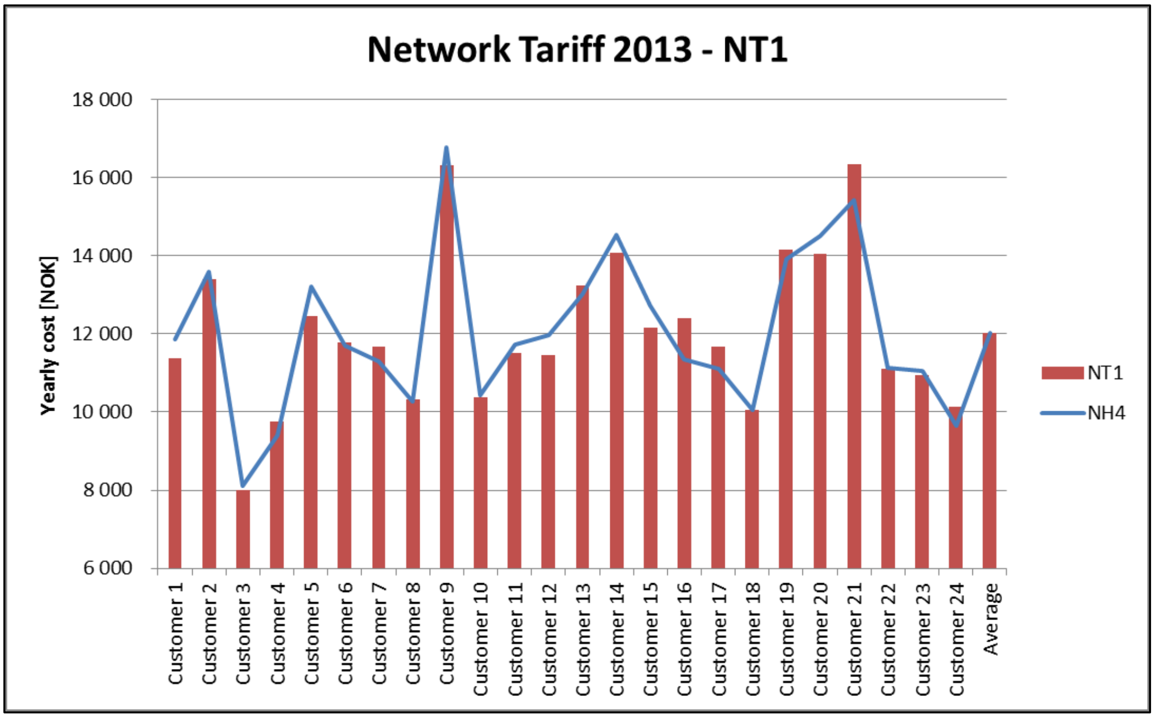

Figure 8.4 Consumer network tariffs for 2013 with NT1

How much increase or reduction in costs each customer experiences, compared to the NH4 tariff is shown in Figure 8.5.

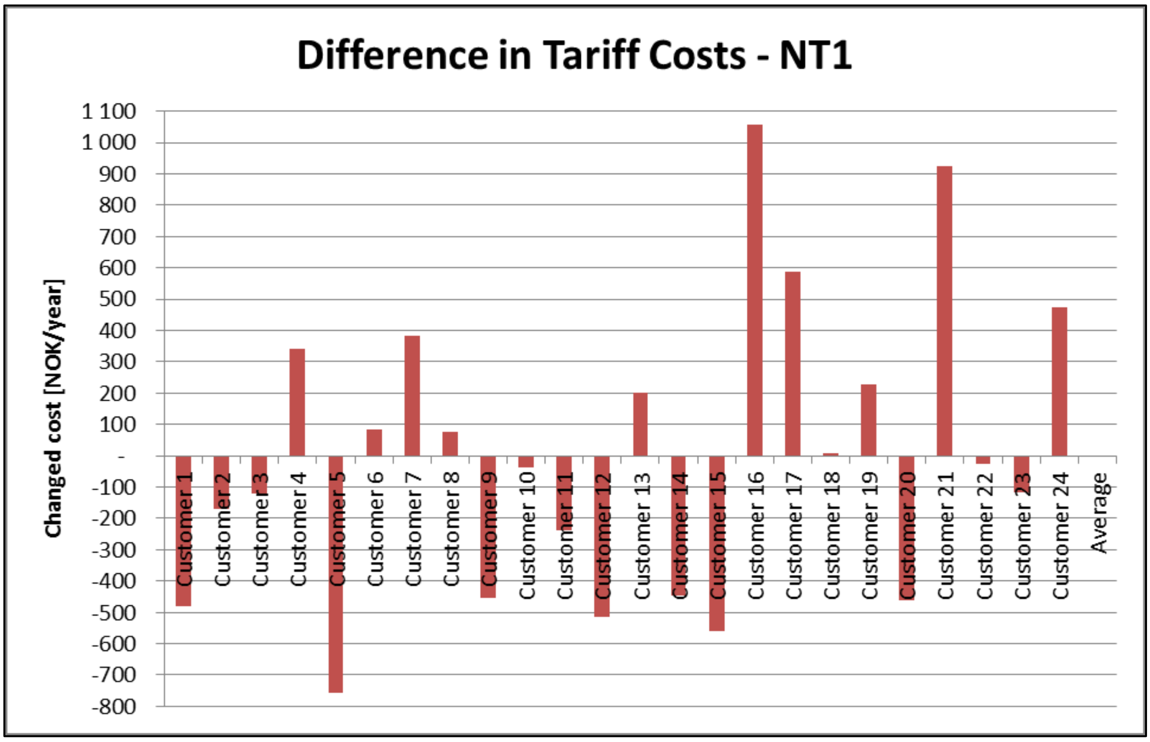

Figure 8.5 Changed tariff costs with NT1

One important factor with this tariff is that the size of the subscribed power demand is right. As Figure 8.5 shows, the customer that experiences the largest increase in costs is customer 16. This customer has a subscribed power demand of 4.5 kW, from the field trial. This gives an increase in tariff costs of approximately 1 060 NOK/year, compared to NH4. If the subscribed power demand instead is changed to 5 kW, the customer's new bill becomes approximately 34 NOK/year cheaper than with NH4. As this shows, the margins can be small and one of the challenges with this tariff is precisely this. Most DSOs have monthly readings of a customer's energy consumption, and little knowledge of hourly use. With AMI and smart meters the hourly consumption will be available, but until this is installed subscribed power demand can be hard to determine. A tariff based on maximum subscribed power can cause an unstable tariff. If customers adapt by reducing their peak demand the cost per kW will increase to keep income for the DSO stable. This in turn provides incentives for further power reductions [41].

Another subject that can be discussed regarding this tariff is whether or not it sends the right signal to the customers. The fees are not time-dependent and customers have to pay for overconsumption, despite of what time it occurs at. From a grid perspective it would perhaps not be a problem if the customers overconsume during nighttime, when demand in general is low, but the tariff offers no discrimination on this. It should also be discussed whether this tariff is easy and understandable for customers. In order for this tariff to reach its full potential, it is important that the customers have a clear idea of what the difference between energy and power consumption is. If they have a clear picture of this, they can understand why the costs can vary for each month, despite that the energy consumption has been similar. When introducing a new tariff like NT1, good and simple information needs to be easily available for the customers. This is an important criterion for any tariff modification, as change does not come easily for everyone.

8.1.1 Testing of Subscribed Power Demand at Demo Steinkjer

In order to see if the NT1 tariff contributes to reduced peak load and increases utilization time, a field trial conducted by NTE at the demo site Demo Steinkjer has been explored. The tariff was tested by the 24 customers between the dates 12.02.2014 to 31.12.2014 [42]. The prices and fees used in the real life test were different than in the example above. In order to compare behavior, the test period in 2014 has been compared with the same period in 2013. This means that approximately one and a half month of winter-consumption not is included in the analysis. January is one of the coldest months, and also the month where these customers had the highest total demand during 2013. It would have been interesting to see results from this month as well.

In Figure 8.6 the temperatures for 2013 and 2014 have been sorted from the lowest to the highest. As the figure shows, 2014 was on average slightly warmer than 2013. As most energy consumption is used for space heating, it would be expected that electricity consumption during 2014 was slightly lower than in 2013.

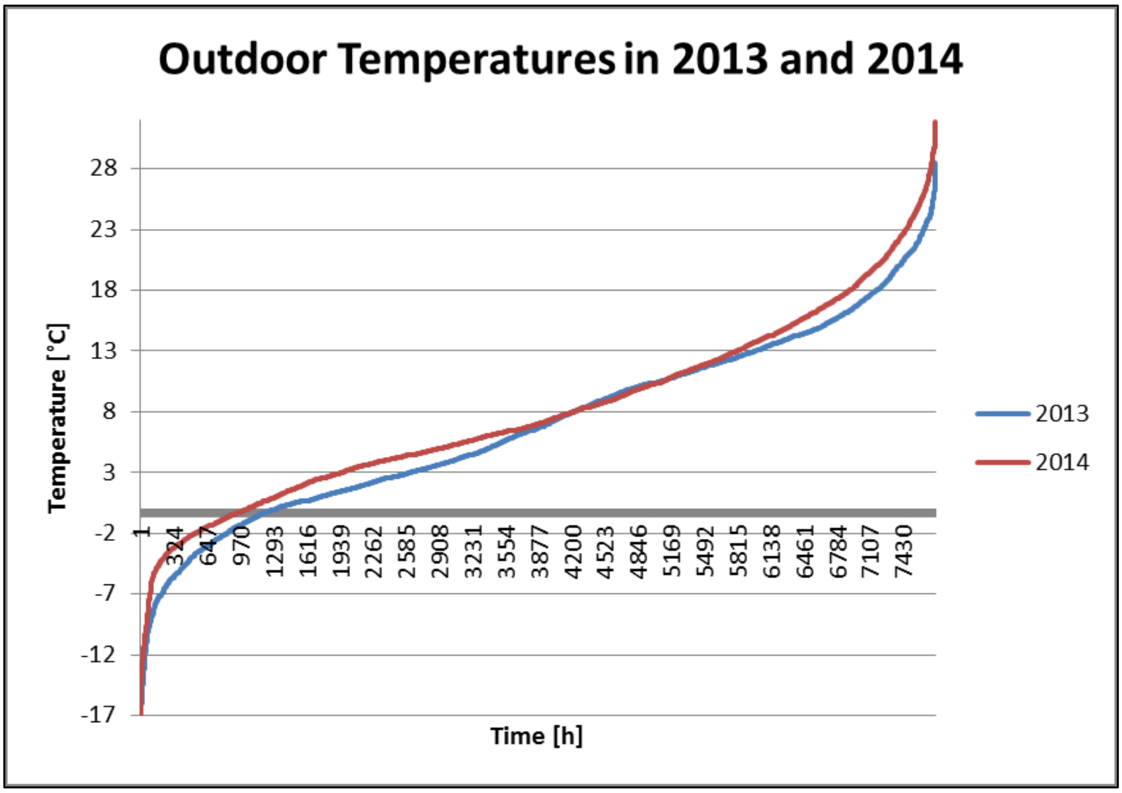

Figure 8.6 Temperature differences in 2013 and 2014

Figure 8.7 shows the average daily consumption profile for the whole time period. The blue line shows the consumption with the original tariff in 2013 and the red line shows consumption with the new tariff, tested in 2014.

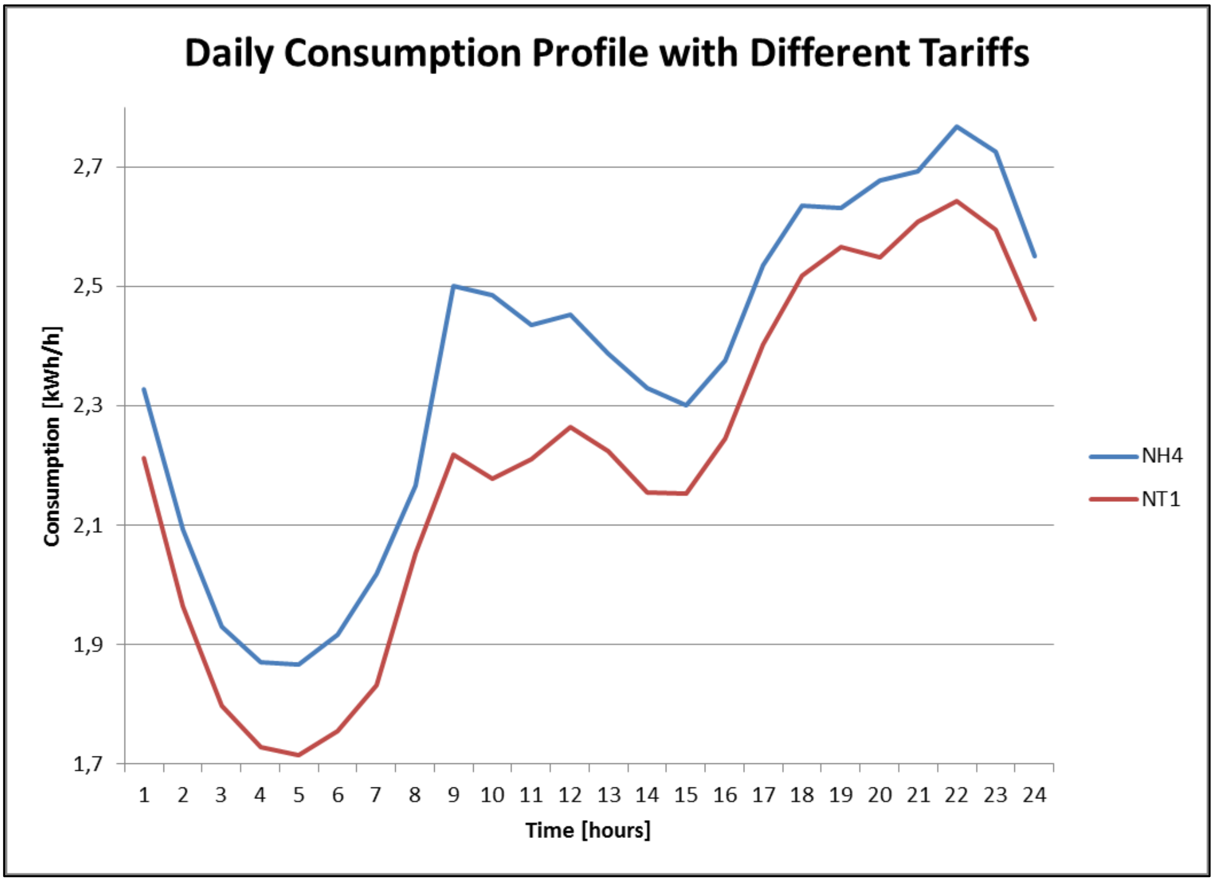

Figure 8.7 Consumption profile for 2013 and 2014

As the figure shows, the average daily consumption during 2014 was lower than in 2013, as expected. This figure shows the average for the entire time period the tariff was tested. By looking at different months individually, consumption profiles looks different, because consumption is so dependent on outdoor temperature. To minimize the effect of temperature differences on the data, the consumption has been temperature corrected according to Appendix C.

Figure 8.8 shows the average daily temperature corrected consumption profile for the whole time period.

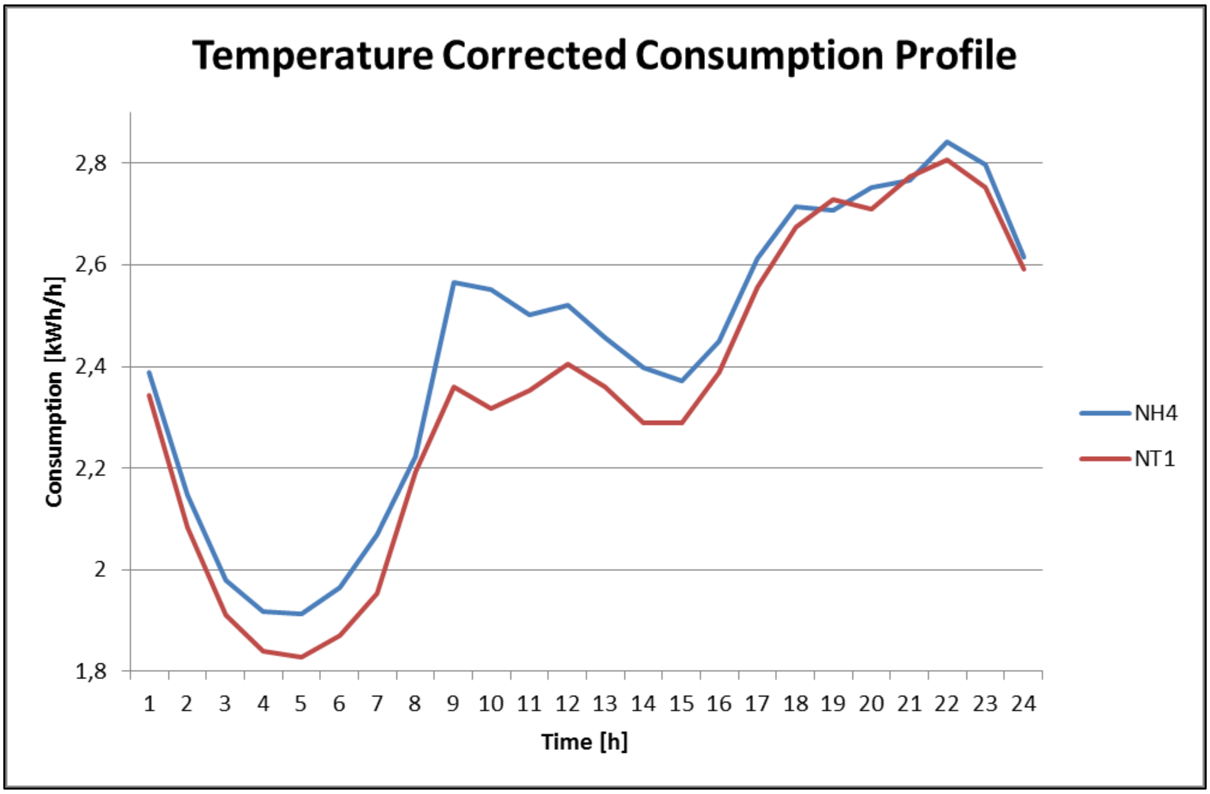

Figure 8.8 Temperature corrected consumption profile for 2013 and 2014

This figure shows that in general the electricity consumption with the new tariff is lower than with the old tariff. This indicates that the customers have reduced their total electricity demand for this period.

This new tariff can be an incentive to reduce peak demand. To see if peak demand has been reduced from 2013 to 2014, the change in number of overconsumption hours according to each customer's subscribed demand from 2013 to 2014 is presented in Figure 8.9.

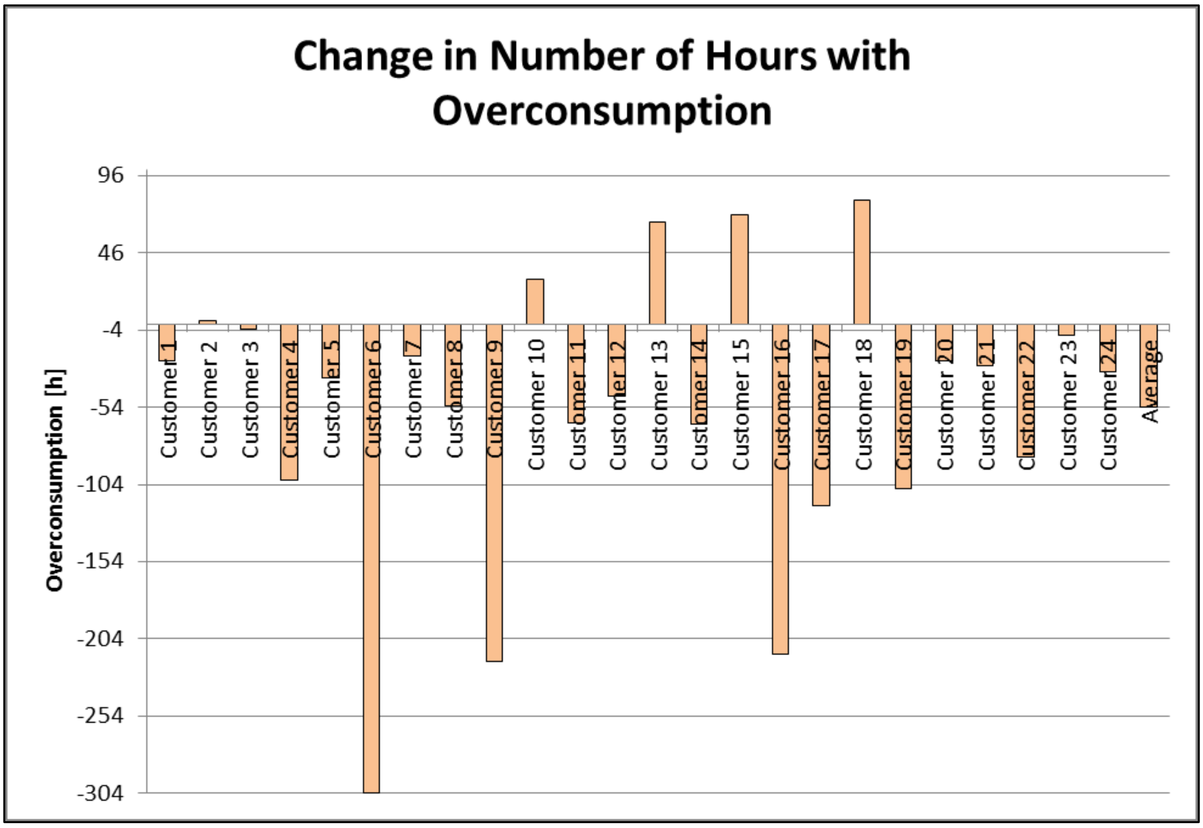

Figure 8.9 Difference in number of overconsumption hours from 2013 to 2014

Figure 8.9 shows the change in number of overconsumption hours for each customer, as well as the average for all the customers. Customers 2, 10, 13, 15 and 18 have more overconsumption hours in 2014 than in 2013, while the rest of the customers have fewer. Customer 6 has reduced the number of overconsumption hours from 2013 to 2014 by as much as 304. It of course needs to be taken into account that during 2013 the customers did no effort to reduce their peak demand.

Utilization time, T_b, is the relationship between total electricity demand and peak power demand for a year. If the utilization time is 8 760 the demand for the entire year has been even at peak demand. The utilization time for a year can be calculated using formula 8.

$$T_b = \frac{W}{P_{max}} \tag{8}$$

Where,

W = Total demand [kWh]

P_{max} = Peak demand [kW]

Because the field trial only lasted for 7 752 hours instead of 8 760 the utilization time is expressed through load factor, A. Load factor is a number between 0 and 1 and for this time period the load factor is found by formula 9.

$$A = \frac{T_b}{7\,752} \tag{9}$$

A high load factor indicates that the ratio between peak demand and yearly average consumption is high, meaning that peak demand is relative small compared to average consumption. This is a desired situation, as it can avoid power demand that is a lot higher than average consumption. For the customers in this field trial, the average load factor with temperature corrected consumption was 0.25 in 2013 and 0.24 in 2014. The difference in customer's load factor from 2013 to 2014 can be seen in Figure 8.10.

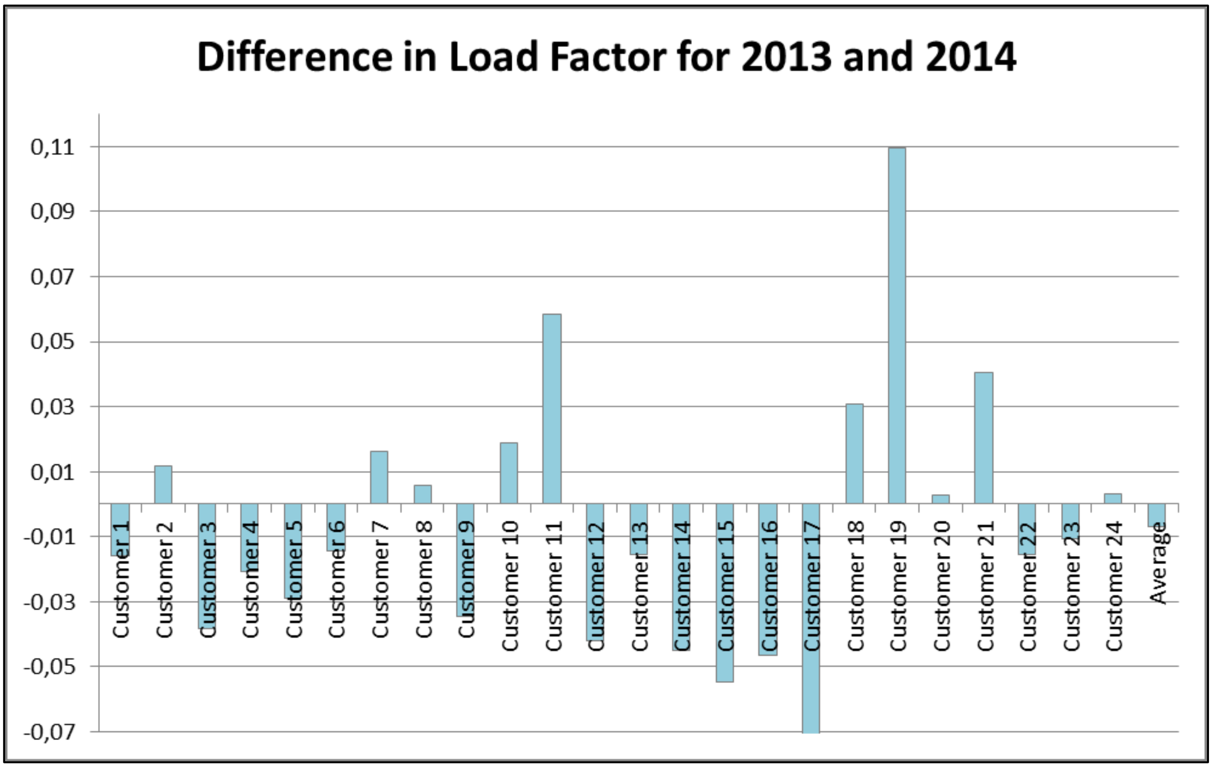

Figure 8.10 Difference in load factor from 2013 to 2014

On average, the load factor and utilization time is reduced, but it varies a lot for each individual customer. This is opposite of the desired situation. Despite the customers having reduced total demand, the maximum power demand is not equally reduced. The load duration curve for these customers shows that on average the consumption was higher in 2013 than in 2014. However, when looking at the 50 hours with highest demand in 2013 and 2014 the demand was higher in 2014, as seen in Figure 8.11. The figure shows the temperature corrected data.

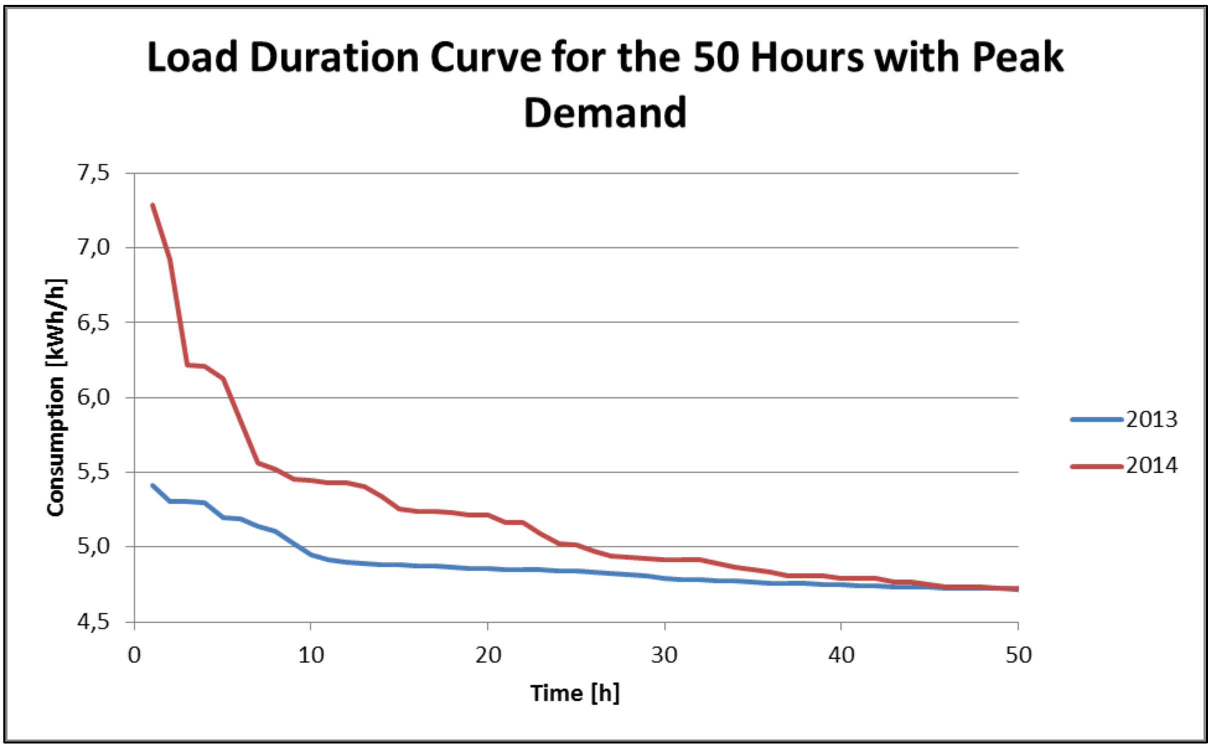

Figure 8.11 Load duration curve for 2013 and 2014

This figure explains why the utilization time is reduced and not increased. The reason why peak demand has increased is uncertain, but could be caused by for example new installations in the households.

Other factors than temperature needs to be taken into account when this study is analyzed. For example changes in life situation, new equipment or appliances and reduction or increase in number of people living in the household will affect demand. Whether or not the customers are engaged and interested in testing the new tariff is important for the outcome, as well as visualization tools for better management of own consumption. Other factors than temperatures are not investigated in this thesis, but is important in a large scale testing of new tariffs. However, this study clearly shows that it is possible to affect a customer's consumption and achieve DR by introducing a new tariff.

8.2 NT2 - Peak Power Demand Tariff

The next tariff is designed with basis in each customer's peak demand during a time period. The hour with the highest demand in each month is multiplied with a price α_{NT2}, and makes up the power segment of the bill. The customers also pay a fixed cost, C, and a variable energy segment, β. The formula for calculating yearly costs with this tariff is given in formula 10.

$$TC_{NT2} = C + \sum_{i=1}^{12}(\alpha_{NT2} \times P_i + \beta \times W_i) \tag{10}$$

Where,

C = Fixed costs [NOK/year]

α_{NT2} = Power segment [NOK/kWh/h]

P_i = Peak demand in month i [kWh/h]

β = Energy segment [NOK/kWh]

W_i = Consumed energy in month i [kWh]

To keep the network owner's revenue constant the following prices are used. They give the network owner decreased revenue of 11 NOK/year for the relevant year:

C = 2 500 NOK/year

α_{NT2} = 56.75 NOK/kWh/h

β = 0.2135 NOK/kWh

One alternative to this tariff is to make the average of three maximum peaks in one month form P_i, instead of just one. In case of a power failure, the startup current can be quite high as the power returns. This can cause the peak demand in a month to be unrealistic high. Deciding the peak demand by using the average of three hours will reduce the cost of a power failure. However, the number of power failures per year is quite low and usually occurs with extreme weather. During 2014 NTE had a down time of 0.03 per cent of the time and failed to deliver 343 000 kWh [43].

Figure 8.12 shows the expected network tariff for each customer using NT2. The blue line represents the costs the customers had with NH4.

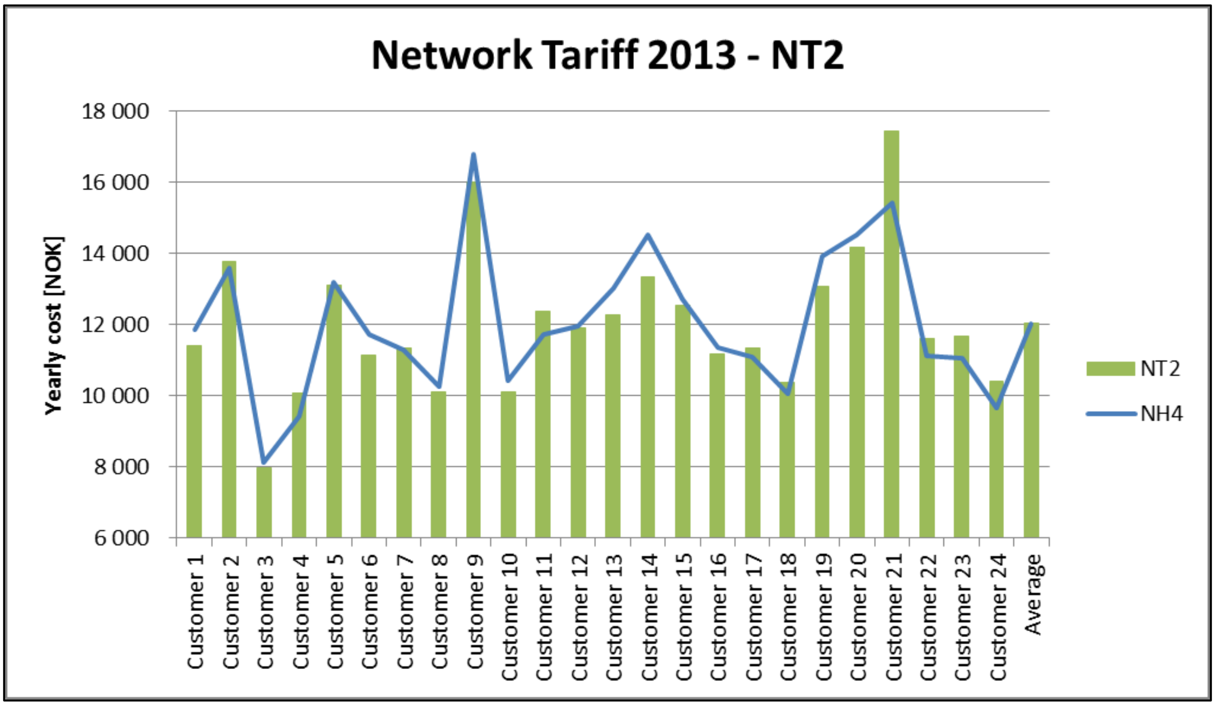

Figure 8.12 Consumer network tariffs for 2013 with NT2

Figure 8.13 shows how great increase or reduction in costs each customer experiences.

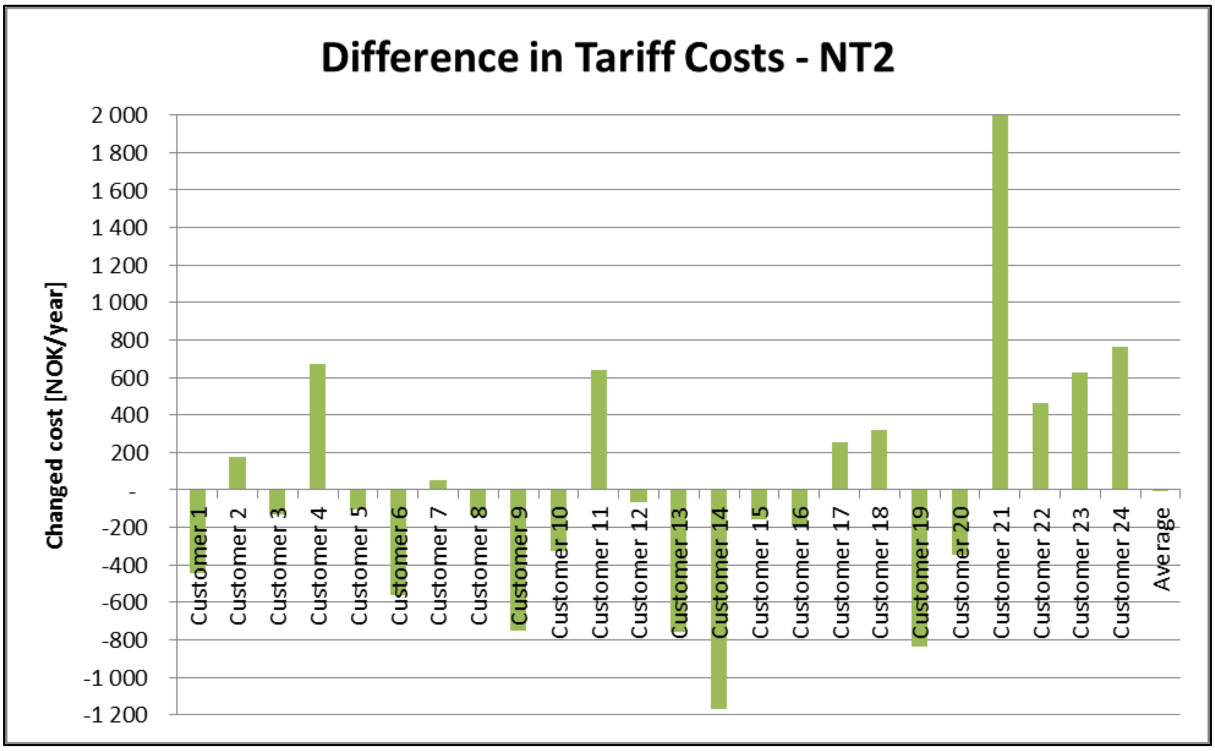

Figure 8.13 Changed tariff costs with NT2

Again, customer 21 experiences a large increase in yearly costs with the new tariff. Just like with tariff NT1, tariff NT2 gives a good incentive to reduce peak demand, but the tariff is not time-dependent. This sends out a signal to the customers that reducing demand outside peak hours in the grid is just as important as reducing demand during low-demand periods. This is not the case, and gives no profit to the DSO. However, many households do have their peak demand during peak hours in the grid, and in this case reducing the demand can be profitable.

As discussed earlier, using the three hours with the highest demand to form the power segment of a customer's bill is an alternative. This could be a good incentive for customers. If a customer is unfortunate and has a high peak demand early in the period, this customer has no incentive to keep demand low after this. However, if the power segment is dependent on the three hours with highest demand, instead of just one, the customer would profit to keep peak demand low for the rest of the period. This is probably a better solution, and can keep the customers motivated throughout the entire period.

This tariff requires customers having a good overview of their consumption at all time. It would also be an advantage if controlling demand was available. For example the customers should be able to turn on and off demand remotely.

8.3 NT3 - Peak Demand in the Grid Tariff

The third tariff that was tested, NT3, has some similarities with NT2. The difference between the two tariffs is that in NT3 the customers do not pay for their peak hour, but for their demand when the grid they are connected to experiences peak load. As discussed earlier, expansion of network capacity is based on how much power it is expected that end-users need when consumption is highest. Timing of customer energy consumption thus has great significance for the development and utilization of the network [36]. The tariff described in this section is a simple model based on collective peaks in the power demand. In this tariff the fixed cost is the same as before and there are two variable costs; one energy segment and one power segment. The energy segment, β, is set to reflect the costs of the marginal losses in transfer of energy, and is multiplied by the consumed energy W_i. The power segment, α_{NT3}, is a fixed cost multiplied by consumed power P_i. P_i is found by looking at the hour with peak load for a distribution substation in a month and finding each customer's demand during this hour. In this model α_{NT3} is constant throughout the year, but having a price reflecting seasons might also be a solution. Formula 11 gives the calculation of yearly costs for a consumer using this tariff.

$$TC_{NT3} = C + \sum_{i=1}^{12} (\alpha_{NT3} \times P_i + \beta \times W_i) \tag{11}$$

Where,

C = Fixed costs [NOK/year]

α_{NT3} = Power segment [NOK/kWh/h]

P_i = Demand during peak hour in month i [kWh/h]

β = Energy segment [NOK/kWh]

W_i = Consumed energy in month i [kWh]

To keep the network owner's revenue constant the following prices are used. They give the network owner increased revenue of 5 NOK/year for the relevant year:

C = 2 500 NOK/year

α_{NT3} = 97.54 NOK/kWh/h

β = 0.2135 NOK/kWh

Figure 8.14 shows the expected network tariff for each customer using NT3. The blue line represents the costs the customers had with NH4.

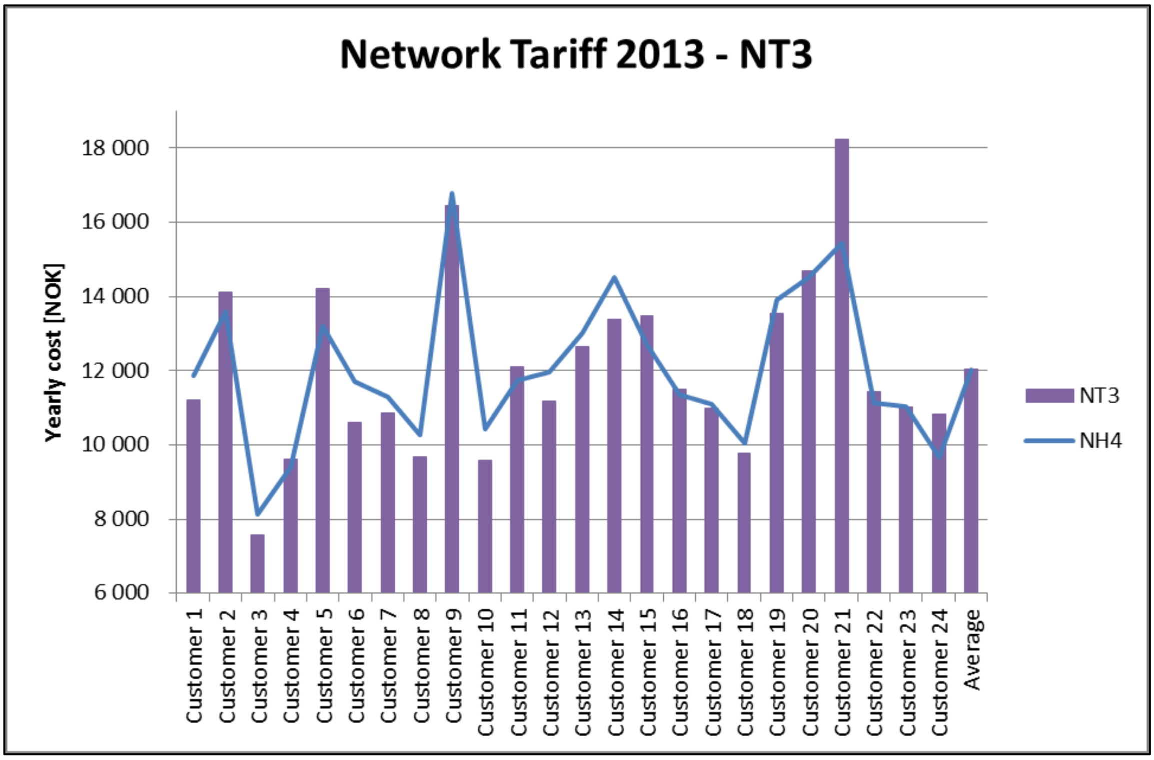

Figure 8.14 Consumer network tariffs for 2013 with NT3

Figure 8.15 shows how great increase or reduction in costs each customer experiences.

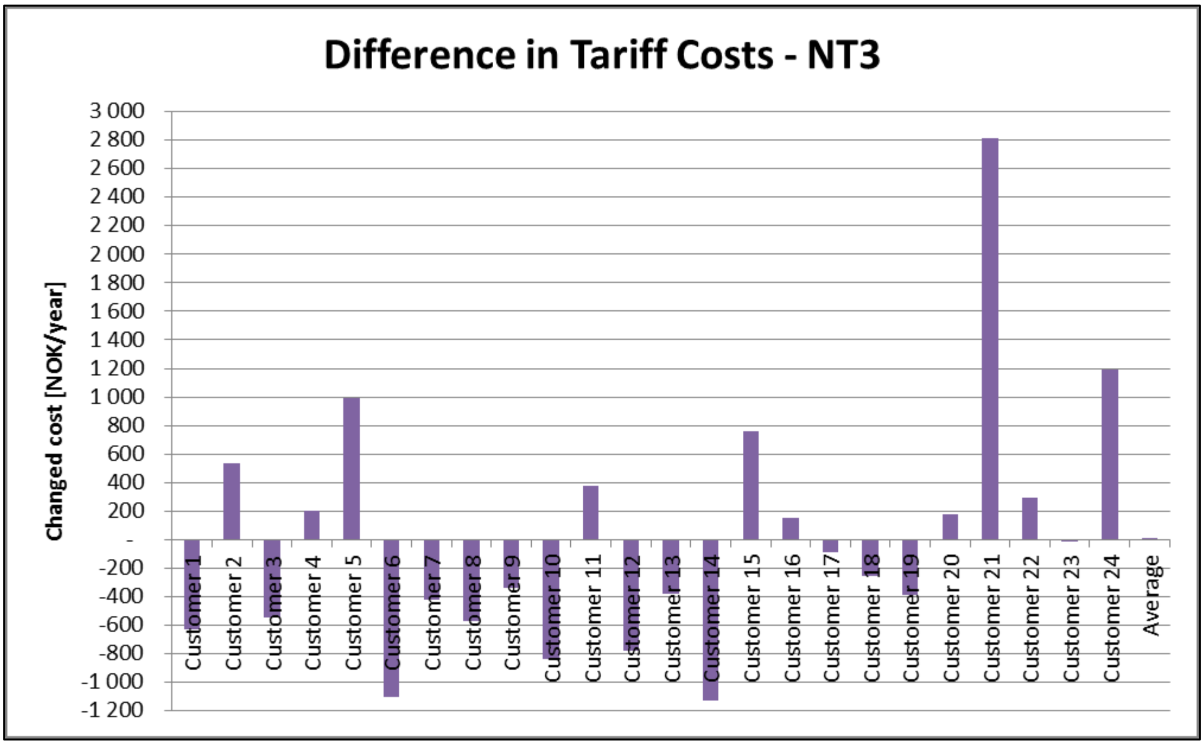

Figure 8.15 Changed tariff costs with NT3

Again, the variation in which customer experiencing the increase or reduction in tariff costs is changed, compared to NT1 and NT2. As Figure 8.15 shows, customer 21 experiences a large increase, compared to NH4.

As the customers pay for their demand when the grid experiences peak load every month, the customers will be rewarded if their contribution to the grid's peak load is low. The size of their individual monthly peak is irrelevant for their costs. Compared to NT1 and NT2 this tariff is directly connected to peak load in the grid. It is difficult for a customer to predict when peak load in the grid will occur and this could also be challenging for the DSO. For this tariff it needs to be decided if peak hours should be predetermined, and if this should be the same for every day of the year or vary. Customers have to pay for their demand during peak hours for every season, even though the grid might not experience any constraints during peak hours for example in summer. Peak load usually occurs when it is cold, and is because of this, to some extent, possible to predict. However, this is extremely variating. If peak hours are not predetermined, it needs to be decided how the customers should be warned that it is coming. If the system for notifying customers in advance is effective, this could actually help reducing peak load in the grid. One suggestion is to let all the customers connected to the same substation watch “live” demand for the entire neighborhood, but this will require new technology in the substations.

Compared to the earlier suggested tariffs, this tariff gives the customers very little control over their costs, and it is important that the customers are aware of when peak load in the grid occurs. Peak load in the grid is dependent on customer consumption. If customer consumption also is dependent on peak load in the grid, this makes consumption very unpredictable. This could cause peak load to be shifted, instead of reduced. It would also create an uneven and random distribution of costs. One example is that if a customer is not at home during the coldest day of the year, this customer will probably get a low tariff cost for this period. This random distribution might be seen as unfortunate.

8.4 NT4 - Coincidence Factor Tariff

Coincidence factor, s_i, is a number between 0 and 1 that shows the fraction of a customer’s peak power demand, when the grid the customer is connected to experiences peak load. It is found by dividing a customer’s demand during grid peak load, by the customer’s overall peak. This can be done every day, or as in this example, every month. The coincidence factor says something about the extent to which the customer has his peak demand at the same time as the grid experiences peak load. Formula 12 shows calculation of coincidence factor.

$$s_i = \frac{P_1(t = t_{max})}{P_{1max}} \tag{12}$$

Where,

P_1 = The customer’s consumption during a hour t [kWh/h]

P_{1max} = The customer’s peak demand during a time interval [kWh/h]

t_{max} = The hour with peak load in the grid

The tariff suggested in this section, NT4, uses coincidence factor to calculate the customer’s grid costs. The tariff costs for one year is calculated using formula 13.

$$TC_{NT4} = C + \sum_{i=1}^{12} (\alpha_{NT4} \times s_i + \beta \times W_i) \tag{13}$$

Where,

C = Fixed costs [NOK/year]

α_{NT4} = Power segment [NOK]

s_i = Coincidence factor in month i

β = Energy segment [NOK/kWh]

W_i = Consumed energy in month i [kWh]

To keep the network owner's revenue constant the following prices are used. They give the network owner increased revenue of 9 NOK/year for the relevant year:

C = 2 500 NOK/year

α_{NT4} = 706.4 NOK

β = 0.2135 NOK/kWh

Figure 8.16 shows the expected network tariff for each customer using NT4. The blue line represents the costs the customers had with NH4.

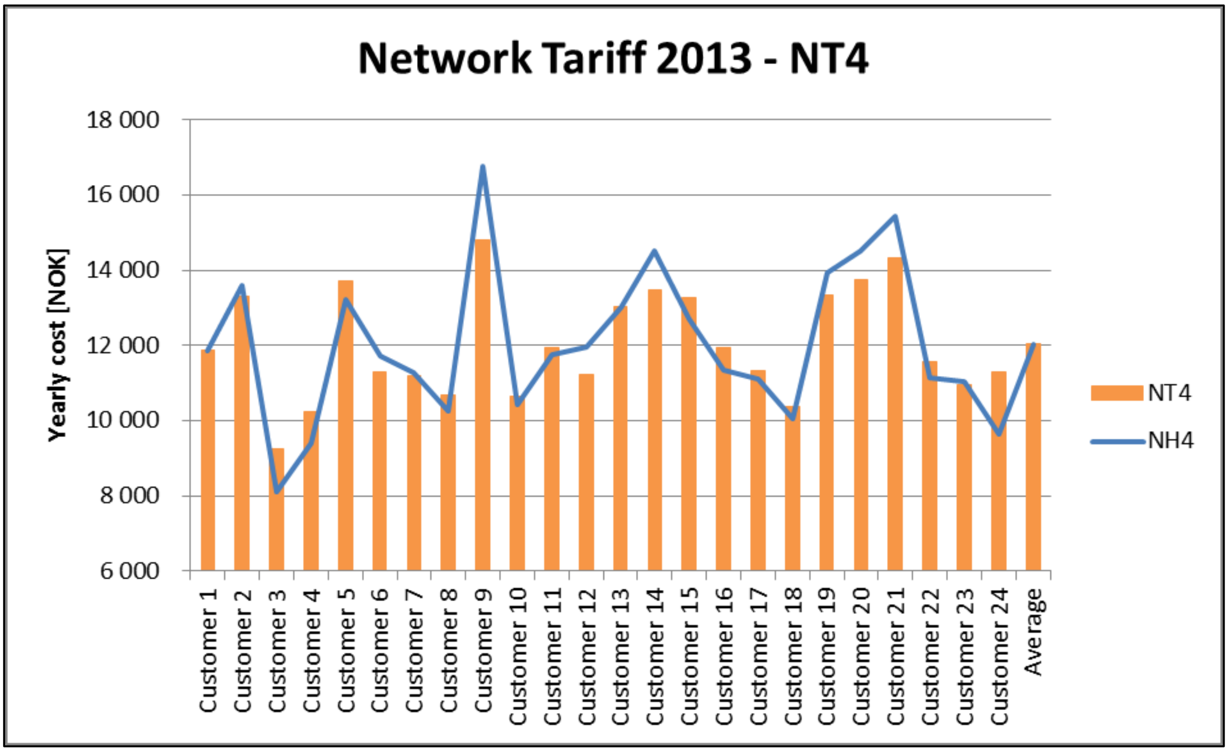

Figure 8.16 Consumer network tariffs for 2013 with NT4

Figure 8.17 shows how great increase or reduction in costs each customer experiences.

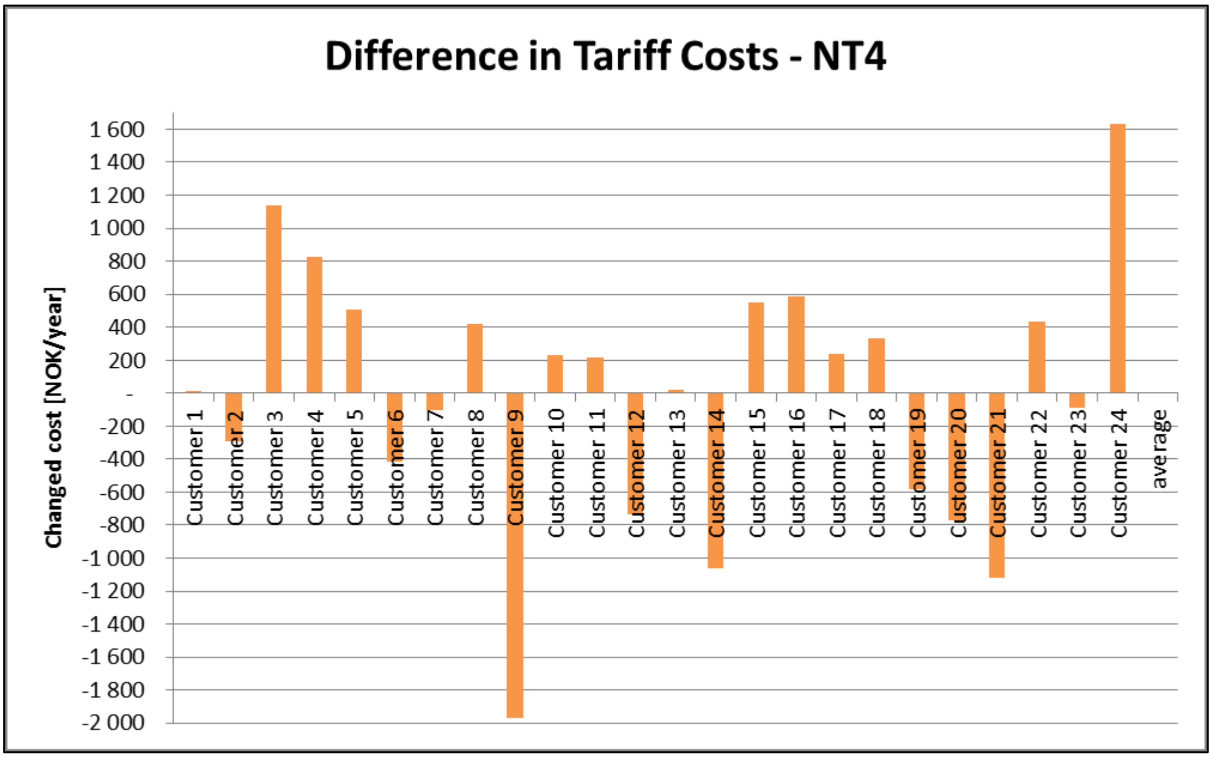

Figure 8.17 Changed tariff costs with NT4

This tariff gives a slightly different cost distribution, compared to the previous suggested tariffs. The idea behind this tariff can be described like this: "The size of your peak is irrelevant, but if you contribute to the grid's peak load you pay".

Just like with tariff NT3, the exact time when the demand occurs is important. In the NT4 tariff the customer's tariff is dependent on when the peak load in the grid occurs. Independent on how much power each household requires, the customers pay for having a high demand during peak load hours. A household that requires 2 kW during peak load hours can end up paying more than a household requiring 10 kW during the same hour. This is because the tariff is decided on how high this demand is, compared to the household's total peak for a given time period. So if the first household's peak in this period is 2 kW, and the second house has 15 kW, the coincidence factor for household one will be higher than for household two.

The tariff encourages households to keep demand low during peak load hours. This can also have a negative effect: if a customer realizes that their consumption during peak hour (for example on a cold day) has been their peak in this period, they can make sure they get a higher peak than this to reduce the coincidence factor. This would be an unfortunate event.

Again, a customer's control over tariff costs is low. Just like with tariff NT3, the customers need to be alerted about peak hours to have any control. The tariff encourages customers to have their peaks outside hours with peak load in the grid. If only half of the customers engage in the changes this tariff brings, positive effects can be seen in the grid. Some of the customers move their peak demand, while others do not. This would lead to a more even demand, because not all the customers change behavior. If all the customers changed, the peak hours would be shifted and this would not contribute to reduced peak load.

8.5 Comparison of Different Tariffs

This section will summarize what has been discussed in section 8.1 to 8.4. Table 8.3 shows the changes in tariff costs for each customer with the different suggested tariffs. If the changes in costs are less than 250 NOK it is marked with a white square. If the customer saves money on the new tariff, compared to the NH4, the square is green and it is red if the customer loses money.

Table 8.3 Change in grid related costs in NOK/year

Customer	NT1	NT2	NT3	NT4
1	-480	-443	-628	12
2	-170	175	538	-293
3	-119	-129	-548	1 136
4	343	674	205	825
5	-756	-104	996	509
6	85	-560	-1 108	-418
7	382	52	-422	-105
8	77	-141	-574	417
9	-453	-754	-336	-1 970
10	-36	-327	-835	233
11	-237	639	379	218
12	-515	-67	-783	-732
13	200	-761	-377	20
14	-446	-1 173	-1 126	-1 061
15	-559	-159	757	549
16	1 059	-187	149	589
17	587	255	-93	240
18	9	320	-256	331
19	226	-839	-389	-583
20	-463	-347	175	-769
21	923	2 008	2 814	-1 119
22	-27	464	293	433
23	-116	625	-17	-87
24	473	765	1 190	1 632

This table is presented to make it easier to see the outcome for all the customers, from each of the tariffs. Changes of less than 250 NOK per year have been neglected, because it is considered to be such a small change in costs that it can be seen as random variation from year to year. Some customers have a positive or negative outcome, depending on the new tariff. There are only four customers experiencing a change of more than 250 NOK for each of the tariffs. These are customers 9, 14, 21 and 24.

By summing the column for each of the new tariffs we get approximately 0 NOK, which was the basis for setting the price elements in the equations. How big each customer's reduction or increase is, varies a lot for the different tariffs. To graphically display the changes the customers experience from each of the tariffs, they have been plotted in Figure 8.18.

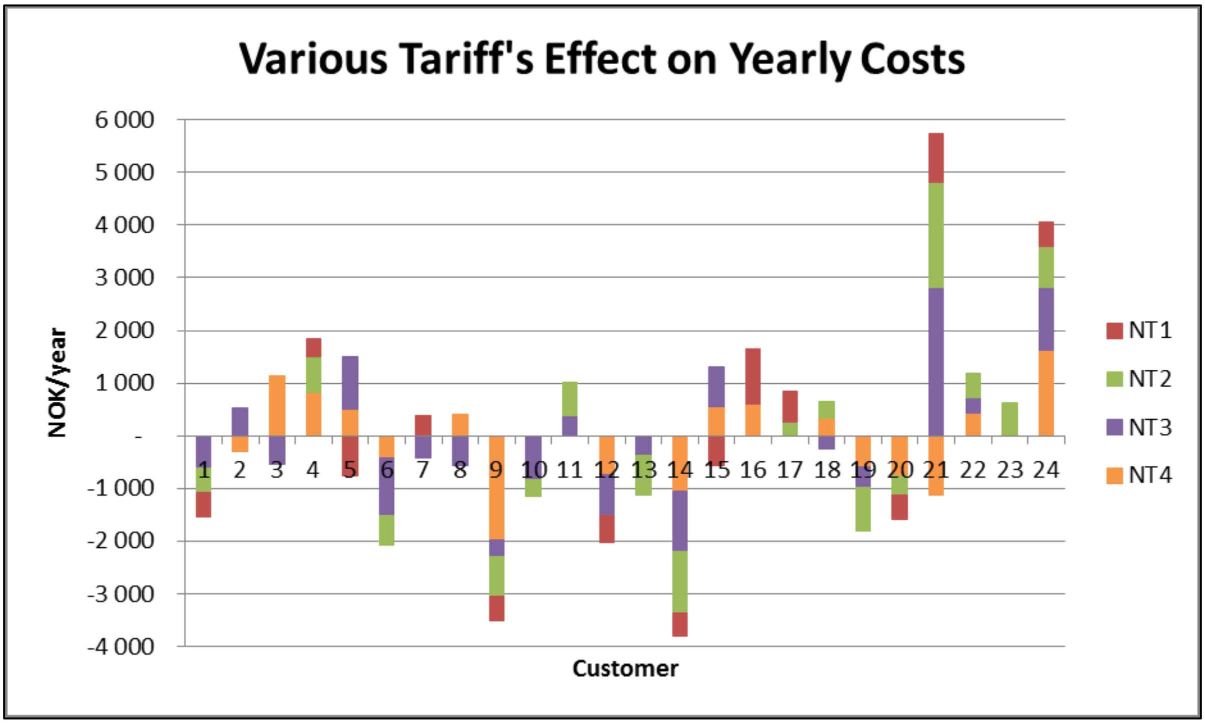

Figure 8.18 The outcome from each of the tariffs for all customers

Here we see that customers 9 and 14 have a positive outcome of the tariffs, while customers 21 and 24 do not. One interesting observation can be made regarding customer 21: this customer has a negative outcome from all the tariffs, except the coincidence factor tariff, NT4. This shows that even though the customer clearly has high peak demand, the highest peak demand occurs outside peak hours in the network. Customer 9 is the one with the highest total energy demand, but this customer reduces tariff costs with all the new tariffs. This is because customer 9 has a constant high energy demand, and the peaks occur outside peak hours in the network.

One thing that it is necessary to discuss, is whether or not these tariffs give the customers incentives to change demand and by this reducing peak demand in the network. For customers 21 and 24 the yearly cost changes by so much that it is safe to say that these customers probably will look at their consumption to see if any changes can be made. For the other customers the change is very variable depending on which tariff is introduced.

How much the tariff costs for each customer will change depends on how the tariffs are decided. Some of the suggested tariffs involve a high work load for the DSOs compared to what it is now, and this needs to be considered when the prices are set. For the DSOs the tariff should be stable and predictable over time. The numbers used to calculate the tariffs in this analysis is just an example of how the tariffs can be designed. In real life these could be different, causing changed results for the customers. Before the prices are set, the DSOs need to decide which one of the following two scenarios is desired. Scenario one: In order for customers to maintain the same cost level as they have today, they need to change their consumption. If they continue to have the same consumption as today it will be expensive. Scenario two: Customers do not have to change consumption from the way it is today, but if they do they can save money on it. The DSOs need to have in mind that the goal is to get a more cost-efficient allocation of the grid related costs, as well as keeping their own income stable. The goal when setting the prices in this analysis has been to keep costs unchanged for the average customer, if consumption does not change. However, the whole point of introducing a new tariff *is* to change consumption. This means that the tariffs will have to be adjusted along the way, to keep the income for the DSO stable. That is unless the change causes the DSO's costs to be reduced, which would be a desired solution.

Independent on which tariff is introduced, two conditions must be met in order for customers to change behavior; First of all, the customers must understand the tariff and secondly the customers need to be able to control their demand. Creating a simple tariff and explaining it to the customers can be a challenge for the DSOs. The tariff system has been unchanged for many years, and the change can be a struggle for many of the customers. On the other side, a sudden change in tariffs can generate sudden changes in consumption as customers feel compelled to adjust demand. Introducing simple technical solutions for customers to control consumption will probably increase DR. If the system is remotely controlled, customers can even adjust demand without being home. A prerequisite for seeing any change with new tariffs is a change in behavior for the customers. In this analysis only theoretical costs have been examined. In order to see the real effect of a new tariff it would need to be tested on real life customers to see if they change.

9 Discussion

This thesis introduces that there without doubt will be even higher peak power demand in the future, especially if the trend for sale of power demanding equipment and the development of battery capacity for EVs continue. This section will further discuss some of the topics that have been addressed in the thesis.

If a customer's peak demand only occurs for a short time period within an hour, it is less likely to contribute to network peak load. To look at an example; an instantaneous water heater has a high power demand, but because it only lasts for a short while it is less important. If all the inhabitants in a neighborhood took a shower using the instantaneous water heater at the same time, this could cause troubles. But because it lasts for such a short time it will be distributed among all the households, and thus not creating *one* short-lasting peak in demand. EVs have the opposite problem: because an EV requires charging for such a long time period is causes problems. All customers taking a 12 minute shower after work is distributed, but all customers charging their EV for at least 5 hours after work creates a huge increase in demand. As we can see, whether or not power demand occurs simultaneously and how big it is, determines if it will cause a problem in the electricity grid or not. If we look at coincidence factor, as given by formula 12, we see that the peak demand in an area can be lower than the combined peak demand from all the customers. This is because the peak demand does not occur at the same time. The longer peak demand lasts, the higher the chance is that it occurs simultaneous in several households.

One challenge with charging a household battery from the grid is the uncertainty. The customer is dependent on having pre-defined time periods when electricity prices are low, to be able to charge in a smart way. This is possible through for example ToU tariffs. If prices suddenly change, the customer can be in the risk of having an empty battery when prices go up and demand is high. Setting these time periods in advance can be challenging, and is perhaps the biggest issue with ToU tariffs. Pre-defined time periods cannot take sudden constraints in the grid into account, caused by for example outages or cold weather. Even though periods with very cold weather are pre-defined as low-price periods, the demand can be extremely high. The DSO does not want extra demand during these time periods because customers with batteries are charging them to save money. The charging and discharging also needs to happen automatically, without the customer having to participate. However, for or the sake of keeping the customers interested, they should be able to monitor their own and the battery's demand.

The marginal willingness to pay for electricity has to be bigger than the willingness to pay for other energy sources, especially for non-electricity specific use, such as heating. If district heating is cheaper than electricity many consumers might chose this instead. If having a solar panel on the roof or a battery that can be charged when electricity prices are low is cheaper than being connected to the grid, some might chose this as well. Grid customers with access to cheap alternatives will have a lower willingness to pay than customers without such access [44]. The consumers with an alternative energy source are more flexible and more price-sensitive. A consumer that only uses alternative energy sources for heating will find that changing electricity consumption might be a challenge. This customer will have to reduce demand in electricity-specific consumption, and this can be seen as a greater inconvenience than turning down the temperature for a short while.

For most customers the problem with alternative energy sources might be high installation costs. The customers do not see any reason to invest, because electricity is so cheap. With new tariffs customers might get incentives to do something about the way they consume electricity. It has been seen earlier that customers embrace new technology, where one example is smartphones. A customer can pay a lot for a smartphone from a specific brand, despite that a similar phone to a fraction of the price can do the same job. This shows that the willingness to pay often is higher than what it needs to be. Streaming of music and movies has become far more common than buying DVDs and CDs. This is another example showing that new technology is entering our houses every day, replacing existing solutions. This interest for new technology might in a few years be transferred to interest for technology for smart homes. For some customers the importance of being for example climate and environmental friendly is more important than always being economically rational [35]. Because of this, technologies that have high investment costs can be installed and used despite that they do not earn back the investment during their lifespan.

The EV's total energy demand in the analysis in this thesis was 108 kWh for the entire week. The total supplied energy from the PV module was 120 kWh. This shows that the PV is able to cover more than the EV's energy demand. The problem, however, is that the supply and demand does not occur simultaneous. The tested solution was to use a battery, but the battery does not have enough capacity to store all the energy. Neither does it have enough power to charge the vehicle according to the specifications. If the new charging option for Tesla, with a power demand of 22 kW, becomes a reality this will have a huge impact on the distribution network and the battery will have even less ability to address the problems. New technology to handle this major increase in power demand will have to be in place, especially if many households get this option. For better utilization of PV and battery combined with EV, the energy capacity and power of batteries have to be improved.

As seen in section 4, the perhaps biggest issue with EVs is that they generate large peak demands in the grid. These peaks are very high compared to the average consumption for the customers. As mentioned, the EV's energy demand is quite small compared to the total energy demand in a household. Because customers only pay for the amount of energy consumed, there are few incentives for a customer to avoid high peak demand. The new tariffs, like discussed in section 8, are perhaps the most important aid to make customer realize that avoiding high power demand is profitable. Even though the battery used in this analysis had little effect on the high peaks generated by EV, they can still be profitable and contribute to reduced costs for customers. As seen above, by the use of batteries like Powerwall the peak demand is reduced by as much as 3.3 kWh/h. This was a small contribution compared to the great peak demand the EV had, but the technology can be useful in combination with other changes, such as new tariffs. In the NT2 tariff suggested in section 8.2 the customer had to pay a fee of 56.75 NOK per kWh/h for the peak demand every month. If a battery can help reduce the peak demand by 3.3 kW the customer can save 3.3 kWh/h × 56.75 NOK/kWh/h = 187.275 NOK per month. This gives an annual saving of about 2 250 NOK. This shows that if new tariffs become a reality a household battery can have more advantages than just storing locally produced electricity. The life expectancy of a Powerwall is 10 years, which would give a total saving of 22 250 NOK during its life period. Comparing this with the price of the Powerwall of 26 000 NOK can give customers an interesting view. Perhaps a solution on how to use batteries can be to promote them either as energy optimized or power optimized, depending on the customer's needs.

As discussed in section 8.5 it is important that the customers get the right incentive for changing demand. An important factor that needs to be in place for customers to change demand is that they understand how the tariffs are designed. In the field trials that have been completed on tariffs there has only been a small group of customers. All these have been in close contact with the DSO and been informed about the design of the new tariffs. If there will be a full-scale deployment of new tariffs the contact with each individual customer has to be reduced. It is therefore important that the tariffs are easy and understandable for each of the customers. The tariffs also have to be able to engage the customer in new ways, compared to before. A well-informed customer is more likely to act than an ignorant one. Despite how simple the tariffs are, the DSO will perhaps never see as significant changes as in a field trial, but this might come over time.

There are a few adjustments that could have been made, in order to make the analysis in this thesis more accurate. Some of these are discussed below.

For the EV implementation it is said that the customer lives in Trondheim, but in fact he lives at Steinkjer. This is because Trondheim-Stjørdal is a road section that many people use EVs. The only main difference between living in Trondheim and Steinkjer is that Trondheim is located at latitude 63.4° instead of 64° so that the PV supply might be slightly higher in Trondheim. As Appendix B shows, the potential for PV is also dependent on for example weather conditions, so placing the customer in Trondheim instead of Steinkjer is considered to have no impact on the results of this analysis.

The PV panels that have been used in the numerical analysis have a peak power, P_{max}, of 0.255 kW_p. That means that the 12 panels have a total peak power of 12 × 0.255 kW_p = 3.06 kW_p. In hour 12 on 29.03.2013 the produced electricity by the PV is calculated to be 3.16 kW. This is 0.1 kW more than the theoretical maximum peak power. This shows that some of the assumptions made in the calculations might have been wrong. The factor with the biggest uncertainty is the assumption that the elevation angle is the same for an entire month. This hour is the only time during the year production is higher than the peak power, so it is not a big problem. In general the PV supply is a little higher than one can expect from this module. This is also expected, because solar noon is used. The REC255PE module is just chosen as an example, and if the customer had a different panel the peak power could have been higher. This small error is not expected to have affected the results significantly.

In the energy segment for the new tariffs in section 8, β, the basis for the marginal losses was the NordPool price from 2013. A more correct estimate would have been given if the price from 2014 was used instead. This is because the basis for the NH4 tariff is the prices from 2015. The NordPool price for NO3 in 2014 was 263.57 NOK/MWh [40]. As the difference between the 2013 and 2014 is so small, it would not have made a significant difference to the final result. In addition, the same price is used in all the different tariffs, and the importance is to separate the tariffs from each other. It is therefore assumed that the 2013 price gives a good enough estimate.

10 Ideas for Further Study

Several subjects that are relevant for consumption profiles for future households have not been discussed in this thesis. In this section some of these subjects will be introduced. These subjects form a good base for further work.

When introducing distributed generation, such as PV, a lot of reactive effect is generated or consumed in the distribution network without further voltage control. It should be investigated closer *if* and *how* this will affect the distribution network regarding things such as and security and quality of supply.

This thesis only looks at household customers. A great portion of the consumption in the distribution network is by larger customers, such as office buildings and factories. How the consumption profile of this customer group will look in the future is closely related to the profiles of households. These customers also offer greater flexibility for demand response, as demand is more price-dependent. DSOs paying for consumer flexibility can affect the constraints in the network. In general it can be investigated how the use of consumer flexibility can be a good alternative to grid investments.

In section 8 only costs related to network tariffs was discussed. A more complete analysis including energy costs could be investigated further.

11 Conclusion

Several elements discussed in this thesis will affect the consumption profiles in the future. The total energy demand in households will likely be reduced. Most of the electricity used in households today is used for space heating, but this will be reduced with new building regulations, as only a certain percentage of heating options can be covered by electricity. Also, new houses have better insulation and technology for local energy generation becomes more available. All of this results in a lower energy demand per square meter in new households, compared to old. Consumption profiles for households will look different, depending on which building regulation the houses are built according to.

From all the technologies included in the analysis in this thesis, the EV is the new technology that will affect the consumption profiles to the most extreme degree. EVs have a power demand that is many times higher than the average demand in a household. The EVs are usually charged in the afternoon, and during these hours the local electricity supply from PV is low, because of little access to solar insolation. In general the PV supply and demand in a household is not coherent on weekdays. To handle this delay, batteries can be used to store the supplied energy from PV. There are two main problems with the battery used in this analysis; it does not have enough capacity to store all the produced energy from the PV and it does not have enough power to deal with the high demand from EVs. Despite using both battery and PV, the consumption profile for the customer in this analysis had high power demand for short periods. This was an issue both when charging the EV every day and when charging twice during the week.

When looking at new suggested tariffs for withdrawals in the distribution network, each of the suggested tariffs gives different results for each individual customer. Some of the customers get highly increased or decreased tariff costs, which should imply that these customers will change demand to save money. The most important factor with new tariffs is that they need to be understandable for the customers. Also, the customers should have the opportunity to affect their electricity bill and be tempted to become more active customers and offer consumer flexibility by demand response. The tariffs should also be designed so they handle the problems related to peak load in the grid in the most efficient way.

The combination of EVs, batteries and new tariffs can persuade more customers to take a more active role in their own electricity consumption. If customers have to pay for their peak demand, a power demanding EV can increase their tariff costs. Installing a battery can help reducing these costs, and can be seen as a favorable solution. It also increases the security of supply, in case of short power blackouts. The capacity of the battery is the key to how much it will influence the future consumption profiles and in what way. A battery with small capacity can help customers save money, but will perhaps not contribute to reducing grid constrains. A battery with large capacity has the opportunity to load leveling and peak shaving. How widespread the use of batteries will be in the future depends on the price, marketing and customer enlightenment.

12 Bibliography

[1] A. V. Skrivarhaug, Writer, *Smartgrids for økt forsyningssikkerhet.* [Performance]. Smartgridkonferansen, 2015.

[2] I. H. Magnussen, D. Spilde and M. Killingland, "Energibruk i Fastlands-Norge," NVE, Oslo, 2011.

[3] Elhub, *Innføring av Elhub for aktørene i kraftmarkedet.*

[4] U.S. Department of Energy, "Benefits of demand response in electricity markets and recommendations for achieving them. A report to the United States Congress pursuant to Section 1252 of the Energy Policy Act of 2005," 2006.

[5] M. Blikø, "Consumption Profiles in Future Households, Specialization Project," Trondheim, 2014.

[6] The Research Centre on Zero Emission Buildings, "ZEB Definitions," 2015. [Online]. Available: http://www.zeb.no/index.php/about-zeb/zeb-definitions. [Accessed 10. November 2015].

[7] S. H. Marschhäuser, "Slik er det å bo i et nullutslippshus," Aftenposten, 9. November 2015. [Online]. Available: http://www.aftenposten.no/bolig/Slik-er-det-a-bo-i-et-nullutslippshus-630751_1.snd. [Accessed 9. November 2015].

[8] Skanska, "Leveringsbeskrivelse for eneboliger Skarpnes," 11. February 2015. [Online]. Available: http://www.skarpnes-nullhus.no/wp-content/uploads/2013/04/Leveringsbeskrivelse-Skarpnes-2015-JANUAR.pdf. [Accessed 9. November 2015].

[9] A. Skjævestad, "Skarpnes boligfelt - Nordens første boligfelt med nullhus," Husbanken, 24. November 2014. [Online]. Available: http://www.husbanken.no/forbildeprosjekter/prosjekt/?id=262553. [Accessed 9. November 2015].

[10] H. Sæle, B. A. Bremdal, T. T. Engan, V. Kristoffersen, J. A. Foosnæs, T. E. Nordal and J. M. Sletner, "Subscribed power - testing new power based network tariffs stimulating for demand response," CIRED, Lyon, 2015.

[11] B. Grinden and N. Feilberg , "D10- Analysis of Monitoring Campaign in Europe," REMODECE, 2008.

[12] D. Saker, M. Vahdati, P. J. Coker and S. Millward, "Assessing the benefits of domestic hot fill washing appliances," *Energy and Buildings 93,* pp. 282-294, 15. April 2015.

[13] Energy Rating, "Frequently Asked Questions – Appliances," 2014. [Online]. Available: http://www.energyrating.gov.au/products-themes/washing-drying/appliances/#faq_4. [Accessed 18. June 2015].

[14] Gudbrandsdal Energi, *Effektkrevende apparater - lading av elbiler,* Vinstra, 2014.

[15] B. Nykvist and M. Nilsson, "Rapidly falling costs of battery packs for electric vehicles," *Nature Climate Change vol 5,* pp. 329-332, April 2015.

[16] SINTEF Energi, *Measurements conducted by SINTEF Energi for the Ecar-project,* 2015.

[17] Tesla Motors, "Lad din Model S," [Online]. Available: http://www.teslamotors.com/no_NO/models-charging#/basics. [Accessed 12. November 2015].

[18] European Commission, *Best Practices on Renewable Energy Self-consumption,* Brussels, 2015.

[19] PVEducation, "A collection of resources for the photovoltaic educator," [Online]. Available: http://www.pveducation.org/pvcdrom. [Accessed October 2015].

[20] Agrometeorology Norway, "Mære 01.01.2013-31.12.2013," lmt.nibio.no, Ås, 2015.

[21] H. Sæle, "Strømforbruk i husholdningene," *Xergi,* June 2010.

[22] Enova, "Hjelp til deg som skal kjøpe solfanger," Enova, Trondheim, 2010.

[23] Å. L. Sørensen and Y. Søetorp, *Solenergi i Energimeldingen - Møte med Eli Jensen, Olje- og energidepartementet, 27.august 2015,* Norsk solenergiforening, 2015.

[24] IEA, "Status of the Market for Solar Thermal Systems," 2015. [Online]. Available: http://www.iea-shc.org/country-report-norway. [Accessed 20. October 2015].

[25] Enova, "Tilskudd for solfangeranlegg," 2015. [Online]. Available: http://www.enova.no/finansiering/privat/enovatilskuddet-/solfanger/tilskudd-for-solfangeranlegg/911/1977/. [Accessed 20. October 2015].

[26] REC, *REC Peak Energy Systems,* REC Group, 2015.

[27] Norsk Solenergiforening, "Statistikk," Creatur Media, 2015. [Online]. Available: http://solenergi.no/statistikk/. [Accessed 20. October 2015].

[28] Enova, "Tilskudd for el-produksjon," 2015. [Online]. Available: http://www.enova.no/finansiering/privat/enovatilskuddet-/el-produksjon/914/0/. [Accessed 20. October 2015].

[29] Y. Kageyama, *In Japan, fuel cells turn up the heat,* Hiratsuka, Japan: ABC News.

[30] Norsk Hydrogenforum, *Hydrogen og brenselceller - viktige deler i et fornybart energisystem,* Kjeller: Next Move, 2013.

[31] B. Fladen, M. C. Lagergren and H. J. Myhrer, "Forslag til endring av kontrollforskriften og avregningsforskriften vedrørende plusskundeorning," NVE, Oslo, 2014.

[32] Office of Electricity Delivery and Energy Reliability Smart Grid R&D Program, "Summary Report: 2012 DOE Microgrid Workshop," Department of Energy, Chicago, Illinois, 2012.

[33] K. Sand, "Mikronett - en del av framtidens kraftsystem," NEF Teknisk Møte, 2014.

[34] Tesla Motors, "Powerwall," 2015. [Online]. Available: http://www.teslamotors.com/powerwall?redirect=no. [Accessed 5. November 2015].

[35] E. Wilhelmsen, "Regnestykker om Teslas batterier," *Energi og klima*, 11. May 2015.

[36] T. M. Andresen and V. A. Mook, "Høring om tariffer for uttak i distribusjonsnettet," NVE, Oslo, 2015.

[37] H. Sæle and O. S. Grande, "Demand Response From Household Customers: Experiences From a Pilot Study in Norway," *IEEE Transactions on Smart Grid, VOL. 2, NO. 1,* pp. 102-109, March 2011.

[38] NVE, "Nettleiestatistikk husholdninger - 2005 og nyere," NVE, 2015. [Online]. Available: http://www.nve.no/no/Kraftmarked/Nettleie1/Nettleiestatistikk/Nettleiestatistikk-husholdninger---2005-og-senere/. [Accessed 1. July 2015].

[39] NTE Nett AS, "nettleiepriser 2015 for private husholdninger," 2015. [Online]. Available: http://ntenett.no/files/PDF/NTE_nettleiepriser_2015_P_small.pdf. [Accessed 2. July 2015].

[40] Nord Pool Spot, "Elspot Prices," 2015. [Online]. Available: http://www.nordpoolspot.com/Market-data1/Elspot/Area-Prices/NO/Daily1/?view=table. [Accessed 2. July 2015].

[41] ECON, "Tariffering av energimålte kunder i distribusjonsnettet," NVE, Oslo, 2006.

[42] P. Efskin, *Conversation about subscribed power*, Trondheim, 2015.

[43] NTE, "Årsrapport 2014," NTE, Steinkjer, 2014.

[44] Econ Pöyry AS, "Optimal network tariffs and allocation of costs," NVE, Oslo, 2008.

[45] T. Boström, Writer, *Solar Energy in northern Scandinavia – does it make sense?.* [Performance]. EFIKS, 2015.

[46] Norwegian Meteorological Institute, "eKlima," 2015. [Online]. Available: http://eklima.met.no.

[47] NVE, "Veileder for lokale energiutredninger," Norges vassdrag- og energidirektorat, Oslo, 2009.

[48] V. Novakovic, S. O. Hanssen, J. V. Thue, I. Wangensteen and F. O. Gjerstad, TEP4235 Energy Management in Buildings, Trondheim: NTNU, 2012.

[49] PVEducation, "A collection of resources for the photovoltaic educator," [Online]. Available: http://www.pveducation.org/pvcdrom. [Accessed October 2015].

Appendix A: Solar Irradiance

Solar irradiance to Earth's surface varies seasonally, due to the tilt of Earth its rotation around The Sun. Where The Sun appears in the sky is given by the declination angle, δ. Earth is tilted by 23.45° and the declination angle varies plus or minus this amount over the year. Despite the fact that Earth revolves around The Sun, it is simpler to think of The Sun revolving around a stationary Earth [19]. This requires a coordinate transformation. In this alternative coordinate system The Sun moves around Earth, as shown in Figure A. I.

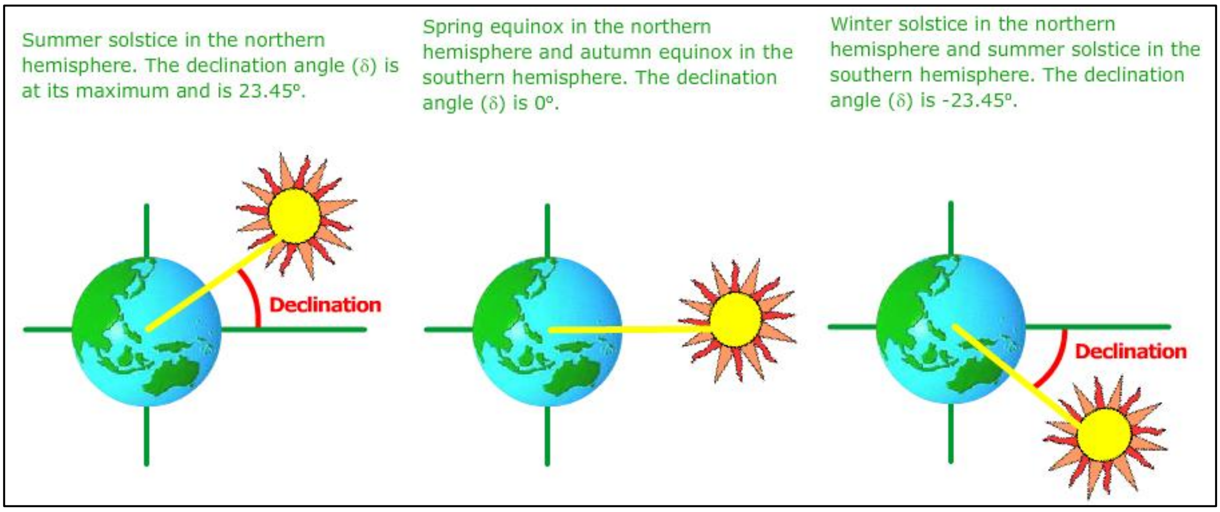

Figure A. I Declination angle [19]

The figure shows the maximum declination angle during summer and winter solstice, which occurs around the dates 22.06 and 22.12 in the northern hemisphere [19]. The declination angle for any given day can be calculated using formula A.I.

$$\delta = \sin^{-1}\left(\sin(23.45°) \times \sin\left(\frac{360}{365}(d-81)\right)\right) \tag{A.I}$$

Where d is day of the year, with January the first as d = 1.

Elevation angle, α, is the angular height of The Sun in the sky measured from the horizon, as shown in Figure A. II.

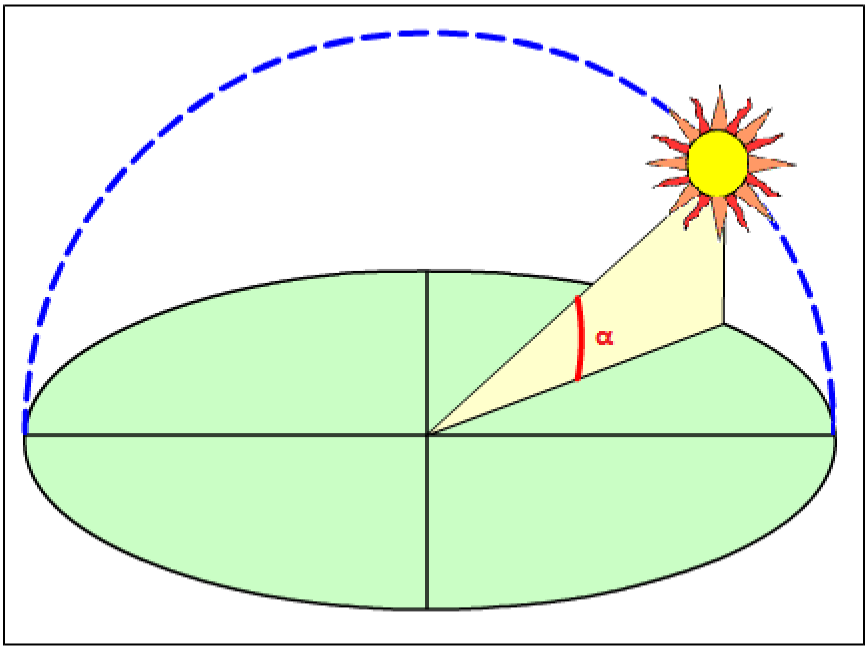

Figure A. II Elevation angle [19]

The elevation angle varies throughout the day and it depends on the latitude of the particular location and the day of the year. For a specific latitude φ, the elevation angle at solar noon for a particular day can be determined using formula A.II. This formula is valid for the Northern Hemisphere.

$$\alpha = 90 - \varphi + \delta \tag{A.II}$$

PVEducation [19] explains how having a tilted surface will affect the solar irradiance:

> *The power incident on a PV module depends not only on the power contained in the sunlight, but also on the angle between the module and The Sun. When the absorbing surface and the sunlight are perpendicular to each other, the power density on the surface is equal to that of the sunlight (in other words, the power density will always be at its maximum when the PV module is perpendicular to The Sun). However, as the angle between The Sun and a fixed surface is continually changing, the power density on a fixed PV module is less than that of the incident sunlight.*
>
> *The amount of solar radiation incident on a tilted module surface is the component of the incident solar radiation which is perpendicular to the module surface. The following figure shows how to calculate the radiation incident on a tilted surface (S_M) given either the solar radiation measured on horizontal surface (S_H) or the solar radiation measured perpendicular to The Sun (S_I).*

This is shown in Figure A. III.

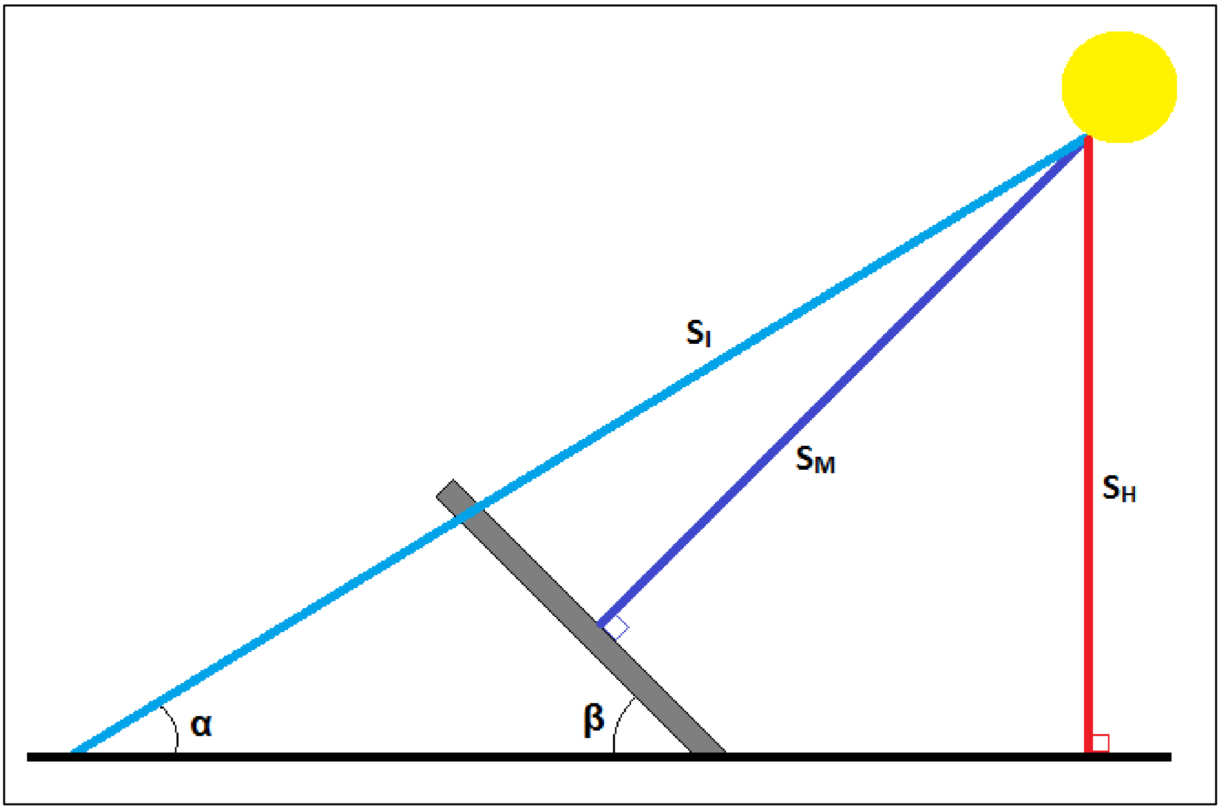

Figure A. III Solar radiation on a tilted surface

In this figure α is The Sun's elevation angle and β is the tilt angle of the module. Using this it is clear that a high tilt angle will be advantageous during winter, and a low tilt angle will be best during summer months. However, as this is a fixed module, the tilt will be the same throughout the year. In this thesis the PV panels will be on rooftops and therefore the angle is chosen to be 30°, to match the angle on existing roofs.

In the analysis of PV panels in this thesis the radiation measurements are given in W/m^2 on a horizontal surface. To be able to see the theoretical radiation on a module tilted by 30°, the radiation perpendicular on the module, S_M, is calculated using formula A.III.

$$S_M = \frac{S_H \times \sin(\alpha + \beta)}{\sin(\alpha)} \tag{A.III}$$

As elevation angle varies for every hour of every day in the year, a simplification has been made. The elevation angle at solar noon on the 22th of every month has been used for the whole month. First, the declination angle is calculated, using formula A.I. Then the elevation angle is calculated using formula A.II and a latitude of 64°. The result is given in Table A. I.

Table A. I Solar angles throughout year

Date	**Day number (d)**	**Declination angle (δ)**	**Elevation angle (α)**	$\frac{\sin\ (\alpha+\beta)}{\sin\ (\alpha)}$
22.01	22	-19.77°	6.23°	5.443
22.02	53	-10.63°	15.37°	2.685
22.03	81	0.00°	26.00°	1.891
22.04	112	11.68°	37.68°	1.513
22.05	142	20.19°	46.19°	1.346
22.06	173	23.45°	49.45°	1.294
22.07	203	20.09°	46.09°	1.347
22.08	234	11.16°	37.16°	1.526
22.09	265	-0.59°	25.41°	1.918
22.10	295	-11.85°	14.15°	2.849
22.11	326	-20.50°	5.50°	6.057
22.12	356	-23.45°	2.55°	12.093

By using these results, the radiation perpendicular on the module for each hour in 2013, S_M, is calculated using formula A.III. The difference between S_M and S_H is biggest during the winter months. This radiation is further used in the analysis, to calculate theoretical power produced by the PV panels during 2013.

Appendix B: Potential for Solar Energy in Scandinavia

Figures B.I to B.III illustrates the potential for solar energy on Scandinavia for three different scenarios. Figure B. I show the irradiation on a horizontal surface, measured in kWh/m^2 for a year.

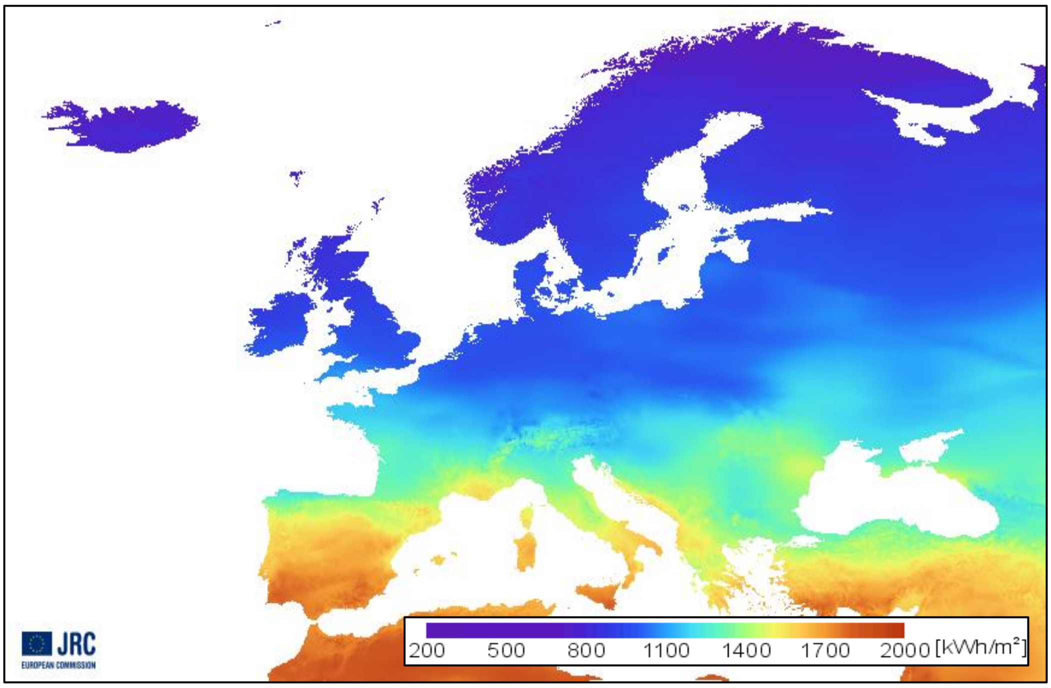

Figure B. I Irradiation on a horizontal surface (kWh/m^2 and year) [45]

Scandinavia is located at quite high latitude, far from the Equator. Because of this, the sun angle is lower, and the irradiance per horizontal area will be lower than at latitude further south.

Figure B. II shows the irradiation on an optimally inclined surface, measured in kWh/m^2 for a year. This potential is bigger that the potential on a horizontal surface.

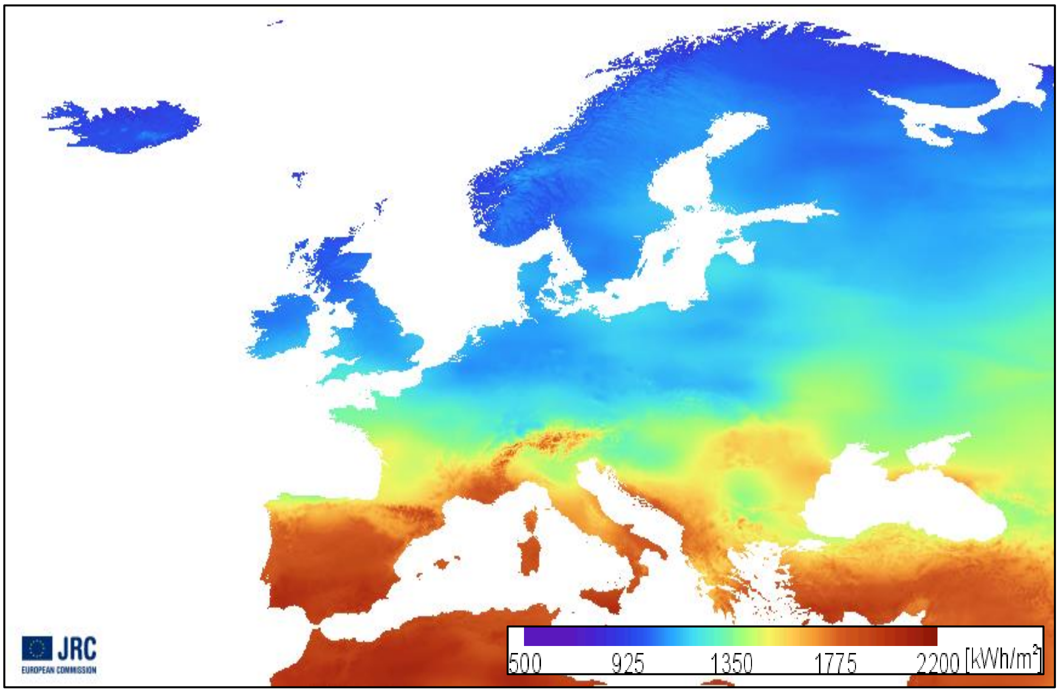

Figure B. II Irradiation on an optimally inclined surface (kWh/m^2 and year) [45]

However, for latitudes above the polar circle The Sun moves 360° across the sky. This causes midnight sun and polar night. Figure B. III shows the potential when using a two axis tracker. The figures do not only take into consideration the latitude, but also weather conditions.

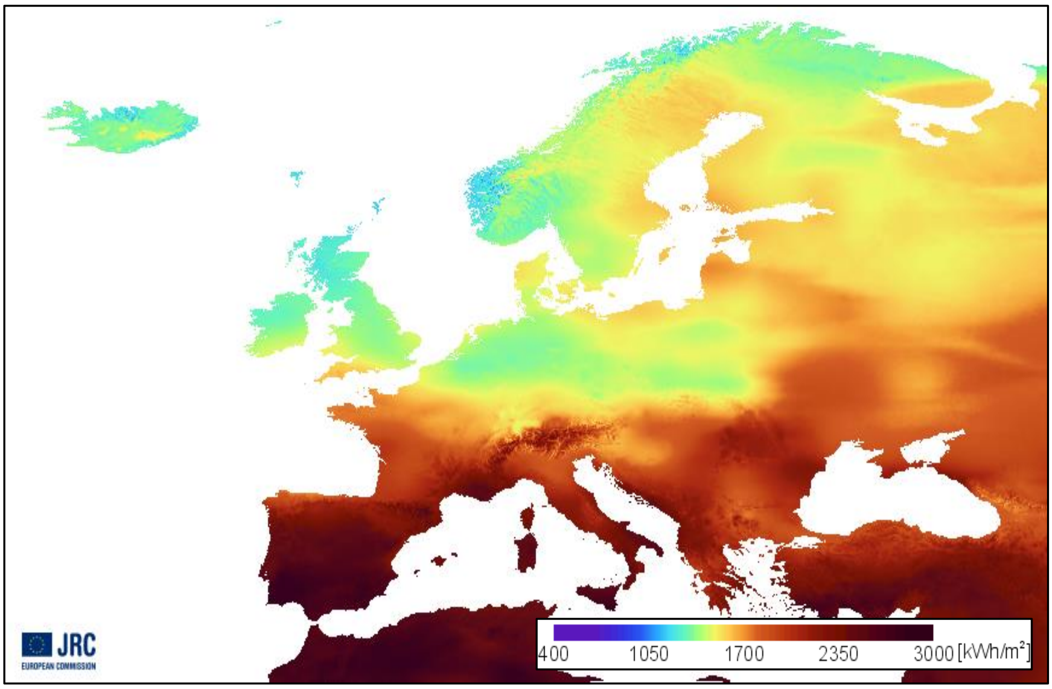

Figure B. III IV Irradiation on a 2 axis tracking surface (kWh/m^2 and year) [45]

As the figures show, the potential for solar energy in Scandinavia can be great.

Appendix C: Temperature Correction

Temperature correction of consumption is a way to minimize the effect temperature differences has on the data. Consumption is corrected according to formula C.I

$$E_{temp\ cor} = E_{measured} \times \left\{ \left(Share_{temp\ dep} \times \frac{G_{normal}}{G_{measured}} \right) + Share_{temp\ indep} \right\} \quad \text{(C.I)}$$

Where,

$E_{temp\ cor}$ = Temperature corrected consumption [kWh]

$E_{measured}$ = Measured energy consumption [kWh]

$Share_{temp\ dep}$ = Share of the consumption that is temperature dependent = 55 [%]

$Share_{temp\ indep}$ = Share of the consumption that is not temperature dependent = 45 [%]

G_{normal} = Degree day number for a normal year

$G_{measured}$ = Degree day number for the relevant year

The degree day numbers are calculated by assuming a desired indoor temperature of 17 °C. This temperature take into account external heat gains from solar radiation, lights, cooking, human presence, warm water and so on. The difference between 17 °C and the measured outdoor temperature gives the degree day number for one day. These have been summarised for each month in Table C. I. The normal degree day numbers have been calculated using the normal temperature for each metering station from 1981 – 2010, provided by the Norwegian Meteorological Institute [46]. The temperature dependent consumption, $Share_{temp.dep}$ is set to 55 per cent, according to NVE [47].

Table C. I Degree day numbers for 2013 and 2014

Month→	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**Sum**
2013	644	559	620	413	161	107	88	97	187	361	455	494	4186
2014	636	404	450	355	230	141	14	73	178	315	458	563	3816
Normal	633	572	540	395	256	142	84	101	215	373	506	602	4419

Only the consumption during the heating season has been temperature corrected. The heating season is calculated from the first day of autumn when day mean temperature falls below 11 °C and to the first day in spring when day mean is above 9 °C.

Table C. II Heating season 2013 and 2014

Year	First day above 9 °C in spring	First day below 11 °C in autumn
2013	08.05	31.08
2014	24.04	16.09