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Large scale transition from conventional to electric vehicles and the consequences for the security of electricity supply

A demand side analysis of electricity consumption

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Abstract

This study investigates how demand-side changes, as a result of a large-scale transition to electric vehicles (EVs), is likely to affect the security of electricity supply in Norway. The study is based on a survey that asked 398 EV-users when they charge their EV during the day and night. By looking at two scenarios for EV market penetration, consumption curves was estimated and analyzed based on power consumption data from 2012. The study finds that the prospected EV-transition is likely to worsen the security of supply, in that the variability in the consumption curve is likely to increase and the frequency balance will therefore be more difficult to maintain, all other factors held constant. The peak demand hours during the winter stand a higher chance of surpassing available installed capacity under the scenarios of EV penetration compared to the power consumption in 2012. The existing plans to improve the Norwegian power grid, increase installed capacity and expand power connections abroad, will likely be sufficient to tackle a large scale transition to EVs and to maintain the security of electricity supply. The study also finds that the power demand from a large EV fleet can potentially improve the security of supply, if EV-users charge their EVs during the hours that are more convenient for the power system, during the night.

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1. Introduction

The Norwegian government has made obligations to cut national greenhouse gas (GHG) emissions by 30% of 1990-levels by 2020. 2/3 of this reduction has to be taken domestically, which means a domestic reduction of GHG-emissions between 15-17 million tons of CO2-equivalents (Ministry of Finance, 2010). One important instrument to meet the domestic requirement of GHG-emission reduction is to replace conventional cars with modern Electric Vehicles (EVs). Because the Norwegian power system consists of mainly renewable energy, such a transition would lower domestic GHG emissions significantly. During the 1990s the government started to introduce several favorable policies for EVs (EV Norway, 2014). During the last years the sale of EVs in Norway has exploded and Oslo has become the unofficial EV capital of the world. The annual percentage growth in EVs in Norway has been enormous: In June 2013 there was approximately 12 500 EVs in Norway. In the beginning of June 2014 the figure was 30 000 (Grønn Bil, 2014). If the trend continues it will not take many years until a large fraction of the 2,5 million personal cars in Norway are EVs.

This thesis is concerned with how this prospected transition to EVs will affect the power system and especially the security of electricity supply in Norway: If most of the conventional cars in Norway are replaced by EVs, this will require a lot of electricity. How will this additional electricity demand manifest itself and is Norway's power system prepared to tackle such a transition?

1.1. Background: The EV transition and the power supply

The electricity system is in many ways the foundation upon which our economy is built. Electricity has become an essential part of all modern organizations and businesses and is in itself an engine in our economy. A lot of new technology relies on it and we organize our society in ways where we take secure delivery of electricity for granted. Since humans have developed to rely so heavily on electricity, secure delivery of it is of vital importance. Imagine if a hospital lost its electricity supply, lives could be lost. In addition, the economic cost of failing to deliver electricity can be enormous. Although difficult to quantify, a report by Vista Analyse (2013) suggest that failing to upgrade the power infrastructure in the greater Oslo area alone would cost the society between NOK 86 - 160 milliards in net present value. The prospected transition to EVs will affect the structure of the power system and this thesis seeks to investigate how this transition will affect the security of electricity supply, which we have come to rely so heavily upon.

The security of electricity supply has two important aspects:

1. The power system's ability to deliver the electricity demanded (aggregated and instant capacity)
2. The power systems ability to maintain the quality of the electricity demand delivered (voltage quality and frequency balance).

This thesis will address the aspect of capacity and frequency quality by looking at demand-side changes of electricity consumption from EVs.

2. Research question

In light of the background for writing this thesis I want to look more closely on how the prospected transition to EVs from conventional cars in Norway will affect the security of electricity supply.

The research question I have chosen is:

How will the prospected transition from conventional cars to electric vehicles affect the security of supply of electricity in Norway?

To address the research question there are three important sub-questions that this thesis is concerned about:

1. How will the overall change in the consumption curve affect the security of electricity supply?
2. Does Norway have enough installed capacity to deal with future peak hour electricity demand?
3. Does the aggregated electricity demand from the EVs pose a threat to the security of supply?

The study is based on two scenarios for EV market penetration in Norway:

Scenario 1: 1 250 000 EVs
Scenario 2: 2 500 000 EVs

These scenarios will be used and compared with power system data from 2012, a year when the number of EVs in Norway went from around 5600 to 9500 and the consequences for the power system from EVs was practically non-existent (Grønn Bil, 2014).

2.1 Ambition: describe, explain and recommend

This thesis tries to shed light on the probable consequences of large-scale transition from conventional cars to EVs in Norway. Its objective is to describe and explain how such a transition will affect the security of supply in the power system. In the end it will point to factors that can alter these changes to the benefit of the security of electricity supply.

3. Literature Review

The literature on the EV's impact on the electricity grid seems to be rapidly expanding. A general comment to the existing literature is that most of the analyses and conclusions made in the papers available are geographically restricted to the area of research. This is natural because power systems in different geographic locations are different from each other. Some of these papers are presented briefly in section 3.2. below. In the case of Norway, there are very few papers on the consequences a large-scale transition to EVs will have on the power system. A paper by Vatne, Molinas and Foosnas (2012) looks into the consequences of a local EV-transition on the power grid in a municipality area in Norway. This is the only paper found that addresses the issue of EVs and the security of supply in Norway as of June 2014. Further research should be conducted on the subject.

3.1. Energy security

The concept of "energy security" or "security of supply of energy" has many aspects to it. Winzer's paper *Conceptualizing energy security* (2012) provides a good framework to distinguishing the different approaches to energy security. In this paper, energy security is a central topic and it is useful to understand exactly which part of energy security that will be addressed.

Winzer points to the many ways which energy security can be and has been described. The concept of energy security can take many viewpoints as is illustrated in Figure 1.

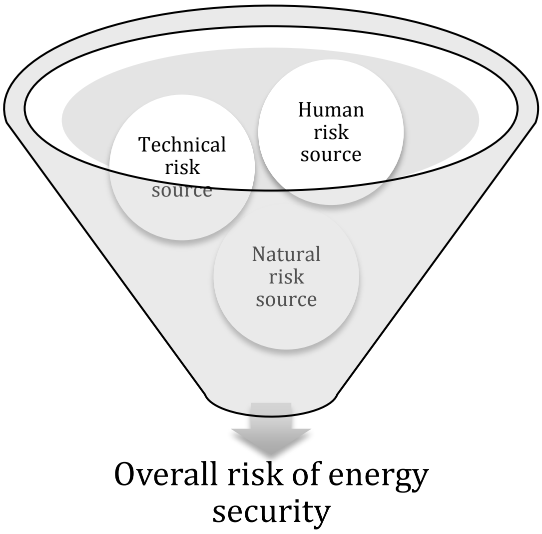

Figure 1: Energy security aspects. Adapted from Winzer (2012)

Winzer separates between three sources of risk when it comes to energy security: technical, human and natural. Technical risk is associated with factors such as mechanical failure and dependency on existing infrastructure. Natural risk is concerned with the risks originating from nature, such as natural disasters and resource depletion. Lastly, human risk is the risk associated with human activities such as demand fluctuations, sabotage and geopolitics. In this thesis, the human risk source of demand fluctuations is the primary concern: this thesis tries to look at how electricity demand changes as a result of a large scale transition from conventional cars to EVs. All the other important and valid aspects of energy security laid out in Winzer's paper will not be discussed in this thesis.

3.2. Studies on EVs and the power system

There are several studies that try to model the electricity demand from EVs and their effects on the power system in different places in the world. A common factor for these studies is that they are valid only in the area for which the research was conducted. This is explained by the fact that power systems and electricity consumption habits among consumers are different in different areas of the world. Another common factor for these studies is that they are not based on charging data from the EV-users themselves, rather, they simulate charging behavior by assuming when the EV-users are charging their vehicles. Weiller (2011) and Harris and Webber (2014) simulate the electricity demand from EVs in the USA by analyzing the driving behavior of American citizens. In short they assume that an EV will be set to charge after a trip. The study by Vatne, Molinas and Foosnas (2012) assume different levels of charging at different times during the day to look at the effect on a local power grid in Norway. They find that the local grid would be able to tackle a 63 per cent share of EVs. Yet another study by T. Masuta, A. Murata, E. Endo (2014) takes a similar approach of assuming when charging will occur.

All approaches are valid for scenario analysis, but the trustworthiness of each scenario conducted in these studies are undermined by the fact that the charging profile used are assumed, with no collection of actual charging data.

In this paper, charging data was estimated through a survey directed towards EV users. All of the studies mentioned have taken an anticipated scenario-based approach to model demand of electricity from EVs. This paper offers a similar analysis, but with charging data that comes from the EV users themselves.

4. Theoretical background: The Power system

4.1. Introduction

The effect of a large scale transition to EVs on the security of supply needs to be understood in the context of what the Norwegian power system looks like today and what it will look like in the future. This part of the thesis provides an introduction to basic concepts about the power system and its prospects. There are four important aspects of the power system that is specifically relevant to the research question that will be presented in this section:

1. The general characteristics of the Norwegian Power system
2. Peak demand: The power system's ability to deliver power during peak hours of demand
3. Aggregated demand: The overall ability to meet aggregated consumption throughout a year
4. The instant power balance: How variability in the consumption curve can affect the security of supply through the power balance

The above-mentioned points are presented below.

4.2. The characteristics of the Norwegian power system

4.2.1. Production and consumption

A high share of flexible hydropower characterizes the power system in Norway. Flexible hydropower can be turned on and off at almost no cost. Consequently most of the power production in Norway is adapted to the price situation in the electricity market. Generally flexible hydropower producers will generate electricity when the prices in the electricity market are high and save generation capacity when the electricity prices are low[1]. With normal conditions this means that flexible Norwegian power producers will generate more electricity during the winter than during the summer and more during

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[1] Flexible hydropower producers seek to optimize the value of the water in the reservoirs, by making a calculated decision on when to save water and when to produce. The water in a reservoir is said to have "water value" which the power producer seeks to optimize (NOU 2012:9).

the day than during the night. It follows that Norway typically exports electricity during the day and imports electricity during the night. Norway has approximately 50 % of the hydro reservoir capacity in Europe. This makes Norway's power system very flexible compared to more thermal dominated power systems in Europe (NOU 2012:9).

Electricity consumption in Norway follows the rhythm of everyday life. Figure 2 depicts three days of electricity consumption and production during November 2013. Consumption goes up in the morning, falls somewhat when people go to work, rises when people come home from work and falls again when the night comes. The nature of electricity consumption has a pro-cyclical effect on the electricity production. Because prices are higher when consumption is high, flexible power producers adjust their production thereafter.

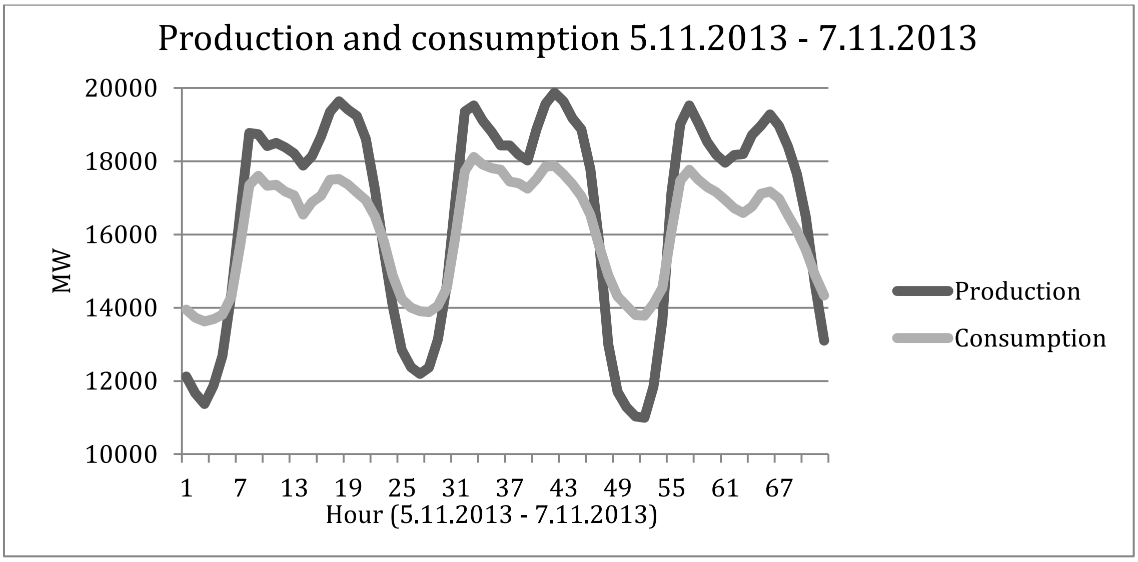

Figure 2: The flexible nature of the Norwegian electricity generation combined with the market mechanism has a pro-cyclical effect on domestic power generation. Data source: Nordpool Spot (2014)

Both prices and demand for electricity is higher during the winter when temperatures are low than during the summer. Flexible power plants therefore build up their reservoirs during the summer and use water during the winter. This can be seen in Figure 3. Production from flexible hydropower is relatively larger during the colder parts of the year (dark area), whereas inflexible hydropower (light area) dominates during the summer when precipitation is high. It follows that flexibility in production is higher during the winter than during the summer (NOU 2012:9). The thin line in the figure shows the precipitation throughout the year.

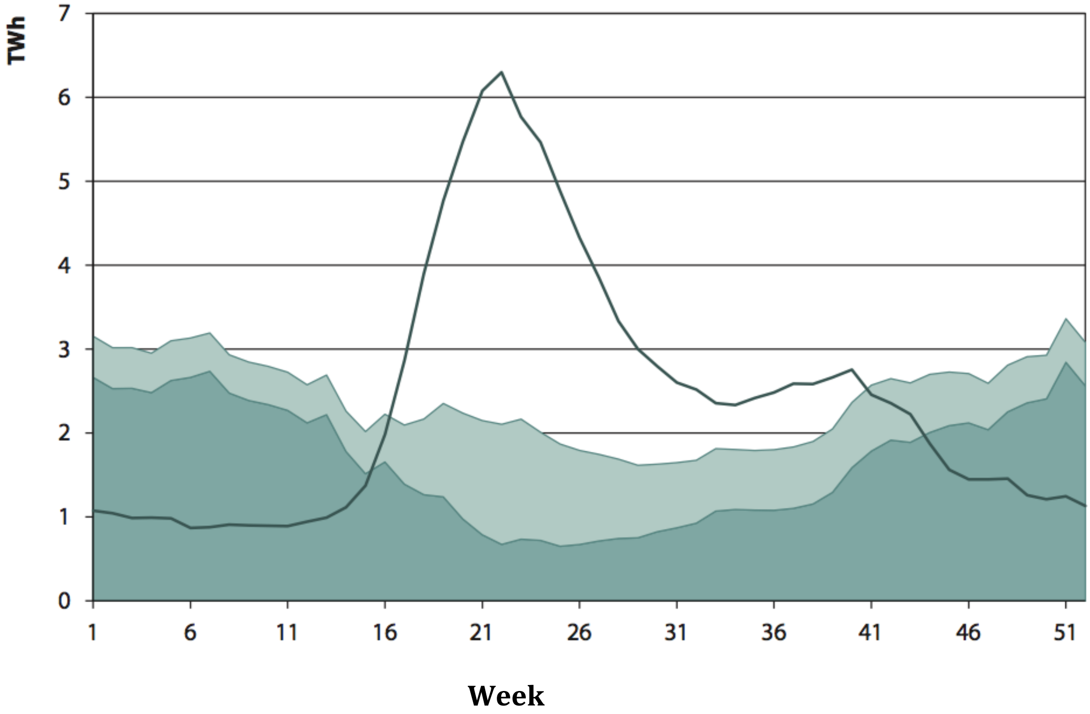

Figure 3: Hydropower characteristics. Source: NOU 2012:9 (2012)

4.2.2. Precipitation

The overall production of the Norwegian power system is dependent on the level of precipitation. Precipitation is the amount of rain and snow that falls over Norway. Because precipitation levels can vary quite a lot from year to year, so can the overall power production. Figure 4 shows the electricity production from hydropower plants since 1990. The difference between the lowest and highest recorded production levels during these years is 60 TWh. This is almost half the energy that the power system normally generates during a year[2].

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[2] According to NVE (2012a), the normal yearly production as of 2012 is 130,5 TWh

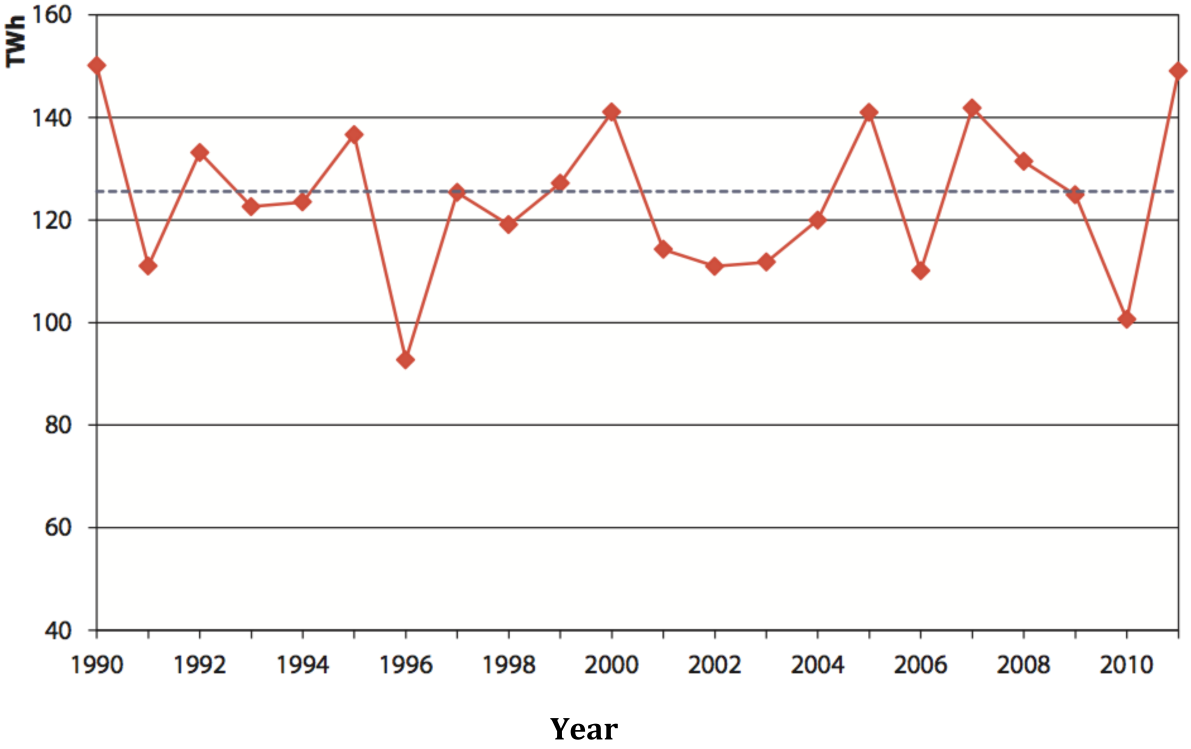

Figure 4: Hydropower production 1990 – 2011. Source: NOU 2012:9 (2012)

4.2.3. International trade

To tackle variable precipitation levels and for flexible power plants to exploit their flexibility, the power system is dependent on the ability to import and export electricity. The power cables that connects Norway's power system abroad is summarized in Table 1. It is meaningful to separate the power cables that are within the Nordic synchronous area[3] from the interconnectors out of the area. This has to do with the nature of the frequency balance, which is presented in section 4.5.

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[3] The Nordic synchronous area is presented in section 4.5.

International power line capacities as of June 2014 are given in Table 1 below.

International power line capacities		
Connection	**Import capacity - MW**	**Export capacity - MW**
Inside Nordic synchronous area		
Norway - Sweden	3995	3745
Norway - Russia	-	56
Interconnectors - outside Nordic synchronous area		
Norway - Denmark	1000	1000
Norway - Netherlands	700	700
Planned interconnectors - outside Nordic synchronous area		
Norway - Germany	1400	1400
Norway - Great Britain	1400	1400
Norway - Denmark	700	700
SUM		
Existing capacities	5695	5501
Existing and planned capacities	9195	9001

Table 1: Sources: ENTSO-E (2014) and Statnett (2014)

4.2.4. Nordpool Spot

The physical electricity trading in Norway and the Nordic synchronous system happens on the Nordic power exchange Nordpool Spot. Electricity is traded in capacity per hour. This thesis will not go into details about the market structures for electricity trade. Further information on how electricity trading is organized can be found at nordpoolspot.com.

4.3. Peak demand: Installed capacity

The power system’s ability to deliver electricity at peak demand hours is determined by the fraction of installed production capacity that is available at an instant moment plus the available import capacity. According to NVE (2012a), the total installed capacity in

Norway as of 31.12.2012 was 32 460 MW[4]. Table 2 shows the installed capacity by power plant type.

Power plant type	**Installed capacity - MW**
Hydropower flexible	24 457
Hydropower run off river	5 715
Wind power	811
Thermal Power	1063
Sum	32 046

Table 2: Overview of installed electricity generating capacity in Norway. Sources: e-mail from Audun Fidje, NVE, Ministry of Petroleum and Energy (2013) and Vindportalen (2014)

If all installed production capacity is exploited and all import connections run at full capacity, the theoretical maximum capacity is:

32 460 MW + 5695 MW = 38 155 MW

Because of variations in precipitation and wind-speed, all power plants cannot deliver their maximum capacity at the same time. The maximum available production capacity under normal conditions in Norway is estimated to be 26 200 MW as of March 2014 (Statnett, 2014. p 39). This makes approximately 80% of total installed capacity. The import capacity is subject to the power situation in the connected areas and therefore a high degree of uncertainty is connected to the available import capacity.

4.4. Aggregated demand: Normal yearly production

The normal yearly production of electricity is according to the Norwegian Water Resources and Energy Directorate 130,5 TWh as of 2012 (NVE, 2012a).

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[4] This deviates somewhat from the figure in Table 2. This is because different sources have been necessary to map the installed capacity by power plant type.

4.4.1 Prospects of installed capacity and yearly production

In addition to the planned interconnectors, the Norwegian-Swedish market for el-certificates has been established to support 26,4 TWh of new renewable electricity production between the two countries. Also, an estimated 10 TWh increase in the precipitation level is expected towards 2050 (NOU 2012:9. p 106). With increased capacity and precipitation levels an increased power surplus is expected for Norway towards 2020 (Statnett, 2014. p 41).

4.4.2. Domestic grid development

To strengthen the power grid's ability to deal with more transmission of electricity, Statnett is in the process of expanding and upgrading the power grid. Most of the old 300 kV high voltage lines are to be replaced by new 420 kV lines. This will improve the power system's ability to transport electricity in Norway and to tackle higher electricity loads in the power system. Domestic grid development is important to maintaining the security of electricity supply (Statnett, 2013).

4.5. Frequency stability

The power system has physical properties that require production and consumption of electricity to be balanced instantly at all times. If this balance is not maintained, the frequency of the power system will deviate from its accepted quantity. Frequency is measured in Hertz (Hz) and one Hz is equal to one cycle per second. Most power systems, including the one in Norway, have a frequency of 50 Hz.

Norway is a part of the Nordic synchronous area, which shares the responsibility to maintain the frequency at 50 Hz. The Nordic synchronous area consists of Norway, Sweden, Finland and eastern Denmark. It is the common task of the transmission system operators (TSOs) in these countries to maintain the frequency balance at 50 Hz. The frequency balance is therefore vulnerable to power system changes in all of the member countries. It is beyond the scope of this thesis to present and analyze the power system in all parts of the Nordic synchronous area and as such this thesis will limit its analysis to the Norwegian power system.

The consequences of frequency deviations can be severe damage on the power system, or worst case a total collapse (Statnett, 2012). In this sense it is meaningful to understand the stability of the frequency as a measure of security of supply; if the frequency is kept stable, the electricity will be delivered securely to the consumers.

4.5.1. Falling frequency quality

Since around year 2000 the frequency quality has weakened. Figure 5 measures frequency deviations in minutes per week in the Nordic synchronous system[5]. The increased frequency deviations are due to a combination of multiple factors. Statnett (2012) points to factors such as tighter market integration with the European grid, less available capacity in the grid, market design and more.

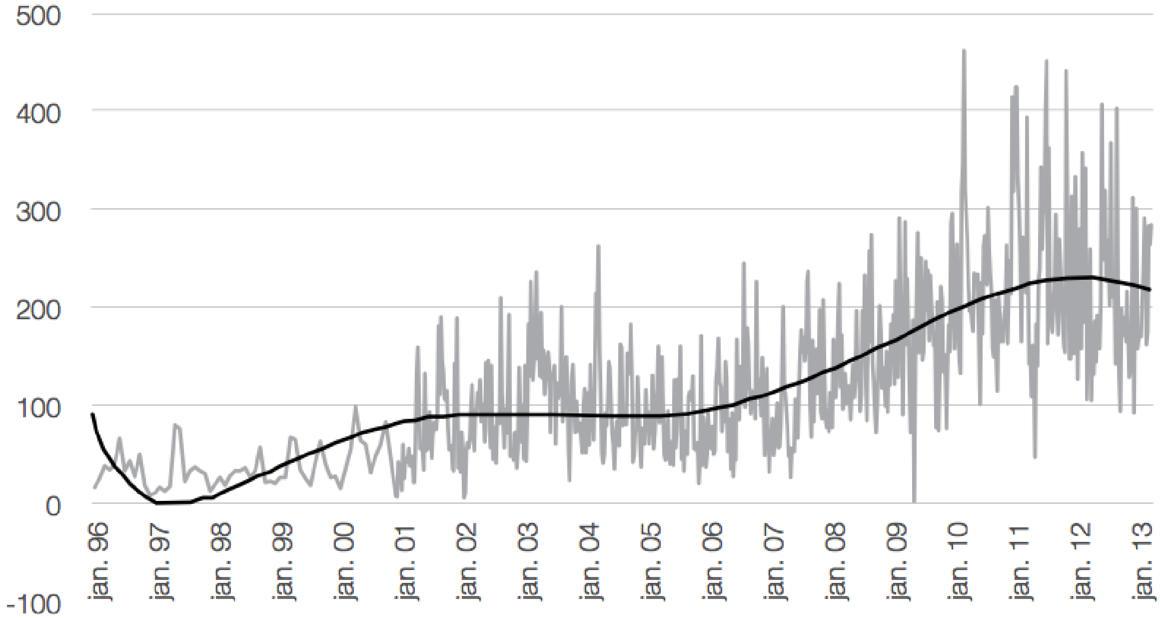

Figure 5: Frequency deviations in the Nordic Synchronous system in minutes outside 49,90 – 50,10 Hz per week Source: Statnett (2014)

The worsened frequency quality seems to concentrate during the early morning hours and the late afternoon hours. This is shown in Figure 6.

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[5] When the frequency falls below 49,90 Hz, or above 50,10 Hz, it is recorded as a frequency deviation (Statnett, 2012).

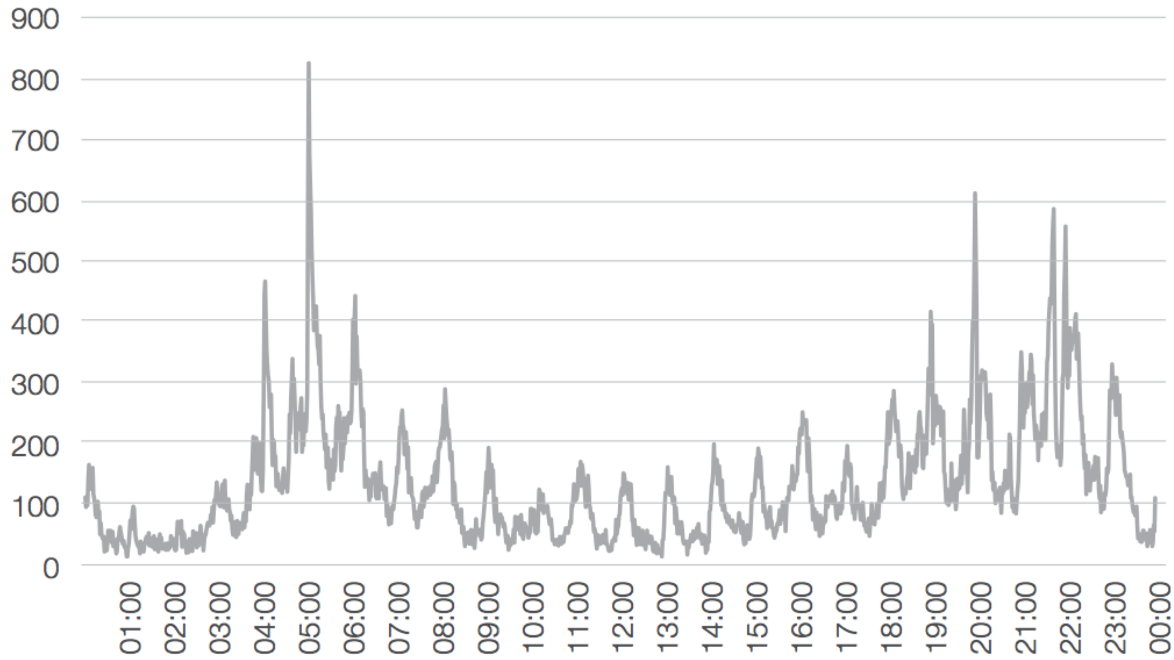


Figure 6: Average number of frequency deviations per hour per day during 2009 - 2010 Source: Statnett (2014)

The electricity demand is a corner stone of the frequency stability: demand dictates how production must adjust to maintain the frequency balance. With a large-scale transition to EVs, the electricity demand curve will change.

Frequency deviation cannot be explained by individual factors such as high consumption, low production, market design or ramping on the interconnectors alone. Rather, it must be explained by a combination of these factors. To maintain the frequency balance is therefore a complex task (Statnett, 2012). This thesis will look at how demand-side changes from a transition to EVs are likely to affect the frequency balance. It will not address the other aspects that affect how well the frequency balance is maintained. For a thorough introduction of the aspects around frequency quality, the reader is referred to Statnett's system- and market development plan (Statnett, 2014).

4.5.2. Ramping and ramping restrictions

The interconnectors in the Nordic synchronous system are subject to restrictions on pace of change on the flow of the electricity. Such change in flow is called ramping and the restrictions on the change of flow is called ramping restrictions. The current ramping restrictions on the interconnectors are (Statnett, 2012):

- Maximum 30 MW change per minute per connection
- Ramping is only allowed during 20 minute each hour: 10 minutes before and 10 minutes after each hourly shift.

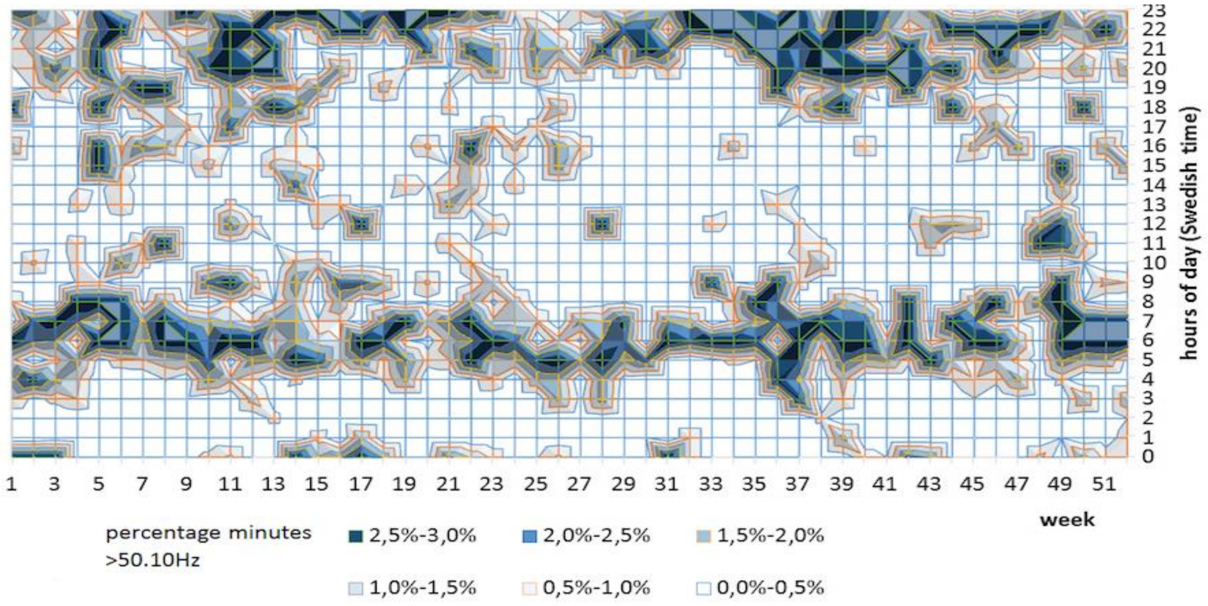
The restrictions are there to make sure that the change in load on the power system from the interconnectors are not too large to handle for the TSOs, with regard to maintaining the frequency balance. By limiting the ramping pace on the electricity load in the system, the possible change in the frequency as a result of the ramping is also limited. To be able to maintain a frequency of 50 Hz in the system, load changes from ramping must be coordinated and equalized with load changes from production and consumption within the Nordic synchronous system. With current arrangement of system operation and production control, unlimited ramping speed would not be ideal, because the system operators would have trouble maintaining the frequency quality (ENTSO-E, 2010).

The effect of ramping on the frequency quality and hence also the security of supply has been proven negative with the current arrangement (ENTSO-E, 2010). Alternative ramping rules are therefore being discussed among central bodies.

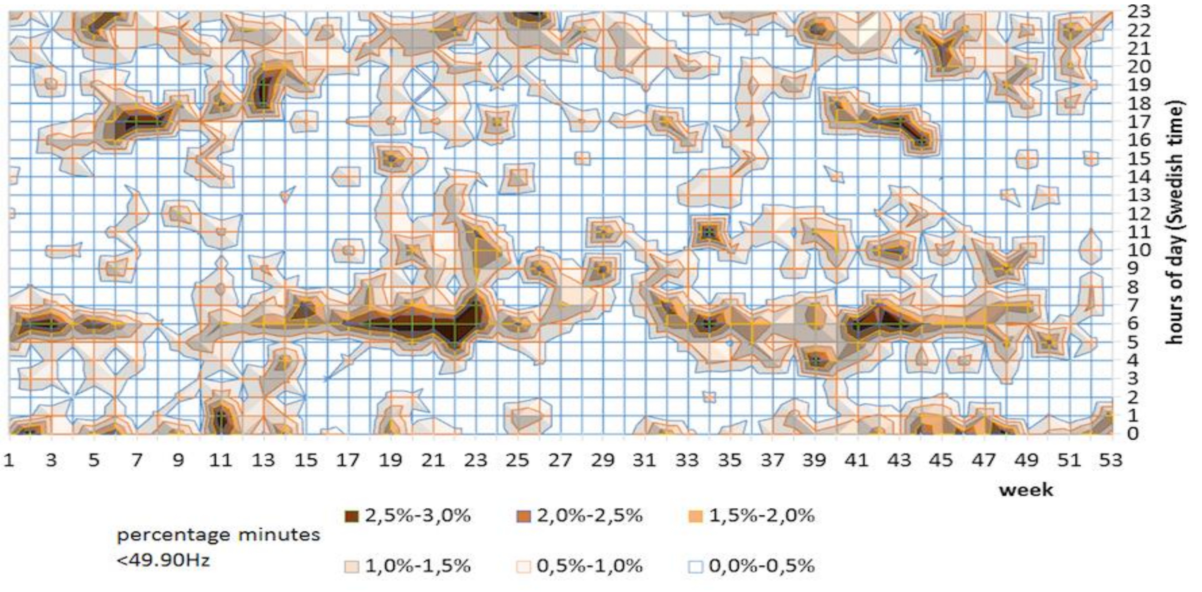
4.5.3 Frequency problems during “ramping hours”

The frequency quality in the Nordic synchronous region has been proven particularly weakened during the so-called ramping hours. These are the hours of the day when import goes to export and vice versa. This is also the time when ramping and consumption behavior changes the most during the day. Figure 7 (a) and (b) show average concentrations of frequency deviations per hour during September 2008 to May 2013. Darker areas indicate higher concentrations of frequency deviations, measured in percentage of minutes per hour.

How the frequency quality can be improved is a complex issue, and cannot be explained by a single factor alone. However, this thesis will assume that increased variability in consumption will weaken the frequency quality. This assumption implies that if variability in consumption is lessened, the frequency quality is likely to improve. When ramping, production and consumer behavior change at the same time, it is impossible to say which factor that causes the frequency quality to decline. The frequency quality data in the Nordic Synchronous system has not been collected and organized for quantitative analytical purposes, because such data does not exist yet. According to correspondence the author has had with Statnett, this is about to change.



(a)



(b)

Figure 7 (a) (b): Hourly concentration of frequency under 49,90 Hz (b) and above 50,10 Hz (a) in the Nordic synchronous system during the period September 2008 to May 2013. Source: Provided by Idar Grimmestad, Statnett.

4.5.4. Light system operation

Frequency quality in Norway is a larger problem during the summer months when overall electricity demand is smaller relatively to demand during the winter (Statnett, 2012). This can be explained partly by the fact that the size of a specific change in demand has relatively greater impact in a system where overall demand is small. This in combination with a generally less flexible production mix makes the frequency balance in the summer period of light system operation extra vulnerable to changes in consumption.

4.5.5. Implications from increased interconnector capacity

With increased interconnector capacity in the future, trade volumes out of the Nordic synchronous area are likely to increase. Because of policies to prevent global warming, the electricity market in Europe is seeing more intermittent electricity production from renewable energy sources such as wind and solar power. This implies that it needs more flexible capacity to ensure the security of supply, since intermittent power sources are by definition not flexible. This can be shown with a simple example: when there is little wind and sun in Germany, Germany will import power from Norway and when wind and sun is abundant in Germany, Norway will import electricity from these sources. In this way, Norwegian flexible hydropower will play a role in ensuring the security of supply in Germany and the European electricity market. Increased interconnector capacity in Norway is seen to have a positive effect on the capacity side of security of supply: In wet years Norway can export more of its power and in dry years it can import more. However, increased trade also means increased ramping on the interconnectors, which is seen as a challenge with regard to maintaining the frequency quality (NOU 2012:9).

4.6. Future Development – Smart grid

The smart grid seeks to enhance market efficiency and security of supply in the power market and power system, by improving communication between the consumers and the producers as well as the TSO. With the current market solution, information is not brought to the end consumer of electricity in a way that affects their behavior in the short run. End consumers such as private households can relate to the electricity price in the long term, which is defined here as a period over multiple days, but not in the short term, which is defined here as the time from one trading unit to the next (one hour to the next). An example might clarify:

If a household is informed about high upcoming electricity prices, they might take action to lower their electricity consumption in this period. However, since they only relate to the electricity price as one single price for all consumption, it does not make sense to alter consumption according to hourly changes in prices. If the end-consumers were exposed to the hourly electricity prices, they would be much better prepared to answer to changes in price. In this way, consumers will be incentivized to consume electricity when prices are low and save electricity when prices are high. With the current market design, prices are high when demand is high. Thus the smart grid is likely to facilitate a change in consumption behavior in that consumers will even out their electricity consumption.

Since the smart grid lies in the future, its successful implementation remains to be seen. This thesis will not include the smart grid in its analysis, but recognizes that the smart grid, if successfully implemented, will have a role to play in the enhancement of security of supply in the future.

5 Study Design

5.1. Overview of study design

The study design has been made to satisfy the three chosen aspects of the research question:

1. Overall change in consumption curve
Data was collected through a survey sent out to Norwegian EV-users in December 2013. The survey was designed to capture the EV-users charging habits. The collected data was used to model an electricity demand curve for a normal day, with two different scenarios for EV penetration.

Scenario 1: 1 250 000 EVs
Scenario 2. 2 500 000 Evs

Historical consumption data from nordpoolspot.com for 2012 was used as a foundation for the modeled scenarios. The modeled scenarios were analyzed by looking at the degree of variability in the overall consumption curves.

2. Peak load and peak production
The power systems ability to deliver instant effect has been analyzed by looking at the estimated maximum instant installed capacity under normal and tight conditions during the winter. These values have been compared to prospected peak loads based on the two different scenarios.

3. Overall demand from EVs in a year
A simple analysis on the overall demand from EVs during a year has been made based on data collected in the survey. This demand is analyzed in the context of the Norwegian power system's ability to meet this additional demand.

5.2. About the survey

The Norwegian Electric Vehicle Association distributed the survey through an e-mail newsletter to its members. With over 10 000 members, as of December 2013, it is the largest interest group for EV-users in Norway. The respondents were asked at what hours they charge their car and how far they drive their EV during a normal day. Also they were asked how strong electrical current they normally use during charging. A total of 398 EV users responded to the survey. The survey questions and answers can be found in appendix 2.

5.2.1. Representativeness

For the survey to be valid for statistical inference the respondents need to be representative to the entire population of EV users in Norway. Representativeness can be measured in many ways and it is important to identify the key parameters to control for representativeness. There is a vast literature on sample representativeness and it is a topic that must be understood in the context of the field of study. However, the basic idea is simple: the sample population should be similar in its structure to that of the entire population on those parameters that are considered important. Which parameters that are important are dependent on the population context and the goal of the survey. In this survey the parameters that are looked into with regard to representativeness are: sample size, availability of target population, demographic representativeness, EV type representativeness and gender representativeness.

Although there are certain representativeness issues with the data collected, the data is considered representative enough to use for statistical inference on behalf of the EV population. The representativeness parameters chosen are presented below. Further discussion on representativeness in general will not be presented in this thesis but can be found in e.g. Ramsey and Hewitt (2005).

5.2.1.1. Sample size

In order to be able to make statistical inference from the data generated from the respondents, the sample size must reach a certain level. Because of the nature of the collected data, this number is difficult to determine exactly because variability in the respondents' answers are difficult to measure. For example: the respondents were asked which hours during the day they are charging. This question has several answers and variability cannot be measured with a standard approach. Therefore variability and standard deviation must be assumed.

The formula for necessary sample size is (Qualtrics, 2013):

$$Necessary\ sample\ size = (Z - score)^2 * Standard\ Deviation * \left(\frac{1 - Standard\ deviation}{(margin\ of\ error)^2}\right)$$

If we use a 95% confidence interval, assume a standard deviation of 0,5 and a margin of error of 5%, which are standard assumptions for survey data (Qualtrics, 2013), we get:

$$Necessary\ sample\ size = 1{,}96^2 * 0{,}5 * \left(\frac{1 - 0{,}5}{0{,}05^2}\right) = 385$$

This means that, given the assumption of confidence and standard deviation, the sample size of 398 is statistically large enough to make statistical inference.

5.2.1.2. Survey questions, population and confidence

The survey questions and the population are clearly defined. The population is all EV-users in Norway and the survey questions can be found in appendix 2. The confidence however is not straightforward in this case. If we were asking how heavy the EV-users were, we would get some distribution and could calculate the confidence according to the distribution. The central question here is: "when do you charge your EV?" The way this question is answered does not allow us to make a statistical distribution like we could, had the question been about e.g. the weight of each person. Therefore we cannot say anything about the confidence.

5.2.1.3. Target population availability for sampling

The entire target population was not available for sampling. This is admittedly a weakness in the gathered data material: At the time of the sample the Norwegian EV Association had approximately 10000 members. At this time there were around 20000 EVs in Norway (Grønn Bil, 2014). Since the survey was distributed through the EV association's newsletter, only the members of the association were reached by the survey. According to Ramsey and Hewitt (2005) statistical inference can only be made on the population from which the sample was drawn. However, there is no reason to believe that the members of the EV-society are different from other EV-users when it comes to driving length and charging habits, which are the central factors of investigation in the survey. Therefore representativeness with regard to the availability of the target population is considered sufficient although roughly half of the population members where excluded from survey participation.

5.2.1.4. Geographic representativeness

We expect car-users in the same part of the country to have similar driving habits. This makes sense because distances and climate vary across the country. Geographic representativeness is therefore considered an important parameter for the overall representativeness of the sample population. Table 3 shows the geographic distribution of the sample population and the entire population at the time of survey distribution.

Area	Sample population distribution	Population distribution
Eastern Norway	57%	59 %
Northern Norway	2%	2 %
Southern Norway	6%	5 %
Middle Norway	6%	9 %
Western Norway	30%	26 %

Table 3: Demographic representativeness Source: The survey and Grønn Bil (2014)

To see if the sample population distribution is representative to that of the EV population, a two-sample Smirnov Kolmogorov (K-S) non-parametric test was conducted. The test results indicate that the sample population is representative to the entire population with regard to geographic distribution on a 5 percent significance level. The K-S test is not a hundred percent suitable to the data material investigated, but it nevertheless tells us something about the degree of representativeness in the sample population. For the entire K-S test statistics, see appendix 3.

5.2.1.5. Representativeness by EV type

EV-type is important because if the sample population is not similar in EVs to the entire population, the statistical conclusions' validity will be limited. An inherent weakness with the EV-type data is that it is changing rapidly as new EVs enter the market. After the survey was conducted new EVs such as the BMW i3 has gained significant market shares. This might change the aggregated charging pattern of EVs as new vehicles generally have larger batteries than the old ones: The Nissan Leaf has a 24 kWh battery pack compared to a Buddy's 14,4 kWh. Increased battery capacity might lead to relatively less charging during the morning and mid-day hours.

Sample population distribution(%)		Popultaion distribution (%)	
Nissan Leaf	48	**Nissan Leaf**	44,5
Tesla Model S	13	**Tesla Model S**	10,2
Mitsubishi i-MiEV	17	**Mitsubishi i-MiEV**	10,7
Peugot	5	**Peugot**	6,6
Citroen	6	**Citroen**	6
Others	12	**Others**	22,1

Table 4: EV model representativeness. Source: The survey and Grønn Bil (2014).

The K-S test results on the EV-type distributions indicate that the distributions are not similar on a five- or ten percent significance level. This weakens the strength of the conclusions in this study. However, when we eyeball the data we clearly see that the distributions are not radically different. Although the degree of representativeness with regard to EV-type could have been better, it is not miles away from being representative and the overall representativeness of the sample population is still quite good.

5.2.1.6. Gender

The gender composition in the sample population can be compared to that of the entire population to further strengthen or weaken the impression of the representativeness of the sample population. The distributions are presented in the Table 5.

Sample population		Entire population	
Male	76%	Male	57%
Female	24%	Female	23%
-	-	Organizations	20%

Table 5: Gender composition among respondents and population December 2013. Source: The survey and Grønn Bil (2014).

The table suggests that the sample population is overrepresented by males. This weakens the representativeness of the data. However if we assume that female and male EV-users drive and charge their EVs in a similar fashion, this lack of representativeness in gender is not a problem for statistical inference from the sample population. It might be that male and female drivers have different driving habits, but the author has not been successful in documenting either similarities or differences between men and women when it comes to driving habits. Therefore this thesis assumes that men and women in Norway have equal driving habits.

Summing up representativeness:

Well aware of some representativeness weaknesses in the data collected, this thesis will draw statistical inference for the entire EV-population. However, when embarking on the scenario analysis, the weaknesses in the data representativeness will limit the strength of the analysis and conclusions that follow.

5. 3. Scenario based modeling of the normal daily consumption curve

The modeling of the consumption curve in section 7 is meant as a best guess given the current available data sources. It is not meant as a prediction of the future, but rather a possible outcome of how the EV will affect the security of electricity supply in the future, based on today's charging habits. It is very likely that the charging habits will change over time and this will change the conclusions that follow in this thesis.

5. 4. Frequency deviation data

To analyze frequency deviations quantitatively is beyond the scope of this thesis. An analysis has been made based on an overview of the frequency data and a discussion of probable outcomes for the frequency quality with regard to changes in the electricity consumption curve. The analysis on frequency deviations deliberately does not include probable changes in production patterns and ramping on the HVDC lines. These factors are equally important as the consumption profile with regard to maintaining the frequency quality. Given the complexity of the problem, the analysis focuses on the change in electricity consumption curve solely.

The frequency deviation figures in section 4 are the best data sources available for frequency deviation. This undermines the robustness of the conclusions that follow, but the data is nevertheless valid for the purpose of a more broad qualitative discussion around frequency quality and the introduction of EVs in the Norwegian power grid.

6. Data from the survey

6.1. Main findings

The main finding from the survey is that slightly less than 1/4 of the EVs from the sample population charge simultaneously during a normal day of charging[6]. The peak hour is between 3-4 in the night where almost 24 per cent of the EVs are charging. The driving distance on a normal day for the sample population is slightly less than 60 km. The average charging time on a normal day is 3,75 hours. An interesting discovery is that these values vary between different types of EVs. For example the Tesla Model S owners in the sample have a different charging pattern than the Nissan Leaf owners. The data are presented below.

6.2. Respondents

Most of the 398 respondents in the survey are from the eastern part of Norway (ca. 56%). This is expected, as the highest concentration of EVs in Norway and the world is in and around Oslo.

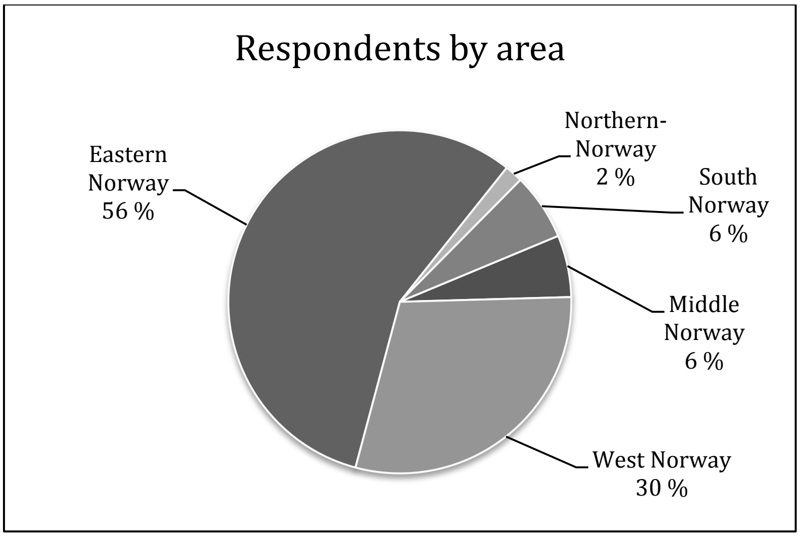


Figure 8: Respondents by area.

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[6] The wording ”normal day of charging” was deliberately used in the survey to capture the charging that occurs during the days of normal usage.

6.3. EV models

The car most frequently used among the respondents is the Nissan Leaf, followed by Mitsubishi i-MiEV and Tesla Model S. The mix of EVs is at a turning point at the time of writing this thesis. The new, larger models such as Nissan Leaf, Tesla Model S and VW e-up are replacing not only smaller EVs such as Buddy and Think, but also conventional cars. The distribution of EVs is changing rapidly as new models are introduced to the market.

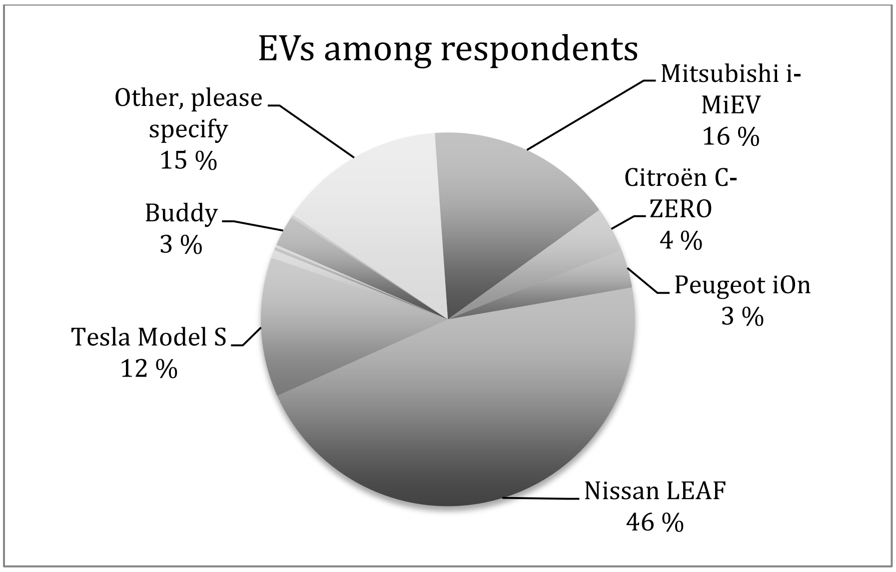

Figure 9: EVs among respondents *"Others, please specify" is primarily Think City users.

6.4 Driving distance

According to the survey the average normal driving distance during a day is approximately 57 km. The Nissan Leaf and the Tesla Model S users have a higher "normal driving distance" in the survey with ca. 64 and 70 km per normal day respectively. The word "normal" was specifically chosen instead of "average" in the survey question: It is the driving distance that succeeding charging that occurs on a "normal day" that is interesting to look at when analyzing the consequences for the power system.

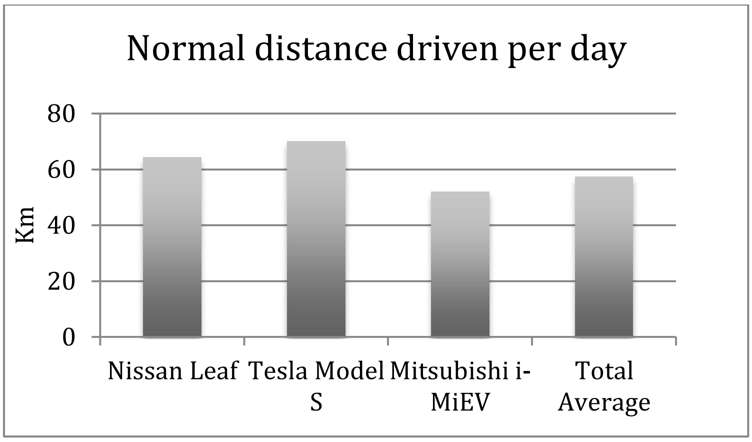

Figure 10: Normal driving distance per day.

6.5. Charging data

The respondents were asked to cross out all the hours that they normally charge their EVs within 24 hours. Figure 11 shows the answers. The results indicate that no more than around one fourth of the EVs are charging simultaneously during a day. The peak hour is from 3 to 4 am where 23,12% of the respondents said they are charging their EVs. The hour from 15 and 16 pm is the trough where only 2,76% of the respondents said they are charging. The period from around 19 pm to around 5 am is the consecutive period where relatively more EVs are charged than during the rest of the day. During this period around 20% of the EVs from the survey stated that they are charging.

A plausible explanation for the charging pattern is that most people do not use their EV during the evening and night. Those who take their EVs to work during the morning put it to charge when they arrive at work. Then charging decreases until people start to come back from work in the afternoon at around 16 – 17 pm. A surprising feature of the data is that relatively few of the respondents state that they charge simultaneously.

Normal driving distance (km)	57,40
Average ampere value	13,80
Normal charging hours per day	3,75
Normal kWh/km*	0,207
Number of respondents	398

Table 6: All respondents' user specifics.

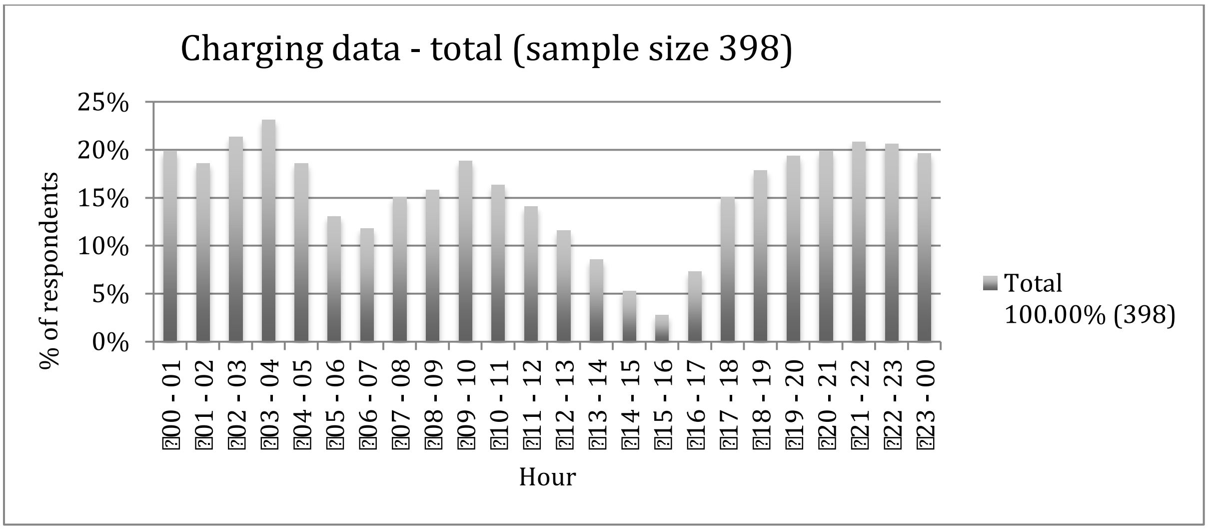

Figure 11: Charging data all respondents.

The EVs in the survey are ranging from relatively old EVs such as the Think City, to the newest models such as Nissan Leaf and Tesla Model S. If these EVs have different charging patterns it can have implications for the future charging-pattern of EVs. Under follows the charging pattern of the most popular models at the time of writing this thesis.

6.5.1. Nissan Leaf

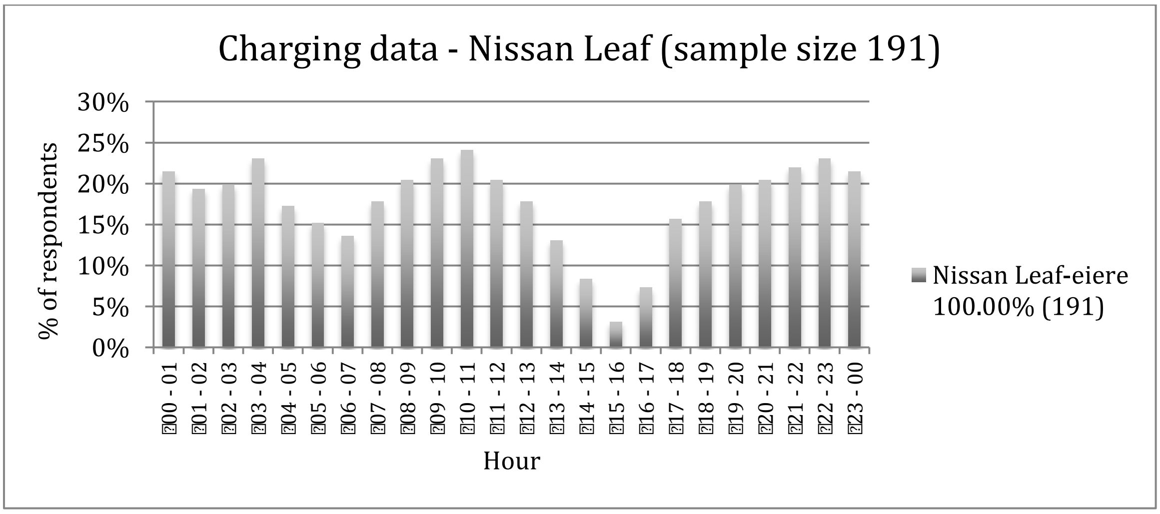

Figure 12: Charging data for Nissan Leaf users.

The Nissan Leaf is the car with the largest market share among EVs in Norway at the time of writing this thesis. The car is similar in size to a VW Golf and has become very popular, being the most sold car overall in Norway in September 2013 and the third most sold car among all cars in Norway in 2013 (Grønn Bil Statistikk). The charging pattern seems to be quite similar to that of the total sample, but with relatively more charging during the "come to work-hours" from 8 pm to 12 pm and overall 0,5 hours longer charging per day than the total sample.

Normal driving distance (km)	64,26
Average ampere value (A)	13,52
Normal charging hours per day	4,26
Normal kWh/km*	0,206
Number of respondents	191

Table 7: Nissan Leaf users specifics.

6.5.2. Tesla Model S

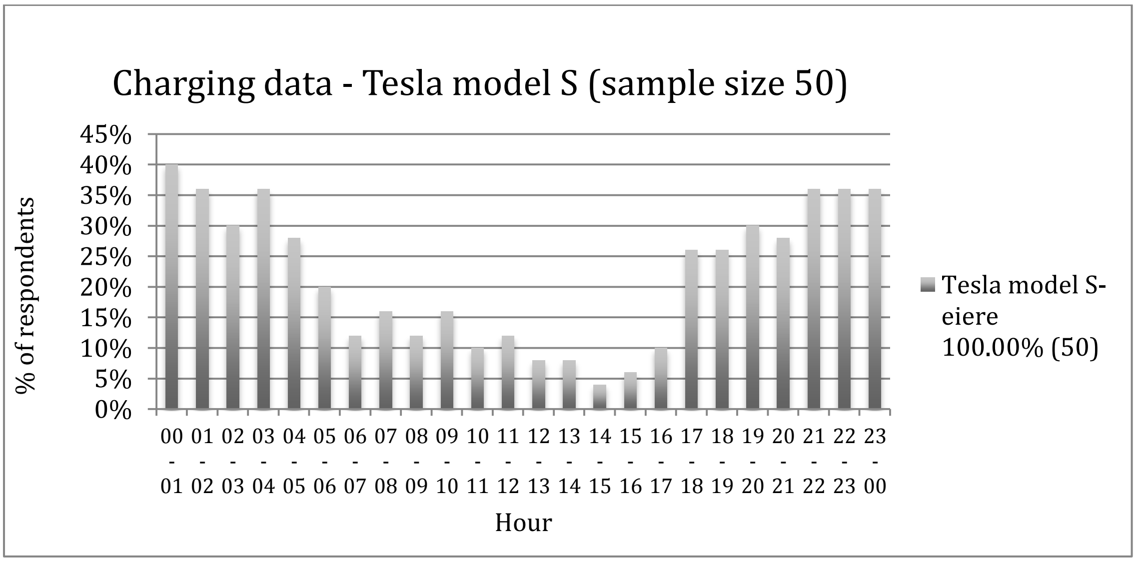

Figure 13: Charging data for Tesla Model S users.

The Tesla Model S is the largest EV on the market with the largest battery pack as of June 2014. Its charging pattern is according to the survey different from that of Nissan Leaf and the total sample as a whole. Charging during the afternoon and night is clearly more normal with peak hours around 35%. Tesla Model S users drive their cars over longer distances and charge for longer hours with higher ampere. According to the survey data the Tesla Model S also consumes more energy per km than the other cars. The entire survey population has an average kWh/km consumption of 0,207 whereas the Tesla Model S has consumption about 50% higher with 0,320 kWh/km.

Tesla Model S user specifics:

Normal driving distance (km)	70,06
Average ampere value (A)	18,70
Normal charging hours per day	5,22
Normal kWh/km*	0,320
Number of respondents	50

Table 8: Tesla Model S users specifics

6.5.3. Mitsubishi i-MiEV

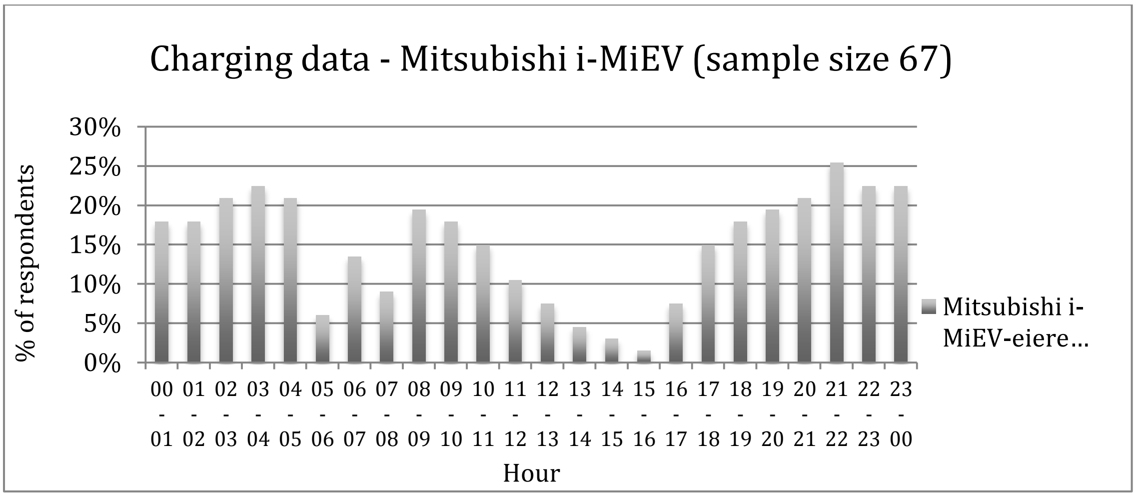

Figure 14: Charging data for Mitsubishi i-MiEV users.

The Mitsubishi i-MiEV users drive shorter distances and charge fewer hours that the average EV-user in the survey. The charging pattern during the day and night is similar to that of Nissan Leaf and the aggregated sample population.

Normal driving distance (km)	51,98
Average ampere value (A)	13,97
Normal charging hours per day	3,58
Normal kWh/km*	0,221
Number of respondents	67

Table 9: Mitsubishi i-MiEV users specifics

6.5.4 Fast charging

Figure 15 shows the respondents answer to the question: ”How often do you charge your EV with a fast charger?” The results show that fast charging is still a rare activity. Only 1,26% of the respondents said that they charge daily with a fast charger. 38,38% said that they never use a fast charger. The results can be explained by two factors:

1. The access to fast chargers is limited
2. People charge their car at home and they normally do not need to take use of a fast charger.

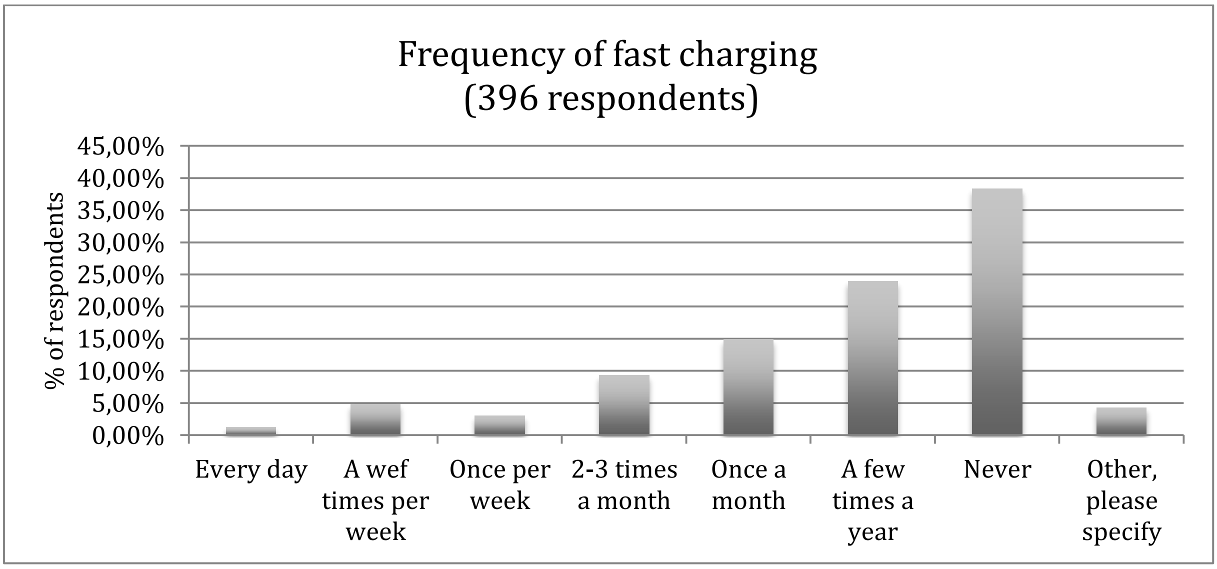

Figure 15: Frequency of fast charging all respondents.

The few who use fast charging seem to be using it during the middle of the day, when normal charging activity is relatively low. However, the number of EV users that use fast charging is so low that the implication for the consumption profile is practically non-existing. The survey respondents were asked when they normally use or would have used a fast charger if that was their normal way of charging. Figure 16 shows the respondents answer. It is interesting to note that if fast charging becomes the standard way of charging, the charging distribution is likely to look very different from the charging profile observed in this survey, with a higher concentration of charging during the day than during the night.

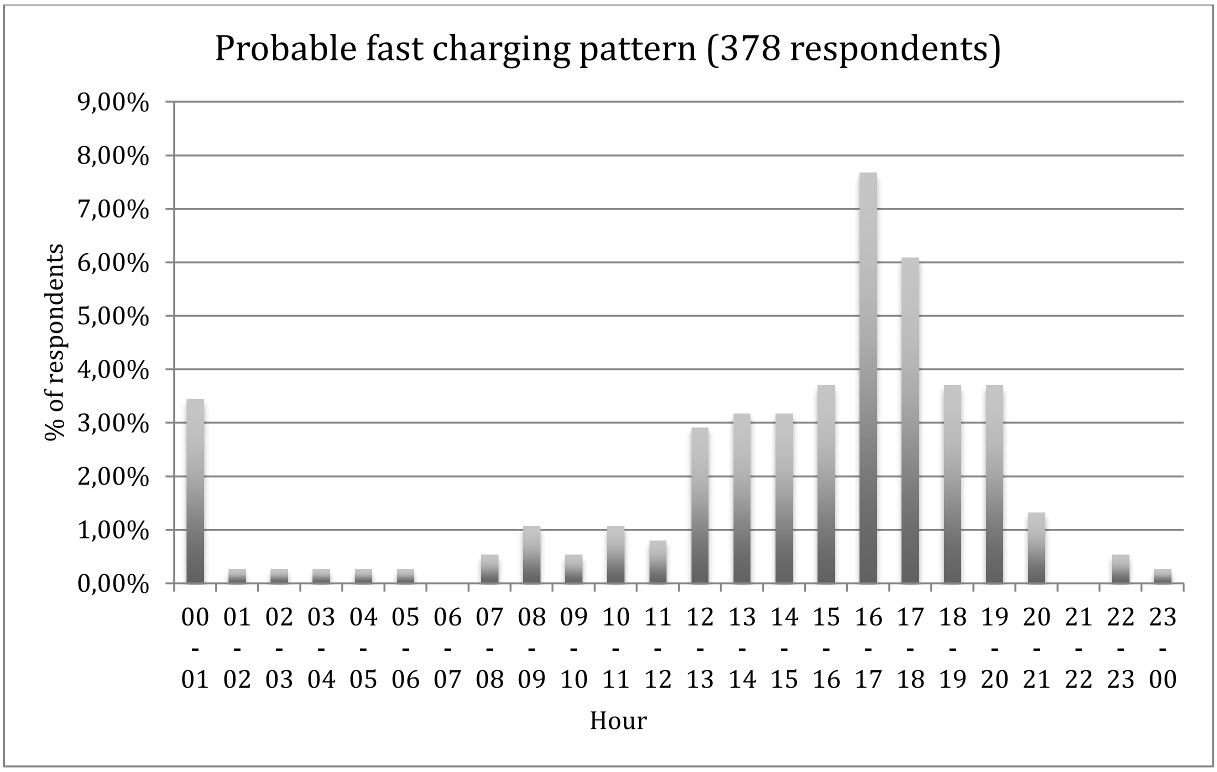

Figure 16: Survey respondents answer to the question: When do you/would you use a fast charger during a normal day?

7 Analysis

The following analysis is based on two different scenarios for EV penetration. This sections look at what happens if we get 1 250 000 EVs and 2 500 000 EVs in Norway given the consumption profile of 2012. These numbers are chosen specifically because they represent roughly half- and the entire personal car park in Norway at the time of writing. The author is well aware that the consumption profile will change further with other new gadgets and trends in electricity consumerism, but the purpose of this analysis is to look at how EVs isolated are likely to affect the overall consumption profile and use this to look at the consequences for the security of supply.

7.1. Main findings

The main findings of the analysis is that a large-scale transition to EVs given charging habits as of December 2013, will alter the consumption curve in a direction of *increased variability*. With today's power system, the analysis finds that the security of supply with regard to the power balance will be slightly worsened by a large-scale introduction of EVs. This effect is likely to be more prevalent during the summer than during the winter, because the relative change in the consumption curve is higher during the summer than during the winter with the EV scenarios.

Another important aspect of the security of supply is the aspect of peak load. The data collected suggests that, at the most, about 1/5 of EVs in Norway charge simultaneously. EVs will contribute to additional demand during peak hours and in today's power system contribute to a worsened peak demand situation with regard to the security of supply.

The aggregated demand from the EVs through a year will not pose a threat to the power system's ability to deliver enough electricity through a year.

Overall a large-scale introduction of EVs will likely worsen the security of supply of electricity in Norway *given today's power system*. However, the planned development of the power system will limit the impact from an EV-transition on the system. If EV-charging can be led to the right hours during the day, an EV-transition can improve the overall security of supply by limiting the relative size of the peak hours and decreasing the variability in the consumption curve.

7.2. Analysis layout

There are three different aspects addressed in the following analysis:

1. The overall change in the consumption profile
2. Analysis of the theoretical peak demand hour
3. Analysis of overall demand from EVs

7.3. Overall change in the consumption profile:

A large-scale transition to EVs will change the daily consumption profile of Norwegian electricity consumption. This change is important because it will have consequences for Statnett, with regard to maintaining the frequency balance in the power system. This section displays how the change will occur based on average hourly consumption data for each season during 2012 combined with the modeled electricity consumption from EVs, based on the data collected in the survey. The EV market penetration is split in two scenarios:

Scenario 1: Average 2012 consumption plus the modeled demand from 1 250 000 EVs
Scenario 2: Average 2012 consumption plus the modeled demand from 2 500 000 EVs

The scenarios are analyzed by using seasonal power consumption data from 2012. Because of seasonal variations in the elctricity demand, an individual analysis of the scenarios have been conducted for all four seasons. A thorough analysis on the winter is presented first, followed by a short presentation of the other seasons. This is because the daily consumption pattern is similar in all four seasons. Because the survey data is exploited to estimate the charging pattern in both scenarios, the scenarios are assumed to have simmilar EV charging patters.

A Tesla Model S scenario is also presented in this section to illustrate how different charging behavior affect the results. The analysis is summarized in the end of the section.

7.3.1 Winter

Figure 17 shows average hourly electricity consumption for December through February and the same data plus scenario 1 and 2. In the EV-scenarios the consumption profile changes toward a more defined double peak-profile with one peak in the morning and another peak in the afternoon. The charging habits from the survey increases the afternoon peak more than the morning peak, relatively speaking. This is because very few EVs charge during the hours just before the afternoon peak and quite a lot of EVs are charging just before the morning peak begins.

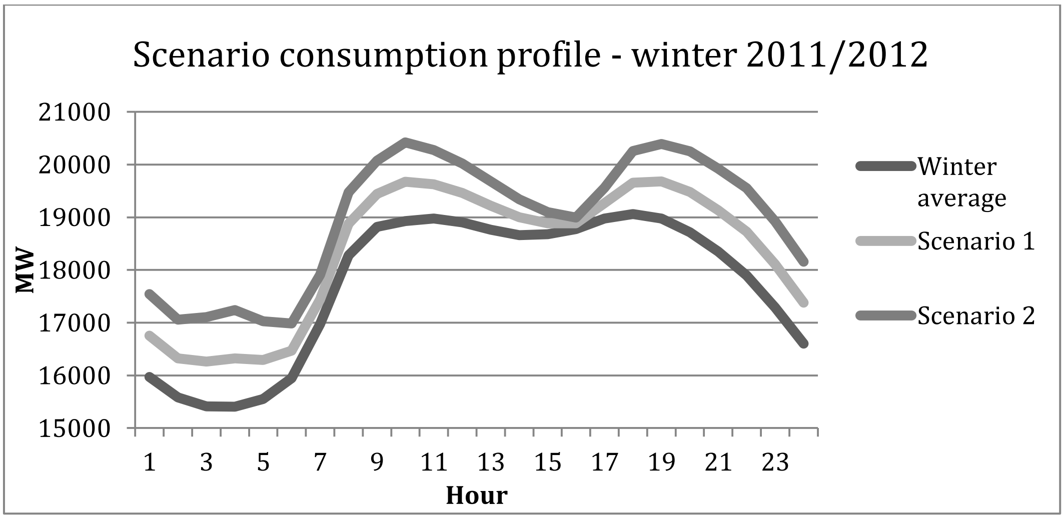

Figure 17: Scenario consumption winter.

To get a grasp of what the consequences are with regard to maintaining the frequency balance, the sum of the absolute value of the hourly consumption differences for each profile has been calculated. Formalized this value is:

$$\sum_{n=1}^{n=23} Abs(C_{n+1} - C_n)$$

Where C_n is electricity consumption in hour n and C_{n+1} is electricity consumption in hour $n+1$.

The sums of hourly consumption differences for the Winter average and the two scenarios, hereby the sum of differences, are given in Figure 18. This number can be interpreted as the overall change in consumption during a day, with consumption treated as a discrete variable[7]. The sum tends to increase with the number of EVs. This generally means that more EVs induce more change in the consumption profile and hence a requirement for more adjustment of production and import/export to maintain the frequency balance. This result must be interpreted with some caution, as the limited number of respondents in the survey makes the scenario-curves more edgy than they likely would have been had the scenarios been the real[8]. The edginess of the curves increases the value of the sum of differences. The sum of differences has been calculated with a simple 3 point moving average of the charging-habit data (see appendix 1). With the simple moving average the sum of differences increase slower, but the same general trend is present: With more EVs the sum of differences increases and the overall variability of the consumption curve increases.

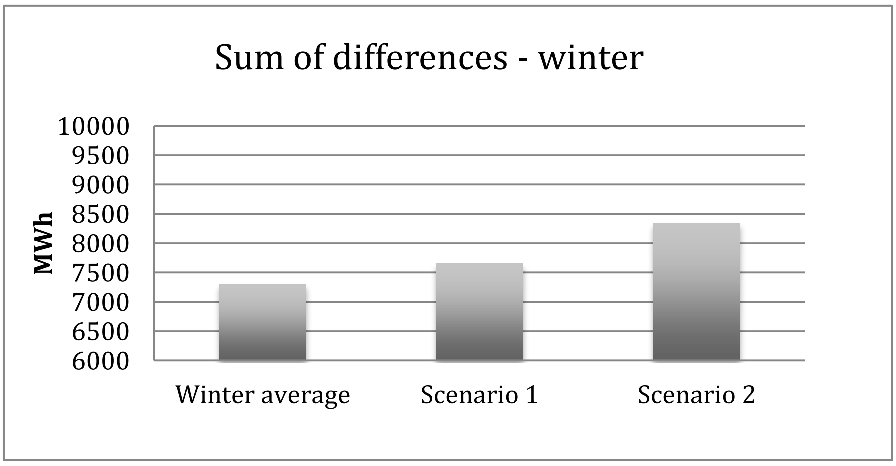

Figure 18: The sum of differences as a 3-point moving average during a day.

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[7] Electricity consumption is by nature a continuous variable. However, the data for consumption is provided as discrete data.

[8] This has to do with the treatment of the data: The electricity consumption data is treated in discrete form, but it is continuous in nature. A simple moving average of the charging data pictures a more continuous version of the data.

During the winter a large-scale introduction of EVs will increase the variability of the consumption curve, more so for scenario 2 than scenario 1. Section 4.5. shows that the frequency balance is especially vulnerable during the morning hours. A factor that affects this vulnerability negatively is the size and speed of the change in the demand curve during this period. Therefore it is interesting to see how the EV scenarios would change the nature of the morning peak hour.

7.3.1.1. Morning peak analysis

The consumption peak during the morning will according to the gathered data be slightly worsened in scenario 1 and 2. That is to say: the relative gap between the low electricity load during the early morning and the high load right before noon increases with scenario 1 and 2. Figure 19 shows this increase. The numbers are calculated by dividing the difference between hour 9-10 and 5-6 by the average load size during the hours from 5-10. A higher value indicates that the relative change in consumption is higher. This increasing trend through scenario 1 and 2 is explained by an increasing percentage of charging EVs during the morning hours. If the trend had gone the other way and EV users disconnected their EVs during the morning, the morning peak would have been decreased instead of increased.

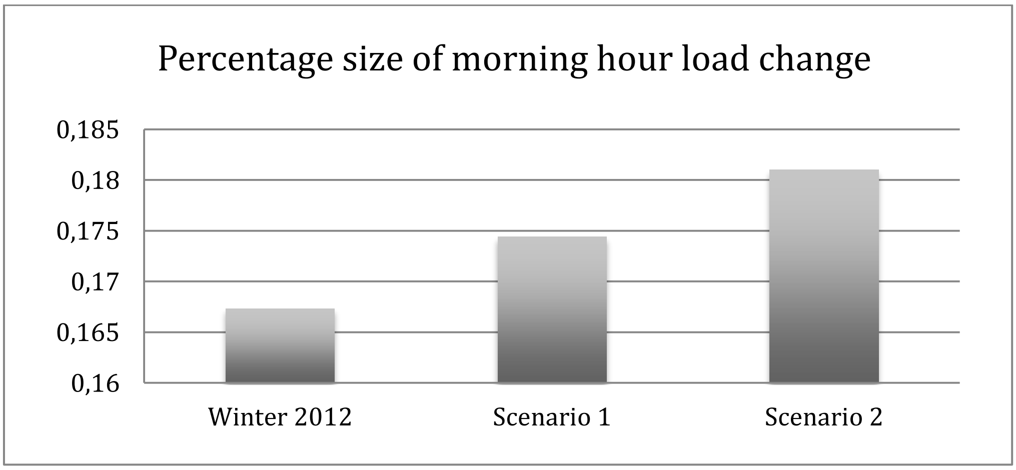

Figure 19: Morning peak difference divided by average morning load.

7.3.2. Spring

Figure 20 shows average electricity consumption for March through May 2012 and the same consumption with the modeled demand from scenario 1 and 2. Similar analysis as for the winter consumption has been done for spring. Most of the lessons learned in the winter consumption analysis apply for spring as well: The overall consumption curve has a more defined two-peak shape than before and the sum of differences increase as more EVs are entering the system. The trend for the morning hour change in the winter is also present during the spring, summer and autumn. The overall change in demand and morning hour peak for the spring can be found in section 7.4.

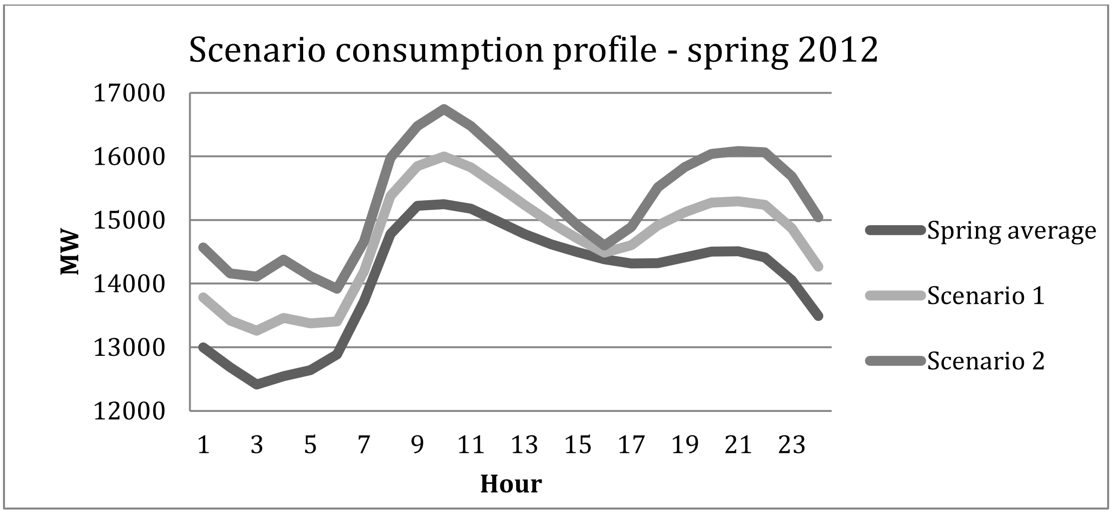

Figure 20: Scenario consumption spring

7.3.3. Summer

The summer season is particularly vulnerable to rapid changes in consumption because of light system operation and a relatively inflexible production mix. Figure 21 shows average electricity consumption for June through August with and without the two scenarios.

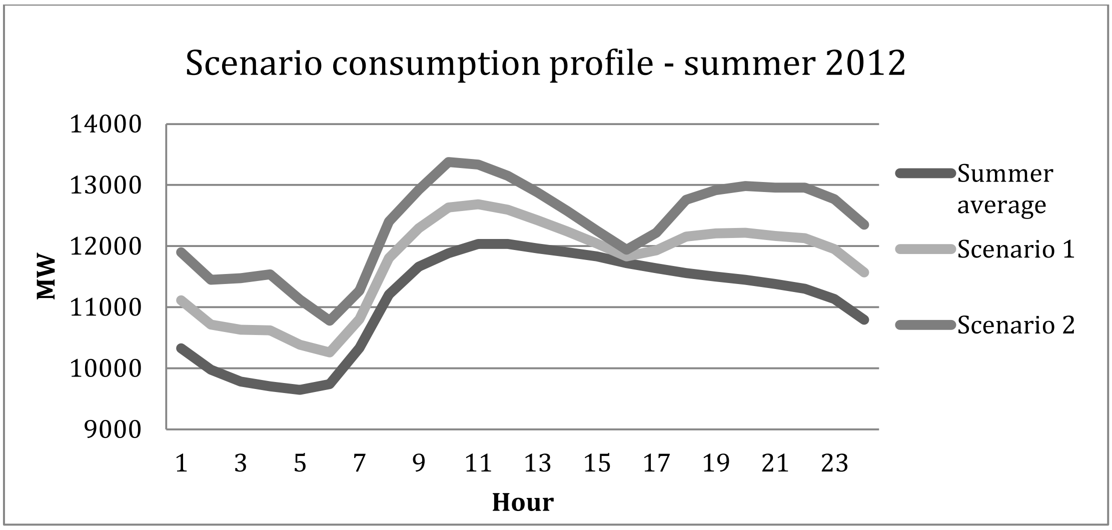

Figure 21: Scenario consumption summer

The sum of differences- and the morning peak change figures for the summer is summarized in table 24 and 25.

7.3.4. Autumn

Similarly to the other seasons the demand curve in the autumn changes towards a more defined two-peaks shape with scenario 1 and 2. Figure 22 shows average electricity consumption for September through November and the same consumption with the modeled demand from scenario 1 and 2.

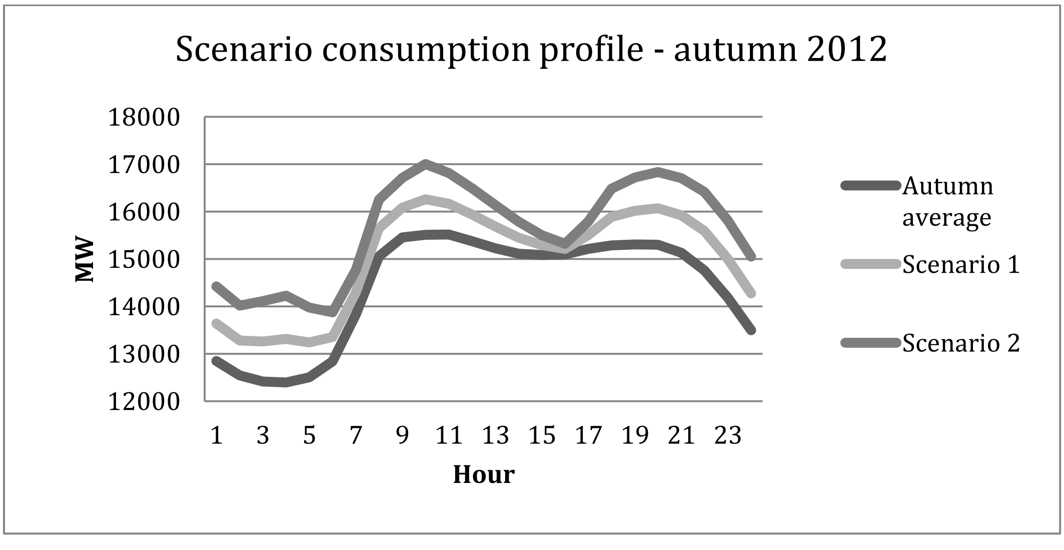

Figure 22: Scenario consumption autumn

During the autumn the sum of differences shares the general trend with what we see during the winter, spring and summer: the sum increases with more EVs, which means that variability in the consumption curve increases for the autumn as well.

7.3.5. Tesla Scenario

The development of the EV is very much an ongoing process and it remains to be seen what the conventional EV of the future will look like. However, if the EV is to replace the conventional car it can be argued that it needs to possess similar properties to it. The EV that has come closest to replicating the properties of a conventional car is arguably the Tesla Model S. What particularly stands out with this EV is that its range is a lot better than that of the others. On the assumption that the future of the EV is similar to today's Tesla Model S, what would the electricity demand from EVs look like?

The charging profile for Tesla users seem to differ quite a bit to the other EV users charging profile (see figure…). The Tesla Model S users to a larger extent charge their vehicle during the afternoon and night that the other EV-users do. The reason for this remains unknown, but a plausible explanation might be the high capacity of the battery.

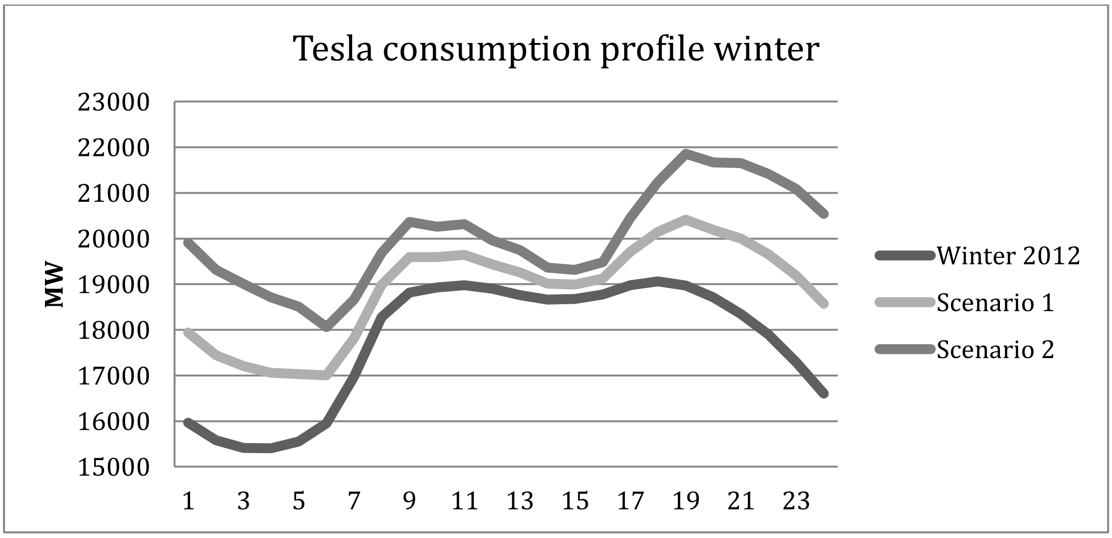

Figure 23: Tesla consumption profile with 3-point moving average values of charging behavior

Figure 23 shows average electricity consumption for the winter 2011/2012 and the same consumption with the modeled demand from scenario 1 and 2 with Tesla Model S cars only. The absolute change in the charging profile is larger than in the other scenarios. This is due to the fact that Tesla Model S users charge for longer hours and at a higher ampere value. It is not realistic that the future Norwegian EV-fleet are all similar to Tesla Model S, which is a large and heavy vehicle that needs more electric power per kilometer than its fellow EVs. But, it is not unlikely that the ampere value the Tesla-users charge with, which is higher than that of the rest of the sample population, is closer to the future normal ampere value than what is observed in the survey in general. This is grounded in an expected increase in the ampere value when charging, as more homes are equipped with charging infrastructure for EVs. Also, if the range for EVs is improved in the future, the charging profile might look more similar to that of the Tesla Model S.

7.4. Overall change in demand curve: Summing up

All other factors held constant, a large-scale transition to EVs seem to increase the variability, expressed by the sum of differences, in the consumption curve for all four seasons and the Tesla Scenario.

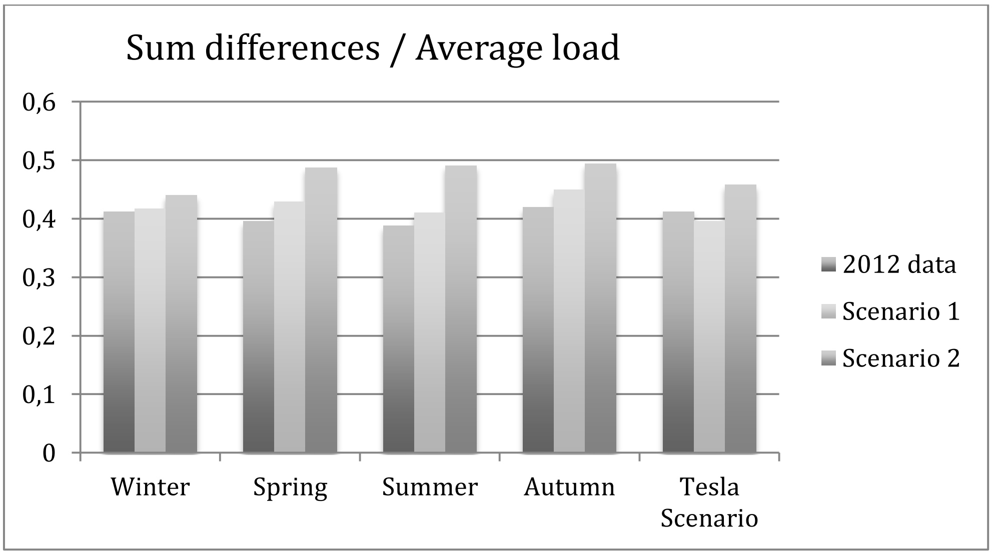

Figure 24: Sum of differences divided by average load with 3-point moving average data

Figure 24 depicts the sum of hourly consumption differences divided by the average load for each of the scenarios and for each season. Another way to put it is that the figure shows the sum of changes in consumption as percentage of the average load. A higher percentage value indicates that the consumption curve varies more. The trend of increasing variability with more EVs also varies between the seasons. During the winter the additional demand from EVs does not affect the overall change in the consumption curve as much as during the milder seasons. This is because the demand from the EVs in the winter constitutes a smaller part of overall demand than what it does in the milder season when the overall load is smaller.

7.4.1. Moring hour peak analysis

In part 4 it was showed that the frequency deviations are especially present during the morning hours when demand increases rapidly. The consumption peak during the morning will according to the estimated consumption profiles be somewhat increased in scenario 1 and 2. That is to say: the relative gap between the low electricity load during the early morning and the high load right before noon increases with scenario 1 and 2. Figure 25 shows this increase for all seasons. The numbers are calculated by dividing the difference between hour 9-10 and 5-6 by the average load size during the hours from 5-10. A higher value indicates that the relative change in consumption is higher. This increasing trend through scenario 1 and 2 is explained by an increasing percentage of charging EVs during the morning hours. Probably it has to do with EV-users plugging in their EVs when they arrive at work. If the trend had gone the other way and EV users disconnected their EVs during the morning, the morning peak could have been decreased instead of increased. In the Tesla Scenario the morning peak is decreased and the security of supply in the morning is improved. This is explained by the seemingly large fraction of Tesla Model S users that charge their car during the night.

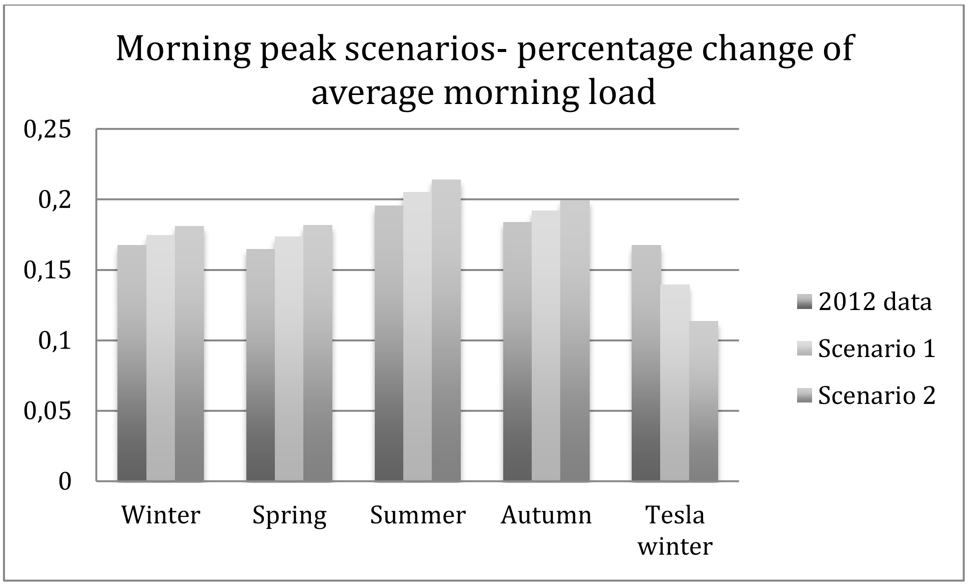

Figure 25: Relative change in size of morning peak in all four seasons and the Tesla Scenario

In all figures the demand from the EVs are modeled according to the results from the survey. The survey did not separate between seasons and asked only how charging was conducted during a "normal day". As such the figures should be interpreted with caution.

7.5. Peak demand

This part of the analysis will address the question:

Does Norway have enough installed capacity to deal with peak hour electricity demand in scenario 1 and 2?

First a brief description of the factors that determine the maximum instant generation capacity will be presented and an assumption of normal and tight maximum available capacity will be taken. Then the yearly Norwegian electricity consumption records during one hour for the last four years will be presented. The highest number will be put together with scenario 1 and 2 to look at the maximum estimated instant demand. This number will be compared to two levels of assumed available capacities, a normal- and a tight level. A sensitivity analysis will be presented before the average peak demand is compared with the assumed normal and tight maximum available capacity. At the end a brief paragraph of the main findings is presented.

7.5.1. Instant electricity generation and its vulnerability in Norway

During the winter the Norwegian electricity generation mainly stems from the hydropower plants with reservoirs. Because of the low temperatures, there is not much water that flows through the run of river plants. It is well known that power shortages can occur in Norway. The winters of 2009/2010 and 2010/2011 are proofs of that. The combination of low levels of precipitation, low electricity generation from nuclear power plants in Sweden plus the downtime of the HVDC cable between Norway and the Netherlands made it challenging for the power system to meet the peak demand during the winter 2009/2010 (NOU 2012:9). Although the power-cables abroad *can* deliver electricity when needed, shortages can occur abroad as well, which limits the reliability of power supply from the cables abroad. The electricity production will be particularly weak if a dry autumn is followed by a cold and long lasting winter. In such a year, record consumption levels could be a nightmare to handle, as available capacity falls with falling reservoir levels.

Because of the many factors that determine Norway's ability to deliver instant production capacity, this analysis will take the power system's ability to deliver maximum capacity under normal production conditions during the winter as a starting point. Statnett (2014) has estimated this capacity to be 26200 MW[9]. A tight maximum capacity scenario is assumed to be 10 percent below this estimate, at 23580 MW.

7.5.2. Consumption records

Table 10 shows that all the consumption records from the last four years have happened in the hour between 08 and 09 in the morning during the winter and early spring. Because this hour seem to be the most critical one when it comes to peak demand, it is interesting to see what the consumption would look like at this hour with the extra load from EVs.

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[9] For a brief comment on this number, see appendix 4

Year	MW	Hour	Date
2011	22129	08-09	21.12
2012	23443	08-09	5.12
2013	24180	08-09	21.3
2014	22957	08-09	13.1

Table 10: Highest registered instant load. Source: Nordpool Spot (2014)

7.5.3. Load from EVs

According to the survey the percentage of EVs that charge during hour 08 and 09 in the morning is 15,8%. Calculated based on the survey data, the estimated extra load from the EVs are presented in Table 11.

Number of EVs	EV load 08-09 AM (MW)
1 250 000	628
2 500 000	1256

Table 11: Estimated load from EVs in hour 08-09

To build a worst-case scenario the record consumption between 08-09 AM the 21.3 2013 is used. The scenario-based aggregated load and a sensitivity analysis in this hour is given in Table 12.

Percentage of EVs charging	Aggregated demand 1 250 000 EVs	Aggregated demand 2 500 000 EVs
15,8 %	24808	25436
Sensitivity analysis		
25	25172	26136
50	26163	28147
75	27155	30131
100	28147	32115

Table 12: Peak demand plus EV demand with sensitivity analysis Source: Nordpool Spot (2014)

With the survey data as a starting point we have a 15,8 percent simultaneous charge between 08-09 in the morning and a demand of 25 436 MW in a worst-case scenario 2. The power system's normal ability to deliver maximum capacity during the winter surpasses this demand with 764 MW. However, the sensitivity analysis shows that if the simultaneous charge from the EVs goes much beyond 25 percent in this hour, the maximum capacity of today would not be large enough to cover the worst-case demand. As for the tight supply situation, the prospected demand in the worst-case scenario surpasses the capacity value already at 15,8 percent simultaneous charging for both scenarios 1 and 2. This shows that if the electricity supply is tight and consumption is record high, the security of supply would be threatened by a large-scale transition to EVs.

7.5.4. Average peak demand

If we compare the simulated scenario demand curves for the winter to the maximum normal available capacity, as is done in Figure 26, it is clear that the additional demand from EVs do not change the picture much: The average peak in scenario 2 is estimated to be slightly under 20500 MW, which is 5700 MW away from the normal maximum winter production and 3080 MW away from the tight production scenario.

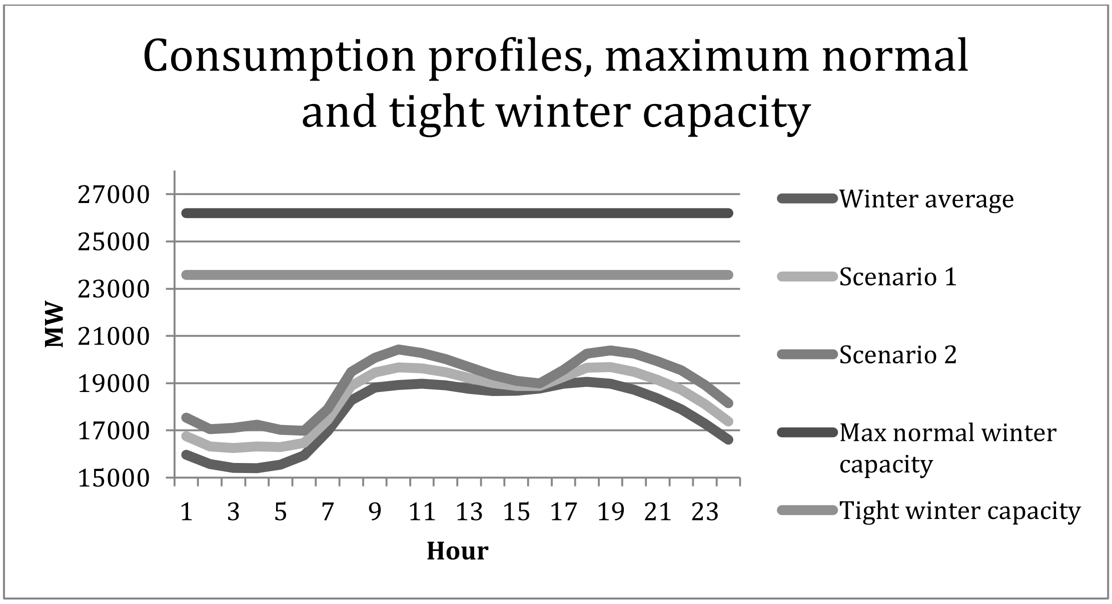

Figure 26: Average consumption profiles and maximum consumption scenarios. Sources: Statnett (2014)

7.5.5. Peak demand analysis: summing up

With today’s power system, under normal production conditions, the security of supply with regard to instant demand could only be threatened in hours of already extremely high consumption combined with very high levels of simultaneous charging from EVs. This particular situation is unlikely to be encountered and so a large-scale transition to EVs does not pose a threat to the security of supply with regard to instant load given normal supply conditions. However, in a year of tight electricity supply and record high consumption the demand from EVs in scenario 1 and 2 might be the factor that makes the power system unable to meet peak demand. The analysis is based on the collected charging behavior and its conclusion will be altered if charging behavior changes over time.

The prospects of a strengthened power grid and more installed capacity points in the direction of increase security of supply with regard to peak demand.

7.6. Aggregated demand

The aggregated demand from EVs in MWh per year will not pose a threat to the security of supply. A simple calculation shows the theoretical scope of the overall demand:

If we assume that one EV drives 12 000 kilometers per year[10] and consumes on average 0,25 KWh per kilometer [11] that gives: 12000*0,25 = 3 MWh per year.

Scenario 1: 1 250 000 * 3 MWh = 3,75 TWh
Scenario 2: 2 500 000 * 3 MWh = 7,5 TWh

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[10] According to SSB (2014) the average personal car in Norway drove 12 560 kilometers in 2013. The average EV drove only 5721 kilometer, but here we are interested in the scenario where the EV replace the conventional car and therefore use the approximate average kilometers driven for conventional personal cars. 12 000 is chosen because it is easier to remember.

[11] 0,25 kWh/kilometer is a high estimate: according to the survey conducted the average energy consumption per kilometer is 0,21 kwh for EVs in Norway and this is likely to decrease as more advanced technology is developed.

Even with 2 500 000 EVs on Norwegian roads the yearly consumption of electricity from EVs will not claim a large part of total electricity production in Norway. The normal generation of electricity in Norway is 130,5 TWh annually (NVE, 2012a). 7,5 TWh, which is a high estimate for the EV consumption of 2,5 million EVs, is just above 5 per cent of average yearly generation. The power demand from 2 500 000 EVs would likely be below 7,5 TWh, as consumption per kilometer will probably be below 0,25 kwh/km as technology develops.

This combined with the fact that more power plants are being set up[12], makes it reasonable to conclude that with regard to overall energy consumption, a large-transition to EVs do not at all pose a threat to the security of supply of electricity in Norway.

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[12] According to the Ministry of Petroleum and Energy (2013a) some 33,8 TWh of potential hydropower can further be exploited in Norway. Some of this capacity is being built at the moment of writing.

8. Conclusion

This study has considered how a large-scale deployment of EVs will affect the security of supply of electricity in Norway. The charging habits of Norwegian EV users have been mapped through a survey directed to the members of the Norwegian EV Society. A total of 398 EV users responded to the survey. The data gathered from the survey has been used to estimate the power demand from EVs in two different scenarios of EV-penetration in the market for personal cars.

The study finds that with the current power system and current charging habits, a large-scale transition to EVs will worsen the security of supply of electricity in Norway. This conclusion is grounded in the analysis of the power balance, where the load from EVs will increase the variability of the consumption curve and therefore decrease the system's ability to maintain the power balance. The variability during the morning peak consumption will increase and make it harder for Statnett to maintain the frequency balance, all other factors held constant.

The study shows that if all personal cars in Norway where EVs, the current power system would be able to handle the instant load demanded on a cold winter day under normal production capacity conditions. However, sensitivity analyses show that the security of supply could be threatened in extreme cases of simultaneous charging during the winter. When production capacity is reduced, charging from EVs pose a greater threat to the security of instant electricity supply. The charging habits of the consumer will change over time. The nature of this change can affect this conclusion.

The aggregated demand from EVs will not threaten the security of supply with regard to the Norwegian power system's ability to deliver enough electricity throughout a year.

The analyses where conducted based on the installed generating capacity of electricity in 2012. Expected increases in precipitation levels, milder winters, plans for further expansion of installed capacity of electricity generation and plans to improve the transmission grid and power connections abroad will improve the power system's ability to tackle a large-scale transition to EVs.

The security of supply of electricity can in theory be improved with a large-scale transition to EVs. If the cars are charged during the late evening and night and disconnected during the morning, when electricity consumption is ramped up, the EVs would contribute to a decreased variability in the electricity consumption curve and therefore make it easier to maintain the power balance and deal with peak consumption hours. Those responsible for maintaining the frequency balance in the power system, the TSOs would be wise to try to affect charging habits in this direction.

8.1 Limitations

This study has focused on the national scale and has not considered the security of supply in smaller, remote household areas. There is a chance that the security of electricity supply might be threatened from a transition to EVs locally. Further research should be done in this subject area.

The security of supply relies on multiple factors such as weather conditions, the balancing market, power grid infrastructure, the structure of the trading units in electricity market and so on. This thesis does not consider all aspects related to the security of supply. Rather than trying to address every aspect, this thesis has looked at how demand side changes from EVs are likely to affect the security of supply, based on estimated charging behavior, all other factors held constant. The charging behavior can and will probably change over time, when new models and more fast chargers are installed. Such a change would alter the conclusions drawn in this thesis.

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10. Appendix

10.1. Charging data table with 3x3 moving averange

Hour	Percentage charging	3x3 moing average	Number of respondents (398)
00 - 01	19,85%	19,35 %	79
01 - 02	18,59%	19,93 %	74
02 - 03	21,36%	21,02 %	85
03 - 04	23,12%	21,02 %	92
04 - 05	18,59%	18,26 %	74
05 - 06	13,07%	14,49 %	52
06 - 07	11,81%	13,32 %	47
07 - 08	15,08%	14,24 %	60
08 - 09	15,83%	16,58 %	63
09 - 10	18,84%	17,00 %	75
10 - 11	16,33%	16,42 %	65
11 - 12	14,07%	13,99 %	56
12 - 13	11,56%	11,39 %	46
13 - 14	8,54%	8,46 %	34
14 - 15	5,28%	5,53 %	21
15 - 16	2,76%	5,11 %	11
16 - 17	7,29%	8,38 %	29
17 - 18	15,08%	13,40 %	60
18 - 19	17,84%	17,42 %	71
19 - 20	19,35%	19,01 %	77
20 - 21	19,85%	20,02 %	79
21 - 22	20,85%	20,44 %	83
22 - 23	20,60%	20,35 %	82
23 - 00	19,60%	20,02 %	78

10.2. Survey

The Survey was consucted in Norwegian language. The English translation follows each original question after the "/" mark.

The first 10 questions of the survey collected general information such as age, gender and income. The general part of the survey is not included in the appendix.

Question11

Har/disponerer du el-bil eller plug-in-hybrid?/
Do you own or use an electric vehivle (EV) or plug-in hybrid electric vehicle PHEV?

Answers:

	Total 100.00% (416)	
Har/disponerer el-bil	94,23%	392
Har/disponerer plug-in-hybrid	0,72%	3
Har/disponerer begge typer	0,72%	3
Har/disponerer hverken el-bil eller plug-in-hybrid	4,33%	18

English translation: 392 respondents have/use an EV.
3 respondents have/use a PHEV
3 respondents have/use both EV and PHEV

Question 12

El-bil og plug-in hybrid vil nå bli referert til som "el-bil". Hvilken el-bil eier/disponerer du?/ EV and PHEV will now be referred to as simply "EV". Which EV do you own/use?

Answers:

	Total 100.00% (398)	
Mitsubishi i-MiEV	16,83%	67
Citroën C-ZERO	4,02%	16
Peugeot iOn	3,52%	14

Nissan LEAF	47,99%	191
Tesla Model S	12,56%	50
VW e-up!	0,75%	3
Renault Kangoo Z.E.	0,25%	1
BMW i3	0,00%	0
Ford Focus Electric	0,25%	1
Renault Twizy	0,00%	0
Buddy	2,76%	11
Mia Electric	0,25%	1
Ford Transit Connect Electric	0,00%	0
Other, please specify*	15,08%	60

*These are mostly Think City, a few of Citroen Saxo and Renault Kangoo.

Question 13

Hvor lader du el-bilen til daglig?/

Where do you charge your daily charge your EV?

	Total 100.00% (397)	
Hjemme / At home	87,15%	346
På jobben /At work	45,34%	180
Offentlig ladestasjon (gratis)/ public charger (free)	17,88%	71
Privat ladestasjon (betale) /Private charger (pay)	1,01%	4
Other, please specify	1,26%	5

Question 14

Om lading: Hvis du setter el-bilen til lading når den er 70 % fulladet, tar det ikke så lang tid før bilen er 100% fulladet. Når bilen har 100% batterikapasitet kan den bli stående med ladekontakten i, og da uten at bilen lader. Med dette i bakhodet: vennligst kryss ut de timene der du mener el-bilen din normalt lader i løpet av et døgn (utelat de timene der kontakten står i mens bilen er fulladet)./

About charging: If you put your EV to charge when battery capacity is 70%, it will not take long until the EV is 100 % charged. When the car is 100 % charged, it happens that the EV is still connected to the car, without actually charging it. With this in mind: please cross out those hours during the day when you normally charge your EV (leave out those hours when the charger is connected and the EV is fully charged).

Answer:

Hour	Total 100.00% (398)	
00 - 01	19,85%	79
01 - 02	18,59%	74
02 - 03	21,36%	85
03 - 04	23,12%	92
04 - 05	18,59%	74
05 - 06	13,07%	52
06 - 07	11,81%	47
07 - 08	15,08%	60
08 - 09	15,83%	63
09 - 10	18,84%	75
10 - 11	16,33%	65
11 - 12	14,07%	56
12 - 13	11,56%	46
13 - 14	8,54%	34
14 - 15	5,28%	21
15 - 16	2,76%	11
16 - 17	7,29%	29
17 - 18	15,08%	60
18 - 19	17,84%	71
19 - 20	19,35%	77
20 - 21	19,85%	79
21 - 22	20,85%	83
22 - 23	20,60%	82
23 - 00	19,60%	78

Question 15

Når du lader el-bilen hjemme, lader du på 10 A eller 16 A?/
When you charge at home, do you charge at 10 A or 16 A?

	Total 100.00% (398)

10 A	39,70%	158
16 A	46,73%	186
Vet ikke / don’t know	4,52%	18
Other, please specify*	9,05%	36

*a mixture of 10, 13, 25 and 32 Ampere

Question 16

Hvor mange km kjører du i løpet av en dag med normal kjøring? /

How many kilometers do you drive during a normal day?

Answer:

Total Respondents:	398
Average km per day:	57,4

Question 17

Hva slags kjøring bruker du el-bilen til? (flere svar mulig) /

What kind of driving do you do with your EV (more options available)?

Answer	Total 100.00% (398)	
Til og fra jobb/ to work and home again	89,95%	358
Kjøring i jobben / driving during work	21,61%	86
Bykjøring / driving in the city	60,80%	242
Langkjøring / long distance driving	17,84%	71
Other, please specify*	18,84%	75

*Typical answers: ”to work out”, ”to the grocerie store”, ”take mye kids around”

Question 18

Open text question:

Jeg kjører el-bil fordi jeg... /
I drive an EV because I…

Answers:
Total Respondents: 53

Typical answers: ”want to save money”, ”because of the public transportaton line availability”, ”fascinated by the technology”

Question 19:

Hvor ofte lader du el-bilen med hurtiglading? /
How often do you charge the EV with a fast charger?

Total Respondents: 396

Answers	Total 100.00% (396)	
Hver dag / every day	1,26%	5
Flere ganger per uke/ more times per week	4,80%	19
En gang per uke / once per week	3,03%	12
2-3 ganger i måneden /2-3 times per month	9,34%	37
En gang i måneden / once a month	14,90%	59
Et par ganger i året / a few times in a year	23,99%	95
Aldri / Never	38,38%	152
Other, please specify	4,29%	17

Question 20:

Vennligst kryss for det tidsrommet i løpet at døgnet der bilen normalt lades ved hjelp av hurtiglader (dersom dette er sjeldent, kryss av for den timen der det sannsynligvis ville skjedd ville skjedd). /
Please cross out the time during a day and night when you normally charge your EV with a fast charger (if this is rare, cross out the hour where it would have happened).

Answers:

Hour	Total 100.00% (378)	
00 - 01	3,44%	13
01 - 02	0,26%	1
02 - 03	0,26%	1
03 - 04	0,26%	1
04 - 05	0,26%	1
05 - 06	0,26%	1
06 - 07	0,00%	0
07 - 08	0,53%	2
08 - 09	1,06%	4
09 - 10	0,53%	2
10 - 11	1,06%	4
11 - 12	0,79%	3
12 - 13	2,91%	11
13 - 14	3,17%	12
14 - 15	3,17%	12
15 - 16	3,70%	14
16 - 17	7,67%	29
17 - 18	6,08%	23
18 - 19	3,70%	14
19 - 20	3,70%	14
20 - 21	1,32%	5
21 - 22	0,00%	0
22 - 23	0,53%	2
23 - 00	0,26%	1
Lader svært sjelden elleraldri med hurtiglading / I almost never or never use a fast charger.	55,03%	208

Question 21:

Har du flere biler i tillegg til el-bilen? Hvis ja hva slags bil(er)?/

Do you have more cars in addition to your EV? If so, what kind of cars?

Answers:

Answers	Total 100.00% (398)	
El-bil / EV	5,03%	20
Bensindrevet bil /Gasoline car	31,91%	127
Dieseldrevet bil /Diesel car	50,00%	199
Hybrid / Hybrid car	2,51%	10
Plug-in hybrid /PHEV	0,00%	0
Har ingen flere biler / Do not have more cars	18,34%	73
Vennligst skriv ned eventuelt andre biler i tillegg til ovennevnte her / please write down any additional cars to those mentioned above	5,28%	21

10.3. K-S Tests

The K-S test, or the Kolmogorov Smirnov test, is a non-parametric test. It can test the equality or inequality between two distributions and can be used to compare a sample distribution to a reference distribution.

Null hypothesis:	The sample distribution is equal to the reference distribution
Alternative hypothesis:	The sample distribution is unequal to the reference distribution

The null hypothesis is rejected if the maximum difference between the cumulative distributions is larger than the critical value, D.

In a two sample K-S test, the value D is given by the formula: $c(\alpha)\sqrt{(\frac{n_1+n_2}{n_1 * n_2})}$

Where $c(\alpha)$ is given by the significance level α in the table below and n_1 and n_2 are number of observation in the sample and reference distribution.

α	0,1	0,05	0,025	0,01
$c(\alpha)$	1,22	1,36	1,63	1,95

Source:
Wikipedia. (2014). *Kolmogorov-Smirnov test.* Retrieved April 7, from http://en.wikipedia.org/wiki/Kolmogorov%E2%80%93Smirnov_test

K-S test for geographic representativeness at 5-percent significance level (5 percent chance of wrongly reject the null hypothesis):

Sample distribution	population	Cumulative	Population distribution		Cumulative	Cumulative difference
Østlandet/Eastern Norway	57 %	57 %	Øslandet	59 %	59 %	-2 %
Nord-Norge/ North Norway	2 %	58 %	Nord-Norge	2 %	61 %	-3 %
Sørlandet /South Norway	6 %	65 %	Sørlandet	5 %	66 %	-1 %
Trøndelag/Middle Norway	6 %	70 %	Trøndelag	9 %	74 %	-4 %
Vestlandet/West Norway	30 %	100 %	Vestlandet	26 %	100 %	0 %
Size of sample	412		Size of population	20000		
	Critical D	6,77 %				
	Max difference	4,04 %				

The maximum difference between the cumulative distributions is 4,04 percent. The critical value is 6,77 percent. The test result is that the null hypothesis is not rejected.

10.4. Maximum available capacity

Comment on Statnett (2014) maximum available installed capacity: 26200 MW

In a sense the flexible hydropower and the thermal power plants in Norway are the only truly reliable sources of power generation during hours of peak demand in the winter, but some capacity from other sources should also be expected. A stated previously Statnett (2014) estimates that the maximum production capacity during normal conditions in the winter is 26 200 MW. To see if this makes sense this number is compared to the combined installed capacity from flexible hydro- and thermal power given in the table below. Statnett estimates a total normal capacity, which is 647 MW larger than flexible hydro- and thermal power combined. This seems reasonable under normal conditions, as some additional capacity from wind, run off river, and import capacity should be added.

Power plant type	Installed capacity (MW)
Flexible Hydro	24457
Thermal	1096
Sum	25553

Table: Source: Audun Fidje, NVE, Ministry of Petroleum and Energy (2013)