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Analysis of Large Scale Adoption of Electrical Vehicles and Wind Integration in Nord-Trøndelag

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Problem Description

With the aim of triggering a discussion on the topic, this thesis presents a methodology for analysing the impact of large scale adoption of EVs on the electrical grid. A specific portion of a real network is selected and two charging modalities for the electrical vehicles will be investigated. The analysis will focus mainly on chargers located at residences, to then explore how the utility can put forward a system for smart charging strategies ("dumb" vs. "smart" charging).

In the second part of the analysis, a series of wind measurement is included into the simulation in order to see if wind power can supply the load of the entire residential area. A design for a suitable energy storage will also be proposed in order for the system to operate as a stand-alone system. Grid stability and power quality will not be investigated in the analysis.

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Abstract

With the 'Agreement on Climate Policy' (Klimaforliket) signed by the Norwegian government on January 17th 2008, Norway has set a goal to reduce emission caused by transportation with 2.5 – 4 million tons CO_2 equivalents compared with the reference for 2020[9]. To reach this goal, high penetration of electrical vehicles is essential, and new technologies and solutions for the infrastructure must be cleared early in the process. With the aim of triggering a discussion on the topic, this thesis presents a methodology for analysing the impact of large scale adoption of EVs on the electrical grid. A specific portion of a real network was selected and two charging modalities for the electrical vehicles were investigated. The analysis will focus mainly on chargers located at residences, to then explore how the utility can put forward a system for smart charging strategies ("dumb" vs. "smart" charging).

Data from a low voltage network was provided by NTE, located in Steinkjer in Nord-Trøndelag. Three different scenarios were analysed. Scenario 1 was given as the base scenario, were the share of EVs where 0%. This was simulated to get a proper comparison. In scenario 2, a share of 10% EVs was implemented in the grid. The share of EVs in scenario 3 was decided to be 60%. The result obtained in the analysis, verified that the smart charging approach causes less strain on the gird. The low voltage network was not capable to handle a large share of EVs (>60%) without any charging scheduling. The smart charge strategy did not cause any extra strain at the grid during peak hours. In addition, the smart charging can introduce the Vehicle-to-Home solution. The EVs can provide ancillary service and support the network with matching supply/demand and reactive power support. A simplified analysis of V2H and reactive compensation was carried out to demonstrate how the grid could benefit from an implementation of EVs.

The second part of the analysis, a series of wind measurement was included into the simulation in order to see if wind power can supply the load of the entire residential area. A design for suitable energy storage was also proposed in order for the system to operate as a stand-alone system. Grid stability and power quality was not included in the analysis. The result from the wind integration, shows that in order for the network to operate as a stand-alone system in the worst-case scenario, there is a need of an enormous storage. It is assumed based on the results, that the system is self-supplied most part of the year. This thesis proposes a storage

consisting of 7 battery-packs from old vehicles, with the capacity of 50 kWh each. This will result in a $\approx 30\%$ reduction of the peak demand from the grid, when wind power is integrated.

The case study addressed in the thesis, present a methodology for analysis the impact of a large adoption of EVs on the distribution network. The results obtained from this analysis, is considered transferable to similar networks. In order to achieve smart charging, there is need for further research on scheduling algorithms.

Samandrag

Norge har gjennom Klimaforliket, som vart inngått i 2008, sett som mål å redusere 2,5 - 4 millionar tonn CO_2 ekvivalentar i forhold til referansebanen i 2020. Ein stor skala integrasjon av elbiler er eit sentralt element for å kunne oppnå dette målet. Teknologi og standarar bør klarerast tidlig i prosessen. Denne masteroppgåva viser ein metode for å analysere kva konsekvensar ein storskala integrasjon av elbiler vil føre til på det elektriske nettet. Hensikta med oppgåva er å starte ein diskusjon om temaet. Det vart valt å sjå på to ulike strategiar for lading av elbilar, ”dum” - og ”smart” lading. Dum lading vert omtala som ukontrollert lading, medan smart lading er den kontrollerte der ladinga vert flytta til periodar med lav last (f.eks. natt).

Analysen vart utført på eit bustadområde i Steinkjer i Nord-Trøndelag. Distribusjonsnettet var gitt av NTE Nett. Tre ulike scenario var analysert. Scenario 1 er basert på dagens situasjon i nettet. I scenario 2 var 10% av kjøretøya elektriske, og i scenario 3 var prosentdelen auka til 60%. Resultata frå analysen viser at den ukontrollerte ladinga vil resultere i større lasttoppar, medan den smarte ladinga vil ikkje føre til meir belasting i periodane med topplast.

Distribusjonsnettet var ikkje i stand til å takle ein andel med 60% elbiler utan at ladinga er kontrollert. Ved bruk av smart lading kan ein fase inn eit større andel elbiler. I tillegg kan smart lading introdusere V2H, ei løysing der bilen både leverer og får energi frå huset. Elbilen kan då støtte nettet med både å lagre og levere aktiv effekt, samstundes som den kan kompensere for reaktiv effekt. Ein svært enkel analyse er utført for å vise korleis V2H og reaktiv kompensering kan vere til nytte for nettet.

I den andre delen av analysen vart ein serie av vinddata inkludert i simuleringa. Dette er gjort for å undersøke om vindkraft kan forsyne heile forbruket til bustadområde. Eit forslag til eit energilager vart også utforma, med den hensikt at systemet skal kunne operere frittståande. Stabilitet og spenningskvalitet er ikkje inkludert som ein del av analysen. Basert på resultata er det forventa at vindkraftproduksjonen vil kunne dekke lasta gjennom store deler av året, men i periodar med svært høg last har systemet behov for eit stort energi lager for å kunne være ”kraftsjølvstendig”. I denne oppgåva er det foreslått eit lager av 7 batteripakkar (Li-ion) frå gamle elbilar, som har ein kapasitet på 50 kWh per elbil. Systemert

vil framleis ha behov for levering av effekt frå det utanforliggande nettet (høgspent nettet), men toppane er redusert med $\approx 30\%$.

Oppgåva viser ein metode for å analysere påverkningane av ein stor skala integrasjon av elbilar i distribusjonsnettet. Systemet som er nytta i oppgåva er eit typisk norsk distribusjonsnett. Resultata som kjem fram i oppgåva er difor rekna som overførbare til andre liknande områder.

Preface

This thesis is the final work in Master of Science in Electrical Power Engineering at Norwegian University of Science and Technology (NTNU) the spring of 2012.

I would like to thank my supervisor professor Marta Molinas, for inspiration and guiding me through this project. You encouraged me to submit a paper to Techno-port, and the experience I gained from this was very valuable to me. I would also like to thank NTE Nett AS for providing data, and especially my contact person at NTE, Jan A Foosnæs, for answering my questions and for being a great support.

At last at I would like to thank all of the people who have helped me finishing this thesis. To the fantastic people at my office. To my friends here at NTNU - thank you for the laughter. To my wonderful friends for encouraging me. To my family for always supporting me. Thank you.

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Abbreviations

NVE	Norges vassdrags- og energidirektorat
EV	Electric Vehicle
ICE	Internal Combustion Engine
BEV	Battery Electric Vehicle
PHEV	Plug-in Hybrid Electric Vehicle
PHS	Pumped hydroelectric storage
CAES	Compressed Air Energy Density
SAE	Society of Automotive Engineers
IEC	Internatinal Electrotechnical Commission
V2G	Vehicle-to-Home
V2H	Vehicle-to-Home
SOC	State of Charge
NiCd	Nickel-Cadmium
NiMH	Nickel-metal Hybrid
NaS	Sodium sulphur
SES	Super-capacitor Energy Storage
SMES	Superconducting Magnetic Energy System
GSM	Global System Mobil
GPRS	General Packet Radio Service
PLC	Power Line Communication
IP	Internet Protocol

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Chapter 1

Introduction

1.1 Problem background and motivation

The transport sector is accountable for more than half of the worlds consumption of oil, and a large amount of this is consumed by passenger cars.[31] A large scale adoption of electric vehicles would reduce the greenhousegas emissions, as well as the dependency of oil. Nevertheless, the environment benefits is dependent of the generation mix. The higher percentage of renewable in the generation, the more beneficial is the integration of EVs.

Renewable resources, such as wind energy, tends to have a stochastic production and will cause surplus energy in certain periods. To have the most efficient usage of the power, a good solution is to implement EVs in the grid. The EVs can also provide ancillary service and support the network with supply/demand matching and reactive power support[31].The solution where the vehicle deliver power back to the grid is called Vehicle-to-grid (V2G), and Vehicle-to-home (V2H) where the vehicle deliver power to the owners home.

All thought the integration of EVs are an intelligent solution to use the energy surplus, the implementation of a large EV fleet causes a lot of challenges. This thesis questions the impact on the distribution grid where the first bottlenecks are likely to occur.

1.2 Electrifying of the transport sector in Norway

1.2.1 Ambitions and driving forces

The 17th of January 2008 the Norwegian government signed Klimaforliket (Agreement on climate policy) declaring that the state of Norway will be carbon-neutral no later than 2030. This agreement stated that Norway have to reduce the emission with 15-17 million tons CO_2 equivalents, a reduction of 25% compared with the 2007 reference [9]. In Klimaforliket it was also stated that the transport sector need to reduce the emission with 2.5 - 4 million tons CO_2 by the year 2020.

The transport sector in Norway is accountable for 19% of the emissions. As a part of the obligation given in Klimaforliket a resource group were formed in December 2008 to elaborate a plan for electrification of the transport sector in Norway. The result from this project was presented in *Handlingsplan for elektrifisering av veitransport* (Plan of action to electrification of the road transportation)[9]. Figure 1.1 present the reduction of emission from different actions.

To reach the goal of a reduction of 25% of emission, the resource group suggest that the traditional vehicle become more efficient as well as an integration of EV and vehicles that runs on biofuel. A share of at least 10% electric vehicles is adequate by 2020. It was also stated in the same report that a share of 50% of EVs would cause a 36% reduction in emission compared to a vehicle-fleet with only efficient traditional gasoline vehicle. An efficient vehicle is calculated with 95 g CO_2 per km. If Norway wants to achieve the ambition of being carbon-neutral, the report

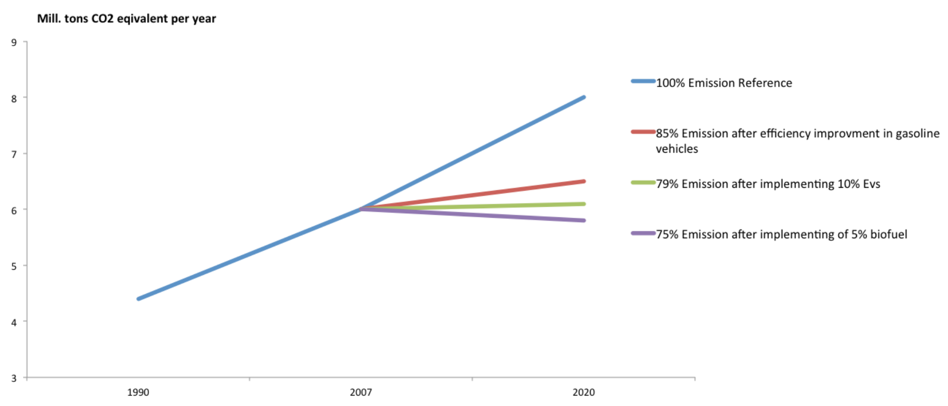


Figure 1.1: Reduction in emission in relation to the 2007 reference[9].

propose a large implementation of EVs by 2030[9].

1.2.2 Electric Vehicle in Norway 2012

As of March 2012, there are according to Grønn Bil 6311 electric vehicles in Norway. The estimated number for May 2012 is 6910[5]. Figure 1.2 is a geographical presentation of what part of the country the EVs are located. The figure shows how the number of vehicles are divided between the north, the middle, the west, the south and eastern part of Norway.

The electric vehicles are mainly located in and around the big cities. Oslo has the largest share with 1545 vehicles. This value is from March 2012. For the same period Bergen had the second largest share with 349 vehicle. In Trondheim the number of vehicles were 311[5]. Grønn bil has also a geographical presentation of where the charging stations in Norway are located on their web page. There are currently 3208 regular and 33 fast charging points in Norway. 6 of these are located in Rogaland, 8 are located in Oslo and Akershus, 3 in Hordaland and 3 in Sør-Trøndelag and Nord-Trøndelag has two fast chargers[5].

Figure 1.2: EVs in Norway in 2012[5].

There are several models available at the Norwegian market today. The Norwegian EVs, Think and Buddy are according to the statistics two of the most popular EVs in Norway. 19% of the EV owners in Norway chose Think, while 17% chose Buddy. Mitsubishi is also a very popular vehicle, and their EV, i-MIEV, is represented with 19% of the norwegian market. Both Buddy and Think were produced in Norway, but currently there are no production of EVs in Norway. Think was liquidated in May 2011, and the estate was bought by Boris Zingarevish from Rusland. Pure mobility, the company that produced Buddy in Økren, was liquidated as of November 1st 2011. Buddy is now owned by Buddy Electric AS that wish to continue production in Norway[10].

For the case study adressed in this paper, Nissan Leaf will be used as the simulation model. Nissan Leaf was selected Car of the Year 2010. According to the sales revenues for May 2012 in Norway, 61% of the models bought in 2012 was Nissan Leaf[5]. Mitsubishi's i-miev which is also very popular in Norway were considered, but according to Bengt Otterås from BKK Nett AS, future charging system in EVs will as the Nissan Leaf have a charging current close up to the limits for the different charging modes[30].

1.3 Wind power in Norway

Green certificates was a centralized theme in the Agreement on Climate Policy (2008). The certificate is now called electricity certificate. As of January 1st, 2012 Norway is a part of a Norwegian-Swedish electricity certificate market. The purpose of implement the certificates is to increase the development of renewable production. Together with Sweden, Norway plan to expand the production with 26,4 TWh by 2020[28]. One of the prior resources for new development is wind power.

Kjeller Vindteknikk have, assigned from Norwegian Water Resources and Energy Directorate, charted the wind resources for Norway, both on and off shore. Icing, average production time and wind speed at different heights is also a part of the map. Figure 1.3 show the wind speed at 80 m height for the entire Norway.

There are, as of today, installed 525,8 MW wind power in Norway. These turbines will deliver approximate 1,2 - 1,3 TWh, which equal 1 % of the energy supply in Norway. In addition to this, there are five wind farms that are under construction

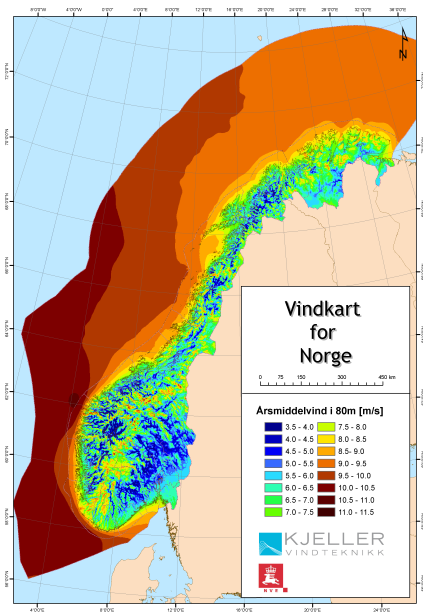
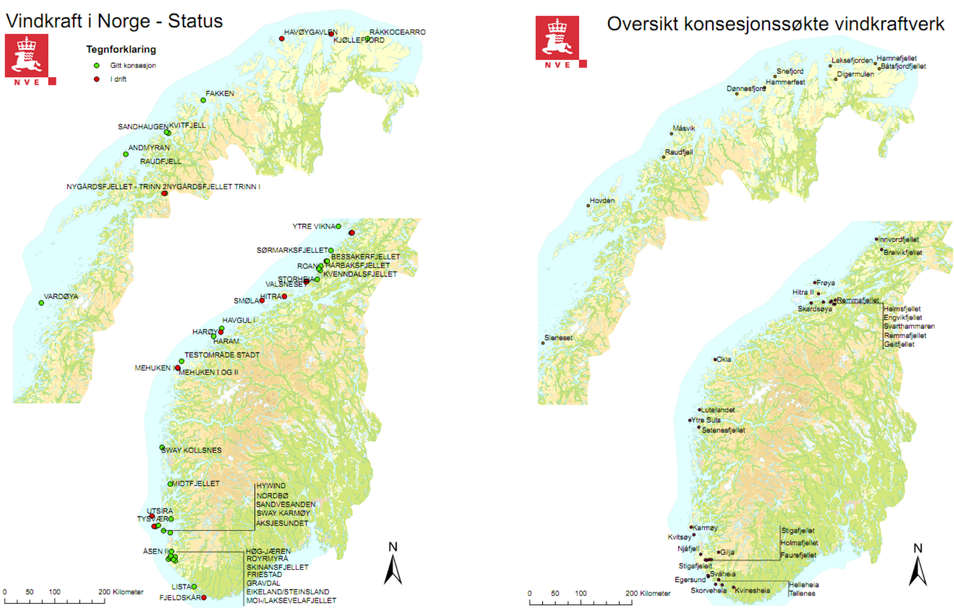


Figure 1.3: Wind resources in Norway measured by Kjeller Vindteknikk[39].



(a) Projects with licence - Status[28]

(b) Projects applied for licence.

Figure 1.4: Overview of wind power in Norway[28].

with a total capacity of 228 MW[28]. An overview of the wind farms and its status is shown in figure 1.4a.

There are also several wind power projects under evaluation at Norwegian Water Resources and Energy Directorate (NVE). The total capacity of the projects that have applied for licence is 5500 MW. The map in figure 1.4b shows the location of the projects[28].

Chapter 2

Electric Vehicles (EVs)

2.1 Background

Already in the 1834 had the electric vehicle its first appearance. During the late 19th century, several companies produced EVs in US, Britain and France.[7] The 1902 Wood's Electric Phaenton had a range of 29 km, a top speed of 22,5 km/h and a cost of $2000. The early 1900s were good years for the electric vehicles, and the production reached its peak in 1912, but in the 1920s the gasoline vehicles started taking over the market. The late 1920s until the 1960s were dead years for the development of EVs, but in the 1960s people started to look on how to be less dependent of oil. Therefore the EV was in the spotlight once again. In 1964 the first Battronic truck was delivered to Potomac Edison Company with a range of 100 km, top speed of 40 km/h[23].

Today, most of the pure EVs, a so-called battery electric vehicle, has a range of typically 100-160+ km [14] before they need to recharge, and a top speed of $\leq$ 100 km/h.[16] However, with today's technology it is possible to achieve a top speed of 300 km/t, like the Japanese 'Eliica' that has a top speed of 370 km/t.[37]

2.2 Types of EVs

There are many different types of electric vehicles. The term EV is used for both BEV and HEV. The definition of electric vehicle is more or less, *a vehicle that uses an electric motor for propulsion.*

Further one can say that the electric vehicle is a type of vehicle that fall into one of these 4 categories:[8]

1. Hybrid Electric Vehicles (HEVs)
   A HEV uses a battery-powered electric motor in addition to a traditional combustion engine. The vehicle will work as a zero emission vehicle (ZEV) at low speed, but at higher speed (< 65 km/t) the combustion engines drives the vehicle.
2. Plug-in Hybrid Electric Vehicles (PHEVs)
   Like the HEV, a PHEV combines an electric motor and a combustion engine, but the PHEV use a larger battery that can be recharged by connecting the vehicle into an electrical outlet.
3. Battery Electric Vehicles (BEVs)
   The BEV is the pure EV, a vehicle that relies only on electrical power.
4. Extended-Range Electric Vehicles (ER-EVs)
   The ER-EV is a cross between the BEV and the PHEV. It uses only electrical power for propulsion, but it has a combustion engine, which can power a generator that can recharge the battery. The vehicle can also be plugged in the grid to recharge the battery.

The last three types are all included in the term grid enabled vehicle (GEV) that is directly implemented in the grid. The term GEV does also include neighborhood electric vehicle (NEV) and medium-speed electric vehicle, but will not be applicable here. For the purpose of this paper the term EV will be widely used for BEVs when not mentioned otherwise. The BEV will also be used in the following simulations.

2.3 Structure

The structure of the EV is simpler than for a traditional gasoline vehicle. The vehicle consist mainly of one or several electric motors for propulsion, a battery where energy is stored chemical, a charger, power electronics that turns the chemical energy into electrical energy and system controls. The electric motor can be either a DC machine or AC machine. Up until now most manufacturers has used DC machines, but more manufacturers push for the use of AC machines due to he fact that AC machines is more robust.[45]

The electric motor can also be used as a generator in the electric vehicle. This is called "regenerative braking". When you go downhill and when the brake is engaged, the energy from the vehicle will be used to generate electric power. This energy will be stored in the battery.[45]

The structure of a HEV is a little more complex than for the BEV. There are three types of HEV; series, parallel and series-parallel. The series hybrid is has an internal combustion engine (ICE) that drives a generator that charges the battery. The propulsion is only based on an electrical motor. The advantage for this solution, is that the ICE is operated with maximum efficiency, and has therefore low emissions. Parallel hybrids use both an ICE and an electric motor for propulsion, as do a parallel-series hybrid, but this solution include an generator so the ICE can charge the battery as well as use the energy for propulsion.[35]

2.3.1 Battery

EVs has usually two battery systems. One is an equipment battery rated at 12V, and the other one for propulsion rated between 70 and 300V. A battery convert electrochemical energy into electrical energy[14]. The propulsion battery require high power and energy density, long endurance, reliability and low production costs. Battery technology is today the one of the biggest limitation in the EV-market[45].

There are several different battery types used in the market today, technologies like Lead-Acid, NiCd and NiMH are widely used and commercialized. Initially, HEVs uses Lead-Acid, but due to the environmental issues lead causes and the advancements in technology NiMH and Li-ion batteries are being used[14]. The battery technology is more explored in section 3.1.

Both Think and Buddy uses Lead-Acid batteries due to the fact that this is a well known technology, but both was also delivered with Li-ion batteries. For future electric vehicles Li-ion battery is said to be the most suited and promising technology due to its high energy density. It is expected that Li-ion can reduce the battery weight with 40-60% and slightly increase in the efficiency. The Li-ion batteries will in addition become more available for a lower cost[14]. Nissan Leaf is delivered with a Li-ion 24 kWh battery[29]. Battery technology will be further explained in section 3.1.

2.4 Charging

2.4.1 Charging standards

There are several standards for charging electric vehicle. In this report it is chosen to look at the SAE J1772 and IEC 61851-1. These are the standard used by the manufacturers. IEC used SAE J1772 as the background for IEC 61851-1.

American standards: SAE J1772

In 1998 the California Air Resources Board classified three levels for charging for EVs. These three levels for charging are and will be used as standards in the USA. In 2001 the Society of Automotive Engineers (SAE) standardized these levels. The standard were called SAE J1772-2001. This is later revised and is now published as SAE J1772-2010.[4].

1. Level 1 charging is a standard 120VAC outlet (for US outlets), designed to be portable. This level is compatible to use for an on-road emergency and driver needs to plug into an available outlet. An empty battery uses about 11-20 hours to recharge at this level. Level 1 is suitable for small electric vehicles, scooters and motorcycles. Level 1 is also suitable to operate at 220V, and will had a recharge time about half of the time that the 120V voltage level has.

2. Level 2 refers to a single or a triple phase AC operating at a fixed location. Designed for charging docks or stations at residences. The charger is rated $\leq$ 240VAC, 60 A and 14,4kW. At level 2 the time for recharging an empty battery is between 3-8 hours dependent of the battery size.

3. Level 3 is rated at $\geq$ 14.4kW and suitable for other city infrastructure. Level 3 chargers is the typically "fast-chargers" that uses only 30 minutes to recharge a typical battery. Level 3 require a 400-600 VAC supply, which can limit the

implementation of this charger in places where the distribution network is based in IT earthing system (230 V)[25].

European standards: IEC 61851-1

In comparison to Europe, where IEC classified the different charging levels as modes in 2010. The charging modes are as defined in IEC 61851-1;[19]

1. Mode 1, (AC) slow charging from a standard household-type socket-outlet not exceeding 16 A and not exceeding 250 VAC single-phase or 480 VAC three-phase, at the supply side, and utilizing the power and protective earth conductors. Mode 1 is the most widely used system today.

2. Mode 2, (AC) slow charging from a standard household-type socket-outlet with an in-cable protection device, not exceeding 32 A and not exceeding 250 VAC single-phase or 480VAC three-phase, utilizing standardized single-phase or three-phase socket-outlets, and utilizing the power and protective earth conductors together with a control pilot function and system of personnel protection against electric shock (RCD) between the EV and the plug or as a part of the in-cable control box. The inline control box shall be located within 0,3 m of the plug or the EVSE or in the plug. Mode 2 requires a control pin, but only on the vehicle side. The supply side does not need a control pin. The control is governed by the control box in the cable.

3. Mode 3, (AC) slow or fast charging using a specific EV socket-outlet and plug with control and protection function permanently installed. Mode 3 connectors require, according to IEC 61851-1, a range of control and signals pins for both sides of the cable. If the there is no vehicle present, the station socket is dead. The pilot pin in the plug on the charger side controls the circuit breaker.

4. Mode 4, (DC) fast charging using an external charger. Mode 4 charging is a solution where the power from the supply is converted in the charging station to DC. Mode 4 allows DC fast charging with currents up to 400 A. As for mode 3, mode 4 connectors require a range of control and signals pins to ensure a safe operation.

Comparison: SAE J1772 vs IEC 61851-1

Mode 1 and level 1 is more or less the same solution. As mentioned, this is the solution that is mostly used today. As for the future, it is expected to use the other modes and levels. Level 2 and mode 2 and 3 chargers are the solution that will be the most common. The chargers will be stationed at residences, workplace and public sites. The difference between mode 2 and 3 is that mode 3 requires more communication and control in on the vehicle side. One can expect that mode 3 will become the standard solution for residence chargers if the V2H is introduced.

Mode 4 and level 3 charging is also called "DC Fast Charge". To be able to replace a large share of the traditional ICE vehicles with EVs, it is necessary to build the infrastructure for it. This include fast chargers at shopping malls, at gas stations and in the streets and at rest stops a long the highway. Lyse, a Norwegian utility company opened the first fast charger in Norway in 2011. The station is placed in Lura in Sandnes in the west-coast of Norway, and is based on the so called "Tepco-protocol". The Japanese utility company Tepco (Tokyo Electric Power Company) has together with Nissan, Mitsubishi and Fuji Heavy Industries formed the CHAdeMO Association.

The CHAdeMO fast chargers include of a primary grounded circuit and an isolated secondary circuit, with a transformer in between that isolates the two circuits. The primary circuit is supplied from the grid with a three-phase 200VAC (200-430VAC). The output circuit is connected to the vehicle. The solution allows an output voltage up to 500 V DC and typically output currents are 125 A. Maximum allowed output current is 200 A[24].

2.5 Charging Operations

The EV charger can operate in 8 different modes, these modes are listed in table 2.1. In mode 2, 7 and 8, the active power (P) is negative. In these modes, the battery deliver power back to the supply.

If one consider $v_c(t)$ as the voltage at charger and $v_s(t)$ as the grid voltage, the relationship between the two term is expressed by $v_s(t) = v_c(t) + jX_cI_c$[26]. This equation is used to form vectors to express the modes in table 2.1. Vector diagram are presented in figure 2.1. Figure 2.1a presents the "normal" operation. This

Table 2.1: Charging Operation Modes[26]

	P	Q	Operation
1	Positive	Zero	Charging
2	Negative	Zero	Discharging
3	Zero	Positive	Inductive
4	Zero	Negative	Capacitive
5	Positive	Positive	Charging and inductive
6	Positive	Negative	Charging and capacitive
7	Negative	Positive	Discharging and inductive
8	Negative	Negative	Discharging and capacitive

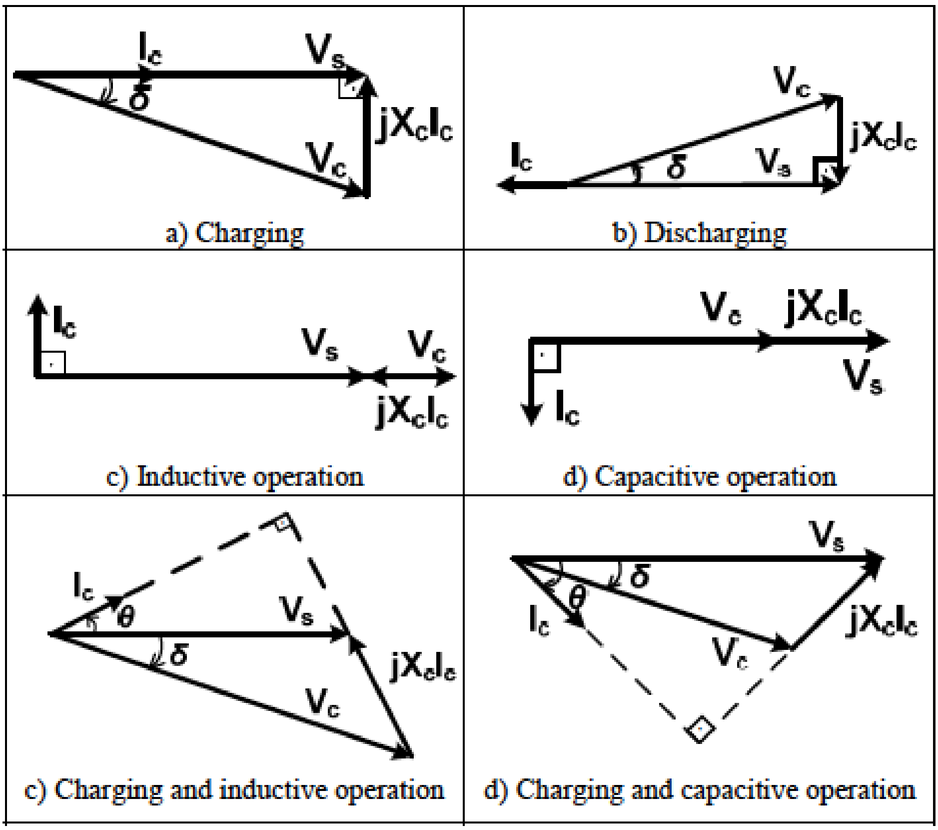


Figure 2.1: Vector diagram for different operation modes[26].

mode is used in the case study. P is positive and Q is zero. When P is negative, the battery deliver power to the grid. This is further called Vehicle-to-Grid or Vehicle-to-Home, and is explained in the section below.

As seen in the figure and the table, there are four modes where reactive power, Q, is "active" - not equal to zero. This means that the charger provide reactive compensating. By controlling the charger voltage $v_c(t)$ and its phase angle, δ or the charger current $i_c(t)$ and its phase angle, θ, one can control the magnitude and direction of P and Q.

A small analysis of reactive compensating will be carried out in the case study addressed in this thesis. By changing the magnitude of Q, one can control the voltage drop ΔV. The purpose is to make a more uniform voltage curve.

2.5.1 Vehicle to Grid (V2G) and Vehicle to Home (V2H)

The term Vehicle to Grid and Vehicle to Home cover the solution were the battery in the electric vehicle delivers power back to the source. To intention is to save renewable unregulated energy in the battery and save it to feed it back to the grid in peak hours. The introduction of electrical energy storage, such as the EV, could improve the efficiency and reliability. The demand on the grid will be smoothed. However, V2G is associated with challenges such as the availability of the vehicles and state of charge (SOC) of the different vehicles. How many vehicles are required to stand by as storage? How can we obtain the reliability, and at the same time the EV owners satisfied? Due to the fact that the V2H solution avoid the infrastructure and tariff problems raised by the V2G solution, the V2G solution has been neglected from this project[15].

In the V2H solution, the load is geographically close to the source that makes transmission minimal, reducing losses. The EV supplies the home with electricity during peak hours, causing less strain on the grid. This may reduce the cost of the transmission grid, and may prevent building new lines. A study made by Gareth Haines, Andrew McGordon and Paul Jennings at this topic present that the V2H solution reduces the peak demand. The work is presented in *The Simulation of Vehicle-to-Home System – Using Electric Vehicle Battery Storage to Smooth Domestic Electricity Demand.* [15].

Figure 2.2 shows Nissans Vehicle-to-Home solution, Leaf-to-Home. The solution in the figure is also a stand-alone enrgy system, which means that the system is

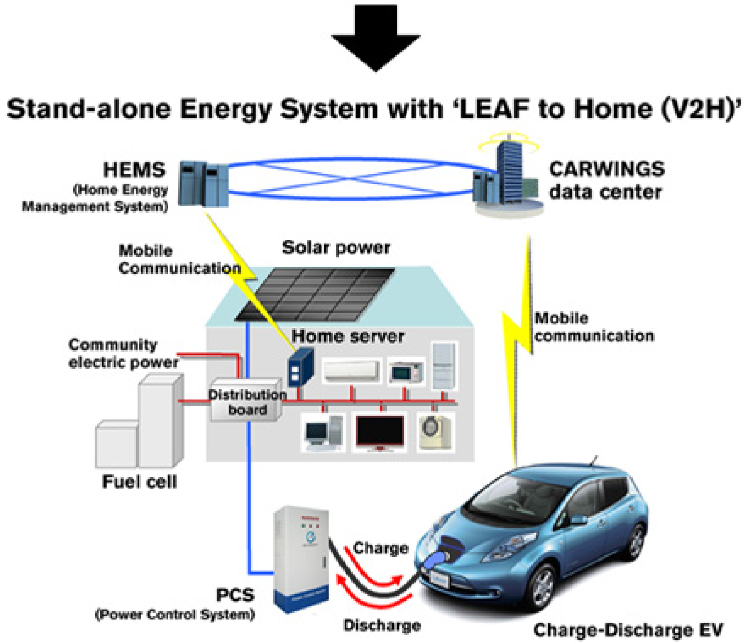


Figure 2.2: Leaf-to-Home .

energy independent. This will be analysed in the second part of the analysis, where a windturbine and energy storage delivers the energy needed to cover the demand and the charging.

The V2H requires smart solutions. In light of the Smart Grid vision the opportunities for a third-party to offer add-ons are huge. What type of services do the different consumers want? Some consumers want to control the power flow themselves, while others want it to go automatically. Can this be a part of the Smart Metering infrastructure or do we need new infrastructure for communication?

Communication

The communication between car electronics and the charger arrange for smart grid opportunities (V2G/V2H)[6]. To be able to optimize the implementation of electric vehicles in the grid there need to be communication between the vehicle and charger. Communication solutions can be Point-to-Point or Point-to-Multipoint.

In Point-to-Point the measurement is transferred directly to the collection point. In the use of a point-to-multipoint solution, the transmission goes via a concentrator,

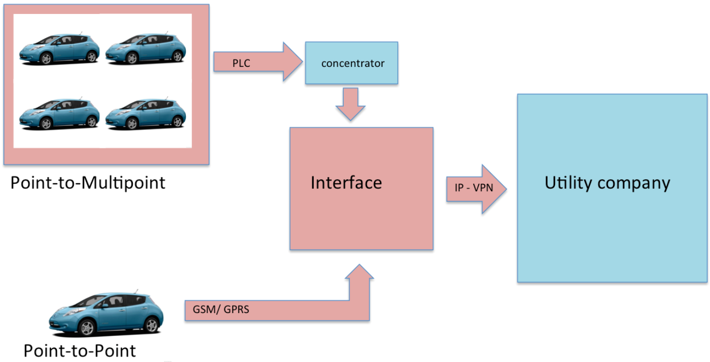


Figure 2.3: Communication solution.

as seen in figure 2.3. An introduction of V2H requires Point-to-Point[46].

An other important factor in the communication, is infrastructure. The different solutions have different investment cost, operating cost and transmission capability. The infrastructure for communication between the monitoring points are essential in the implementation of smart meeter. Table 2.2 give a overview over the different infrastructures and their characteristics.

GSM(Global System Mobil) is the most popular mobile network in the world. It is secure and it already exist. GPRS (General Packet Radio Service) is a upgraded version of GSM. GPRS is packet oriented, which means that you pay for the volum rather than the time. The disadvantage for GSM and GPRS is that you need a SIM card for each terminal which need to be operated by a telecom operator. This may cause high operating cost. Communication over radio is dependent on good geographical terms. PLC (Power Line Communication) is an existing structure, and

Table 2.2: Infrastructure[46]

	Investment cost	Operating cost	Capacity
GSM	low	high	high
GPRS	low	high	high
Radio	low	low	moderate
PLC	low	moderate	high
Optic Fiber	high	low	high
IP	low	low	low

has therefore very low investment costs. Disturbance from different components may cause higher operating costs. The usage of optic fiber as a communication system is a a very good solution were this solution is already implemented for broadband. About 70 % of the utility companies in Norway have introduced fiber in one or more parts of the transmit. Fiber has a great capacity and there are almost no maintenance. The disadvantage of the fiber is the investment cost. The solution the utilities look at as the most optimal solution is IP (Internet Protocol), due to the infrastructure is highly implemented. The solutions does not, however, have the same capacity as the solutions mentioned above[46].

Chapter 3

Energy Storage

There is a wide range of technologies of energy storages available, with different applications and qualities. The storages can be divided into two main groups;

1. Power applications
2. Energy applications

Power application storages can also be divided into two groups; power quality and bridging power. Power quality is fast response, applications that can support the grid with fast discharge such as transmission and distribution stabilization, and transient and end-use ride through. Storage is applied for seconds or less to ensure quality. Bridging power is stored energy that is used for seconds to minutes for short or long discharge. Voltage regulations, spinning reserve, peak shaving and short discharge for renewable matching is typical applications for the other power application group.

Energy applications are long discharge functions. These applications can be long discharge renewable matching, load levelling, load following, emergency and renewable back-up. This group of storages ensure consumer to be grid-independent.

3.1 Energy Storage Technologies

Figure 3.1 present the features of the storages, where the discharge time is given as the y-axis and the rated power as x-axis.

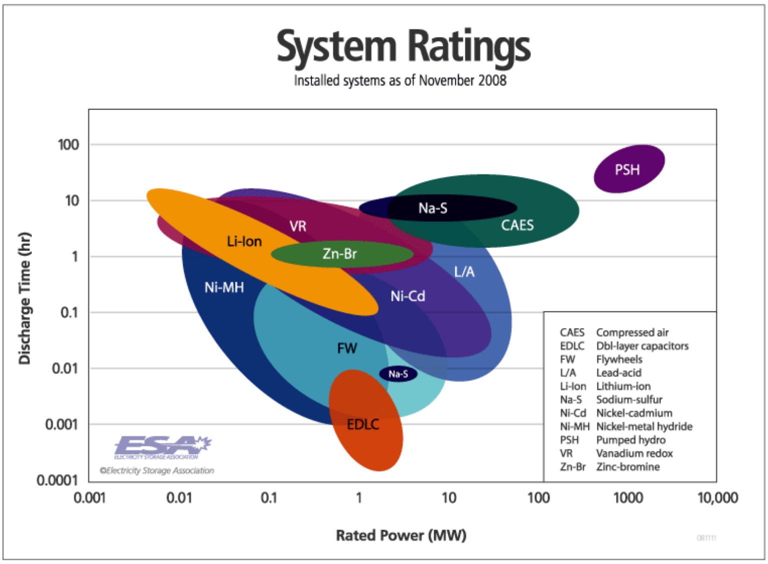


Figure 3.1: Features of storage system[11].

As mentioned, the storages are divided into three functional categories with discharge as main division. Storages that supply power quality functions are placed at the bottom part of the figure. The energy application is found in the top section, where most of them are towards the right. The figure shows that the power rating increases as the discharge time increases.

3.1.1 Pumped hydroelectric storage (PHS)

The most used energy application is pumped hydroelectric storage[11]. A PHS-system work as a conventional hydropower plant during peak-hours. When the demand is low, the water is pumped from the lower reservoir and up to the higher reservoir. The system can consist of a turbine and a pump or by a pump-turbine. A pump-turbine is a Francis turbine that can both work as a turbine and a pump. The efficiency of a PHS-installation is 60-85%. The main advantage for pumped hydro is the large capacity and the low operation costs. A installation can have a power rating of 30-4000 MW[27]. The spesial site requirement is the main disadvantage of pumped hydro as storage. The sea can also be used as the lower reservoir, but this is not common as the salted seawater may destroy the installation. This is however being explored[11]. PHS is mainly a energy storage, but can supply short discharge function such as spinning reserve as well.

3.1.2 Compressed Air Energy Storage (CAES)

An other long term energy storage is CAES. Air is compressed and injected into an above ground system (pipes and/or tanks) or an underground structure, for example a cavern, aquifer or abandoned mine. Natural gas is then added to the compressed air, and the mix is then burned and expanded in a gas turbine to produce electricity. A conventional gas turbine uses 40% more fuel than a CAES-system. Today there are only two running CAES plants; a 290 MW unit in Hundorf, Germany and a 110 MW unit in McIntosh, Alabama[11].

3.1.3 Flow Batteries

A flow battery is a rechargeable fuel cell, including typically Polysulphide Bromide (PSB), Vanadium Redox (VRB) and Zinc Bromine (ZnBr). In the flow batteries energy is stored as potential chemical energy. Modern flow batteries consist usually of two electrolyte system. The two electrolytes acts as liquid energy carriers and are pumped through the cell stack, which is were the reaction occur[11]. The flow battery technology provides very high power and capacity. The power capacity depends on the size of the cell stack, while the energy capacity is a function of the electrolyte volume[27].

3.1.4 Sodium sulphur (NaS)

In a sodium sulphur battery, the cathode is containing liquefied sulphur and there are liquefied sodium at the anode. The electrolyte is solid β-alumina, this electrolyte allows only the positive sodium ions to pass through the electrolyte and combine with the sulphur. The process is dependent of a operating heat of 300-350° Celsius, and it is therefore need of internal heaters in the battery[11]. The NaS battery has a high efficiency, rating between 86-89%, as well as a high life cycle (4500 cycles). An other main advantage of the sodium sulphur is its high capacity; power capacity up to 200 MW and energy capacity up to 1200 MWh[27].

3.1.5 Storage batteries

Storage batteries has both high power and high energy density. The storages work best as power application, but are feasible as energy application as well. There are three main types of storage batteries:

Lead-acid

Lead-acid batteries uses a sulphuric acid as the electrolyte. The anode is lead and the cathode is lead dioxide. The efficiency of the lead-acid batteries is between 75-85%. The storage has both high power and energy capacity, but a low lifecycle. The capacity for power is rated as 10 MW and 40 MWh for energy capacity[27].

Lithium based

Lithium based batteries, for example Li-ion, have a higher energy density and efficiency than the other storages batteries (lead-acid and nikel based). The energy density is up to 150 Wh/kg and the efficiency is rated at 90-100%. Li-ion has also a lower self-discharge and a higher lifetime, but does however have a greater production cost. The anode in the battery is made of carbon while the cathode is lithium cobalt oxide ($LiCoO_2$). The Li-ion battery is used in Nissan Leaf - the EV used as the model in the case study.

ABB, 4R Energy, Nissan North America Inc. (NNA) and Sumitomo Corporation of America have formed a partnership to evaluate the re-usage of Li-ion batteries from old Nissan Leafs. The batteries installed in the EVs have a longer lifetime than the rest of the vehicles components. The remaining capacity of the battery after ten years is up to 70%. The team want to develop a prototype with a capacity of $\geq 50kWh$. This size is enough storage to supply approximate 15 residences for two hours[2].

Nickel based

Nickel based batteries uses nickel hydroxide as the cathode and a potassium hydroxide as electrolyte. The anode is made up of the second material in the battery, typically cadium, zinc and a metal hybrid. Nickel-cadium (NiCd), nickel-zinc

(NiZn) and nickel-metal hybrid (NiMH) are the storages included in the term nickel based batteries. NiMH has the highest energy density for the three types with 80 Wh/kg. The energy density for NiZn is 60 Wh/kg and 50 Wh/kg for NiCd. On the other hand, the NiCd has the highest life cycle. In comparison to lead-acid, the nickel based batteries has lower efficiency and a higher self discharge rate[27] The nickel based batteries are reasonable for energy applications[11].

3.1.6 Flywheel

A flywheel energy storage is a rotating mass storing kinetic energy. The wheel is connected to a motor-generator group and can store and release energy by acceleration and deceleration. Low-speed flywheel rotate with a rotational speed of 10000 rpm and can provide 1.65 MW for a time period of two minutes. A high-speed flywheel can provide 750 kW in a time period of one hour, with a rotational speed of 80000 rpm. The flywheel can provided a very high amount of power, but the storage has a low energy density and a high self-discharge ratio[27].

3.1.7 Super-capacitor Energy Storage (SES) and Superconducting Magnetic Energy Storage (SMES)

As for a traditional capacitor, the energy is stored in an electric field , in the super.capacitors. The difference is that the plate area is increased due to porous materials, as well as the distance is reduced to a few molecular diameters. The main advantage is the high power density and its lifecycle, and the main disadvantage is the low energy density and high cost[27].

In a SMES system the energy is stored in a magnetic field. This is done by DC-current flowing inn a superconducting coil. The coil is kept cool, using liquid helium or nitrogen, to avoid resistive loss in the coil. The capacity and its efficiency is the main advantages, with a capacity of up tp 2 MW and efficiency given as 95-98%. The efficiency is highly dependent to temperature, which is the SMES maid disadvantages, in addition to low energy density[27].

Chapter 4

Case study

4.1 Network Description

For the purpose of this case, a low voltage distribution network was chosen to be simulated. The real data is provided by NTE[17]. This low voltage network is located in Steinkjer, Nord-Trøndelag.

The map in figure 4.1 shows the area of the low voltage network in Steinkjer. The provided system includes a distribution network with primary voltage level of 22 kV transfer down to the low voltage level of 230 V. From the substation there are six outgoing feeders, supplying together the load of from 35 residences. There are also 3 residential loads that are supplied directly from the substation. This gives a total load of 38 residences. The feeders are marked as white boxes in figure 4.1. For a more detailed and structured overview, a simple schematic sketch of the system is presented in figure 4.2.

NTE provided hourly consumption from *one* of the residences (residence number 020 in figure 4.1), and yearly demand from the other residences in the network in Steinkjer. To be able to make a 24 hour load curve for the entire system, a power coefficient was introduced.

$$\kappa = \frac{T_\eta}{T_{020}} \tag{4.1.1}$$

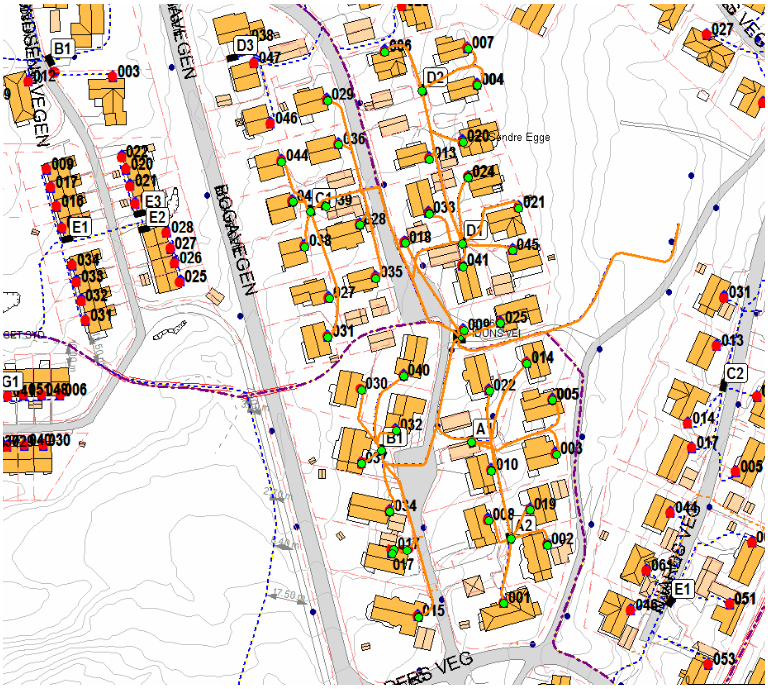


Figure 4.1: Map of the residences, provided by NTE.

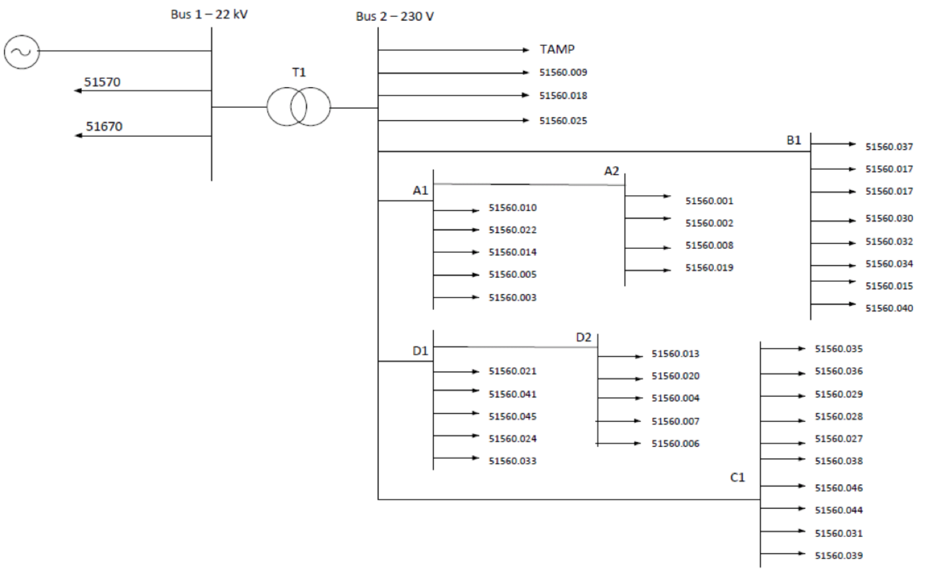


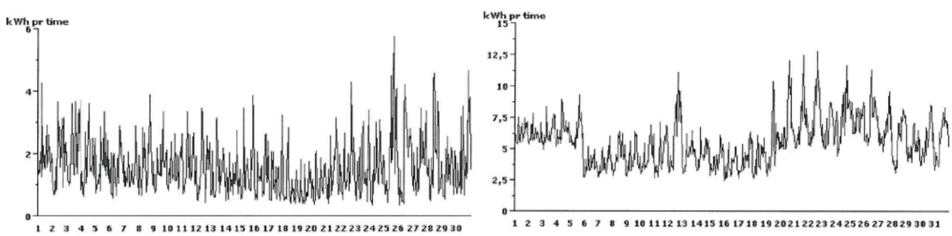
Figure 4.2: The low voltage distribution network.

$$P_\eta = P_{020} \cdot \kappa \tag{4.1.2}$$

The coefficient κ is the relationship between the yearly consumption for residence 020 and the yearly consumption for any other residence in the system, as seen in equation 4.1.1. Since there was no information about the hourly reading from the other residences, a 24 hour consumption were calculated for each residence. The momentary demand for any residence, P_η, is scaled from the momentary demand for residence 020, like shown in equation 4.1.2. It is therefore assumed in this case, that every residence has the same load curve throughout the day.

Figure 4.3 shows the load profile for the given residence in the network, respectively for winter and summer for the year of 2010. Figure 4.3a represent the month of June 2010, while figure 4.3b represent the month of December 2010. The difference in the demand between winter and summer is significant, as seen in the figures. While the hourly demand in the winter has average value of 5,565 kWh/h, the an average value for the summer is 1,49 kWh/h. Due to the fact that demand is highest in the winter, it is beneficial to analyse this case. It is therefore chosen to use the load from December 2010 from the given residence as the simulation data.

The hourly real time data from December 2010 for the residence in Steinkjer was used to calculate the daily hourly average demand for the residence. This value is shown in figure 4.4. The grey line is the average demand throughout December. The dotted line in the figure, is the demand for December 22nd. It was decided to use this date as the "simulation date", because it would represent the worst case scenario as the demand were highest at this date. The figure shows the difference



(a) June 2010

(b) December 2010

Figure 4.3: Monthly demand for a residence provided by NTE

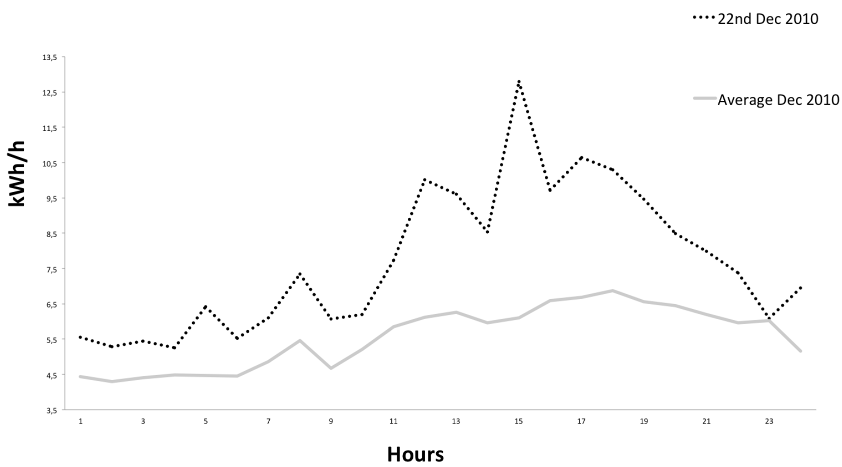


Figure 4.4: Average daily load for a residence in December 2010.

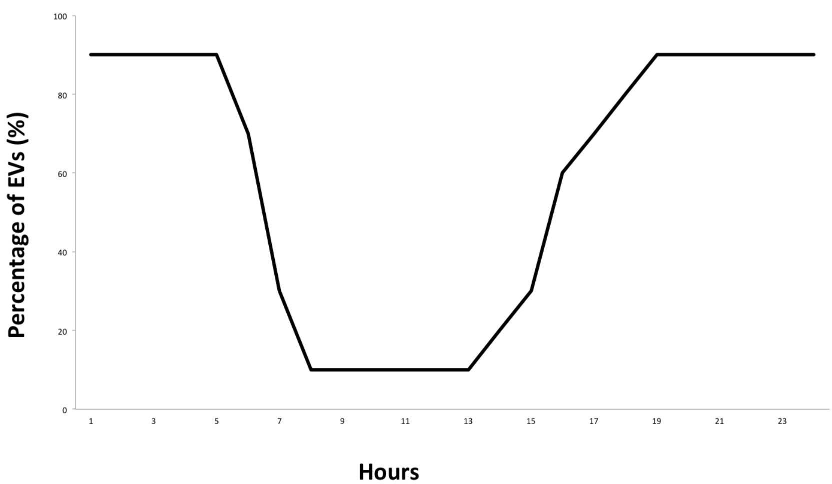


Figure 4.5: Percentage of EVs connected to the grid.

between the average demand for the month, and the demand on the simulation date. The demand peaks are, as expected, in the afternoon. However, it was expected that the highest peak would occur later. For the chosen simulation date, the highest peak occurs at 15.00. It is expected that for an other day this peak would occur later, like shown on the average where the peak occur around 18.00.

It is expected the EVs will be connected and start charging during these peaks, and cause higher peaks. To be able to simulate this, the average number of EVs connected to the grid during the day was determined. This was made on general assumptions, and is only a calculated value. It is however used in other analysis [20] and will correspond to the real situation. These values are shown in figure 4.5. As seen on the figure, the electric vehicles are connected from approximate 16.00 until 06.00. However, the recharge time is assumed to be less than the connection time.

4.1.1 EV Charging Model

In the study addressed in this case, a simplified charging model will replace the actual charging process. The EV is considered as a constant power demand. Further, the following is assumed:

1. All EVs are charged at rated power
2. Initial SOC is assumed to be 0%
3. EVs will be charged to full capacity

To determine the load and recharge time for the EVs in the simulation, Nissans electric vehicle, *Nissan Leaf* is used as a basic for the electric vehicles in the analysis. The Nissan Leaf has a Li-ion battery with a capacity of 24 kWh. The recharge time depends on which charging level or mode is used. As of the solutions used today, a charging dock 220/240V and 40A has a recharge time of 3.5 hours (level 2 - USA)[38], while a 220/240V and 16 A the recharge time will be 6.5 hours(mode 1 -EU)[29]. In this analysis it is preferable to assume a 4 hours recharge time. In the American solution mentioned above (level 2) the dock has a 40 A charging current, mode 2/3 allows a maximum current of 32A. It is therefore assumed that the recharge time in a mode 2/3 dock will be equal to 4 hours. As stated in section 2.4 mode 2/3 will be the preferable level in the future in Europa. The assumption of a 4 hour recharge time is also used in the Portuguese publication *Smart Charging*

Strategies for Electric Vehicles: Enhancing Grid Performance and Maximizing the Use of Variable Renewable Energy Resources by J. A. Peças Lopes[20].

$$E_{batt} = 24\ kWh \tag{4.1.3}$$

$$T_{charge} = 4\ h \tag{4.1.4}$$

$$P_{EV} = \frac{W_{batt}}{T_{charge}} = \frac{24}{4} = 6\ kW \tag{4.1.5}$$

To simplify the analysis, it was assumed that the modelled EVs would consume a linear load. As mentioned, the Nissan Leaf has a 24kWh battery and a recharge time of 4 hours. From the equations 4.1.3, 4.1.4 and 4.1.5, it is determined that the EV, during charging, will consume 6 kW per hour.

It was determined that average value of vehicle per household is equal to 1.5 vehicle, which gives a total number of vehicles enclosed in the area of the network, are calculated to be 57 vehicles. This was based on that the vehicle density in Nord-Trøndelag is, according to Statistics Norway (Statistisk sentralbyrå), 566 per 1000 citizen[33]. It is further assumed, in this case study,that all the EVs will charge during the 24 hours analysis.

4.2 Simpow Model

The simulations made in this analysis were performed in the power system simulation software SIMPOW by STRI.

4.2.1 Components

The information about the LV-network provided by NTE included cables identification, consumption for the nodes and hourly real time measurement for one node. This is attached as appendix A.

Cables

The model used for the cables is a π-link which correspond to the connection of two AC nodes with a resistance and a reactance in series, and a susceptance at each sides of the cables. The model of the π-link is shown in figure 4.6. The parameters R, X and B is given in ohms and siemens. The cables impedances was collected from *Planleggingsbok for kraftnett, Tekniske data* (Quire for power grid, Technical data) provided by SINTEF[3].

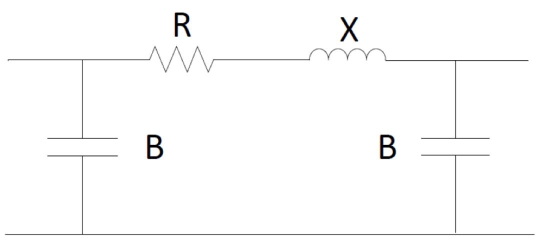


Figure 4.6: π-link model.

Substation

The substation in the system is rated to 315 kVA. Due to the up scaling of load, the rated size of the substation was to small, and it was therefore simulated with 400 kVA. In the Norwegian distribution grid, the typical substation ratings in kVA are

50, 100, 200, 315, 500, 800, 1250, 1600 and 2000. In this case, the reason for rating the substation to 400 kVA is to make the system resemble the real life values.

In Simpow, substation are represented with the following parameters; $S_N, U_{N1}, U_{N2}, E_{R12}$ and E_{X12} The short circuit impedance, $e_z = 4,37\%$, and the the loss in the transformer, $P_K = 3340W$, was given from Møre Trafo[36]. The short circuit resistance and reactance are found from equations 4.2.2 and 4.2.3.

$$e_z = \frac{Z_K I_N \sqrt{3}}{U_N} = 4,37\% \tag{4.2.1}$$

$$e_r = \frac{R_K I_N \sqrt{3}}{U_N} = \frac{P_K}{S_N} = \frac{3340}{315 \cdot 10^3} = 1,06\% \tag{4.2.2}$$

$$e_x = \sqrt{e_z^2 - e_r^2} = \sqrt{4,37^2 - 1,06^2} = 4,24\% \tag{4.2.3}$$

Source

The supply, the 22kV grid, were set as a swingbus(constant voltage and constant phase angle) in Simpow. The phase angle at this in the network is close to constant. Figure 4.7 is provided by NTE and shows the variation in $cos\Phi$ during the year. As seen on the figure, the value of $cos\Phi$ is changing rapidly. The value measured in Steinkjer was more constant, which differs from the values at the two other substations. This is because there are production connected to the substation in Steinkjer. The 22kV grid is therefore looked at as a strong grid, and in Simpow, this is represented as a swingbus. $cos\Phi = 0.966$ in Steinkjer. This value was given from NTE as a function of equation 4.2.4. Phase angle in degree is then found from equations 4.2.7.

$$cos\Phi = \frac{P}{\sqrt{P^2 + Q^2}} \tag{4.2.4}$$

$$S = \frac{P}{cos\Phi} \tag{4.2.5}$$

$$Q = \sqrt{S^2 - P^2} \tag{4.2.6}$$

$$\Phi = 0.2615rad = 14.983\circ \qquad (4.2.7)$$

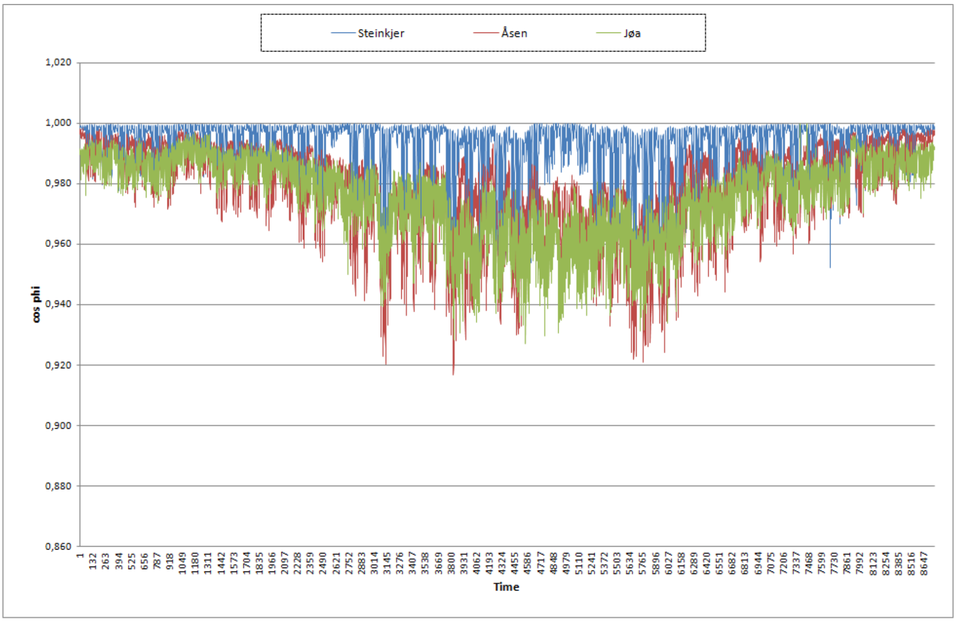


Figure 4.7: Variation in $cos\Phi$ during the year

4.2.2 Load modelling

To model the dynamic load, an mathematical model described in Machovwski's *Power System Dynamics* is used. The model assume on of the following features:

i. Constant power demand (P)

ii. Constant current demand (I)

iii. Constant impedance (Z)

The slope of voltage characteristic is referred to as the voltage sensitivity of the load[22]. Equations 4.2.8 and 4.2.8 shows that the voltage sensitivities k_{PV} and k_{QV} is expressed as the relationship between power and voltage with respect to the given operating point.

$$k_{PV} = \frac{\Delta P/P_0}{\Delta V/V_0} \qquad (4.2.8)$$

$$k_{QV} = \frac{\Delta Q/Q_0}{\Delta V/V_0} \tag{4.2.9}$$

If the voltage sensitivities is small, the load is considered *stiff* at the given operating point. A voltage sensitivity equal to zero, represent a *ideal stiff* load, meaning that the power demand does not depend on the voltage. If the load is voltage sensitive (high voltage sensitivity), a small change in the voltage will cause high change in the demand. In Simpow, the power is modelled by the exponential load model. In this model the power is related to the voltage like shown in equations 4.2.10 and 4.2.11.

$$P = P_0(\frac{V}{V_0})^{n_p} \tag{4.2.10}$$

$$Q = Q_0(\frac{V}{V_0})^{n_q} \tag{4.2.11}$$

$$n_P = k_{PV} \tag{4.2.12}$$

$$n_Q = k_{QV} \tag{4.2.13}$$

Where the parameters n_P and n_Q express which feature the load is represented by. Constant power is applyed by $n_P = 0$, $n_P = 1$ expresses constant current and $n_P = 2$ gives constant impedance. In the model applied here, the parameters n_P and n_Q are equal to the voltage sensitivities (ref: equations 4.2.12 and 4.2.13).

The load are expressed with constant impedance, leaving $n_P = n_Q = 2$ in the optpow-file. This makes it possible to change the load with a table in dynpow. In optpow the load were expressed as P_{max}. A dynpow-file were created for each scenario and charging approach. The dynamic change in load were carried out in dynpow with regard to $P = P_{max} \cdot P_{TAB}$. The optpow and one of the dynpow files are attached as appendix C.

In the data provided for NTE, it was given that the yearly consumption of one the residence (039) were 1 kWh. This value was so small, that the consumption of this residence were neglected. It is neither accounted for further in the analysis.

4.3 Scenarios

According to the Norwegian government's plan for electrifying the transport sector, it is determined that at least a share of 10% of the passenger vehicle must be chargeable by 2020. Further it was stated that if the share of electrical vehicles reached 50% in 2050, it would cause a reduction in CO_2 emission with 36%[9]. In consideration to this, three different scenarios were analysed. The scenarios are presented in table 4.1. The numbers in the table is based on assumptions made earlier in this chapter.

The first scenario is an analysis of the system without EVs. This was done to have it as a base to compare the other two scenarios with. In scenario 2, a small scale integration of EVs were simulated. The share of vehicle is ≈ 10% of the total number of vehicle, and reflect the governments goal for 2020. Six EVs were added into the grid. These EVs were placed in six different residences, shown in figure 4.8. The extra demand caused by the charging of EVs were added to the hourly measurement. The demand was added during 14.00 - 21-00 as a direct function of figure 4.5 as shown in section 4.1.

For the third scenario it was decided to exceed the governments ambition of a share of 50% EVs by 2050. It was chosen to see what consequences a >60% share of EVs would have in the LV-grid. Thirty-six EVs were added in the system, leaving 95% of the residences with one electrical vehicle. This can be seen in figure 4.9. The extra demand was, like in scenario two, added to the hourly measurement.

Table 4.1: Scenario Overview

Scenario	1	2	3
N of vehicle	57	57	57
N of EVs	0	6	36
Percentage of EVs[%]	0	10.53	63.16
Total demand [MW]	4.77	4.91	5.63

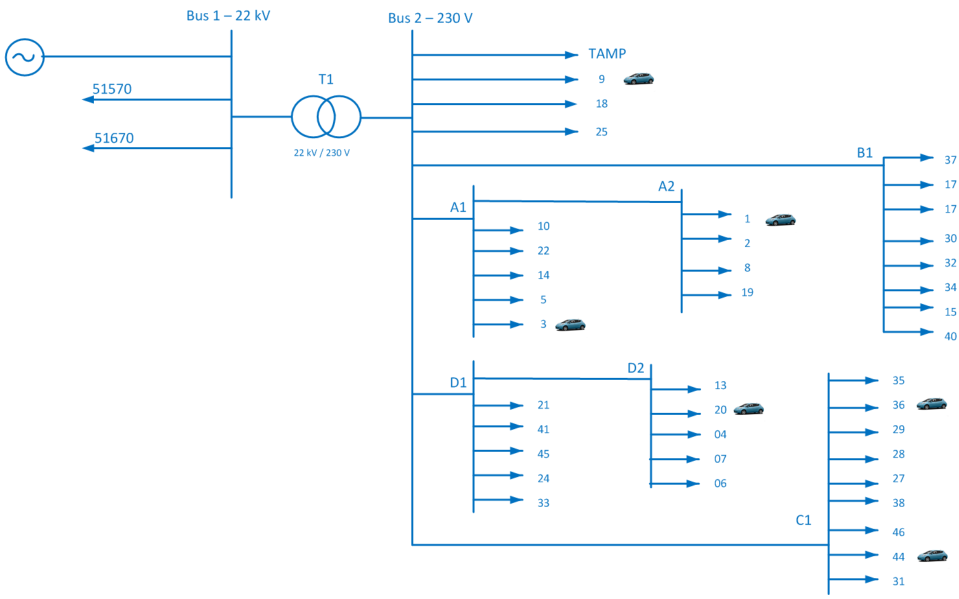


Figure 4.8: Scenario 2 - 6 EVs are connected to the grid

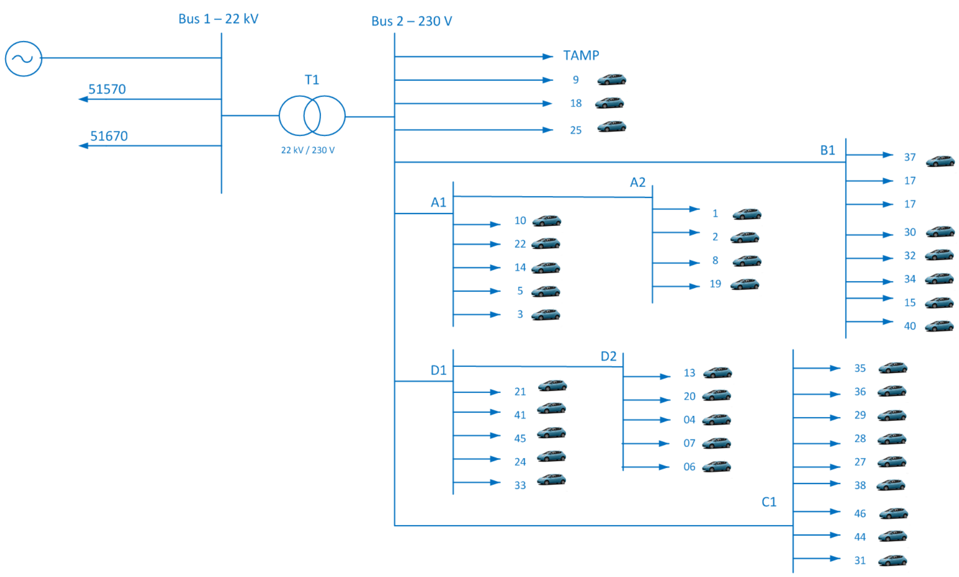
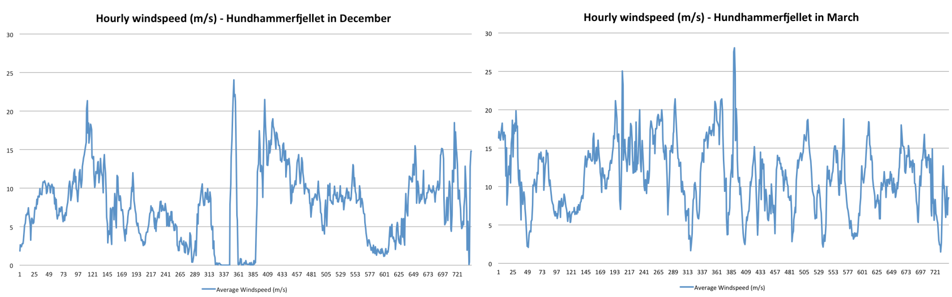


Figure 4.9: Scenario 3 - 36 EVs are connected to the grid

4.4 Wind power model

Further it was decided to look at a case where the small residential area was supplied with wind power. A series of wind-measurement data was also provided by NTE. The measurements are collected from NTE's windfarm at Hundhammarfjellet. Hundhammarfjellet is located in Nærøy county, which is also in Nord-Trøndelag. The total rating of the windfarm is 53,7 MW and it has a yearly production of 170 GWh. The plant was completed in the summer of 2008, and includes 17 turbines delivered by 3 different contractors; ScanWind AS, which now is owned by GE Energy, delivered 14 turbines with a rating of 3 and 3.5 MW. Enercon delivered two turbines; E-70 2.0 MW and E-70 2.3 MW and Vesta delivered one V66/1,65 MW turbine.

NTE provided wind measurement for December 2010 and March 2012, seen in figure 4.10. The wind speed measured in December 2010 is shown in figure 4.10a, and the same measurement for March 2012 is found in figure 4.10b. The mean wind speed throughout the months are respectively 7,8 m/s for December 2010 and 11,34 m/s for March 2012.



(a) December 2010 (b) March 2012

Figure 4.10: Hourly wind speed, provided by NTE

The typical cut-in wind speed for small scale turbine is 3-4 m/s[21]. The wind speed is lower than the cut-in wind speed 22,55 % of the time in December 2010. The wind speed does not exceed the cut-out speed of typically 25 m/s. This means that the turbine can not produce 22,55 % of the time due to low wind speed. As for march, the percentage of time where the turbine can produce is 94,08 %. The wind speed exceed the cut-out speed 0,404 % of the time and below the cut-in speed 5,518 % of the time.

The analysis will compare a 24 hour power analysis for a day in December 2010 and a day in March 2012. It is expected that there will be produced more during the day in March, due to the difference in the wind measurement (ref: figure 4.10a and 4.10b). In addition to more production, the demand is not nearly as high in March than December. It is therefore expected a energy surplus in March, and a need for energy storage.

In the case addressed in this study, one turbine was assumed connected to the high voltage side. The sizes of the turbine was determined on the bases of calculations made in a previous study. Appendix D is a paper on this study, presented at Technoport RERC conference in April 2012. It was determined to choose a turbine with a power rating that stayed under the respective capacity of the system. The limit is the thermal capacity of the cables, 380 kW. Further it was decided to run a second analysis with a turbine of 500 kW. It was desirable to have a large enough turbine to supply the low voltage network alone, and from the result presented in the paper (ref: appendix D) one can see that a 330 kW turbine might not provide enough power.

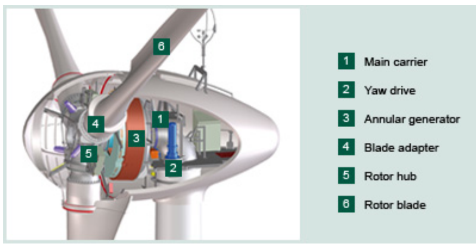
It was decided to use Enercon turbine models for the analysis. The 300 kW turbine was modelled after Enercon's E_{33}(330 kW). Since none of the largest wind turbine manufacturers produces a 500 kW turbine, the specifications was determined by Enercon's E_{33}(330 kW) and E_{48}(800 kW) turbines. This assumption is supported by the fact that the two models have correlating Cp-curves. Cp is knows as the power coefficient, and is a function of the rotor power and the power in the wind. This is explained by equation 4.4.1[21]:

$$Cp = \frac{P}{\frac{1}{2}\rho U^3 A} \tag{4.4.1}$$

The power coefficient is a value for how much of the power in the wind the rotor can extract. If two turbines have correlating cp-curves, they will have the same power output from the rotor. That means that the difference between a 330 kW, a 500 kW and a 800 kW turbine is the rated power on the generator.

The E_{33} - 330 kW turbine from Enercon, was used as the model for the case study. A picture of the turbine (4.11a) and a overview of the nacelle (4.11b) is shown in figure 4.11. The technical specifications are listed in table 4.2. The hub hight for the turbine varies, but it was chosen to use a hub hight of 50 m in this study, because this was also a turbine hight for the 800 kW. The wind data provided by

(a) E_{33}



(b) Overview nacelle

Figure 4.11: Enercon's 330 kW wind turbine[12]

Table 4.2: Technical specifications[12]

Enercon's E_{33}	
Rated power	330 kW
Rotor diameter	33,4 m
Hub hight	50 m
Cut-inn wind speed	3 m/s
Nominal wind speed	13 m/s
Cut-out wind speed	25 m/s

NTE was measured in the middle of the wind farm at a hight of 82.6 m. In order to simulate the wind speed at 50 m, the wind profile power law were applied. The law represent a simple model for vertical wind speed[21]

$$\frac{U(z)}{U(z_r)} = (\frac{z}{z_r})^{\alpha} \tag{4.4.2}$$

where $U(z)$ is wind speed at the hight z, $U(z_r)$ is wind speed at reference hight z_r, and α is the power law exponent. In simplified studies, like this analysis, the power law exponent α is set to $\frac{1}{7}$ which indicate a correspondence between wind profile and flow over flat plates. Equation 4.4.3 shows how the wind speed is adjusted for the turbine hight.

$$U(z) = U(z_r)(\frac{z}{z_r})^{\frac{1}{7}} = U(z_r)(\frac{50}{82.6})^{\frac{1}{7}} \tag{4.4.3}$$

In practice α is effected of terrain, temperature, time of day and season. A method to calculate α was proposed by C. G. Justus and is shown in equation 4.4.4 where U is given in meter per second (m/s) and z_{ref} in meter (m). α can also be found from J. Counihan's model where the correlation is dependent on surface roughness. Equation 4.4.5 present the model, where z_0 is surface roughness.[21]

$$\alpha = \frac{0.37 - 0.088ln(U_{ref})}{1 - 0.088ln(\frac{z_{ref}}{10})} \tag{4.4.4}$$

$$\alpha = 0.096log_{10}z_0 + 0.016(log_{10}z_0)^2 + 0.24 \tag{4.4.5}$$

In a more detailed analysis it had to be accounted for that α is a variable parameter. For the work addressed in this report, the assumption $\alpha = \frac{1}{7}$ is adequate.

4.4.1 Calculated power curve

To calculate the produced power for the given time period it is assumed a linear power curve between cut-inn wind at 3 m/s and 5 m/s, and between 5 m/s rated wind speed at 13 m/s. It was determined that for wind speed between rated wind speed and cut-out speed at 25 m/s is it assumed that the E_{33} produces 335 kW. Figure 4.12 shows the simplified calculated power curve (blue line) and the power curve given from the producer Enercon (red line). The figure shows that the calculated production will be a little bigger than the estimated production for wind speed between 5 - 9 m/s and a little smaller for wind speed between 9 - 13 m/s.

Model of the 500 kW turbine The specifications for the 500 kW turbine was determined based on the data from Enercon's E_{33} and E_{48}. Figure 4.13 shows the power curve for all three turbines, where the red line is the curve for 500 kW. As the figure show the power curve is scaled from the two other curves. The power curve for a 500 kW turbine was designed in the same way as the 330 kW was, as explained in the paragraph above.

According to Enercon, the cut-out wind speed for the turbine is 28-34 m/s due to

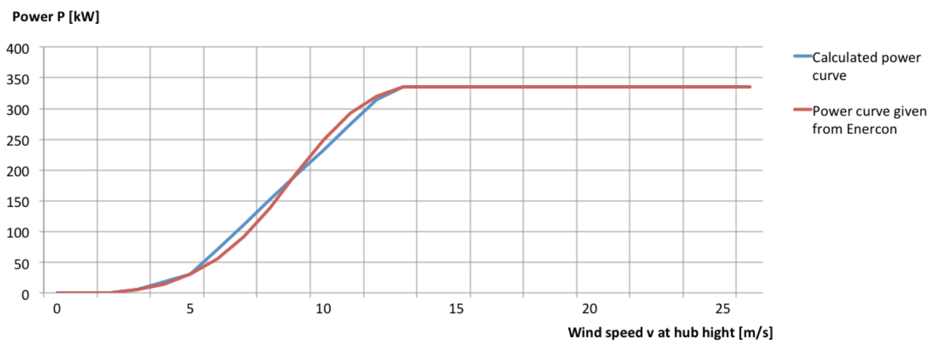


Figure 4.12: Simplified and actual power curve for E_{33}

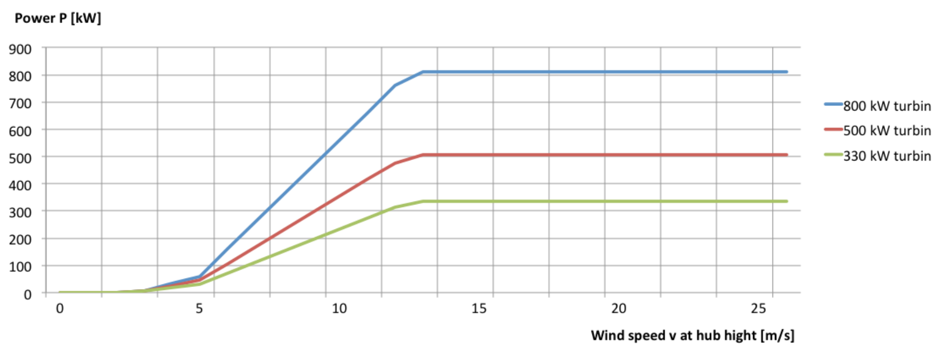


Figure 4.13: Power curve comparison between 300 kW, 500 kW and 800 kW

ENERCON storm control. This control enables turbine operation in the event of large wind speeds, and it prevent typical shutdowns witch cause high yield losses. The storm control enables reduced production for wind speed > nomninal wind speed as seen on figure 4.14. In order to simplify the analysis, the storm control was not applied, and turbine were set to shut down for wind speed > 25 m/s.

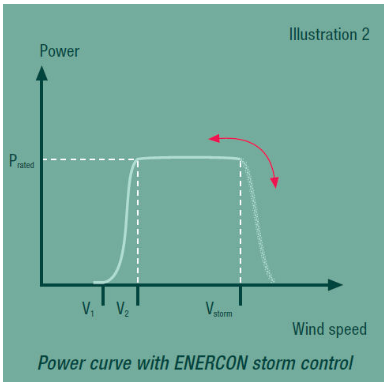


Figure 4.14: Illustration of storm control for E_{33}[12].

4.5 Charging Strategies

As it is previously mentioned, this paper will focus on the impact electric vehicle will have in a distribution network. Figure 4.4 and 4.5 illustrate that implementation of EVs in the grid *can* cause a capacity problem in the afternoon.

There is an existing peak in the afternoon and when a large share of EVs is implemented, the peak will increase. That may result in a capacity problem, a situation where the grid is not able to handle the heavy load. For the case study addressed in this work, two different charging strategies for EV charging were analysed:

Strategy 1 - *"Dumb charging"*

In the first approach it is assumed that the electric vehicle owners can connect the vehicle to the grid whenever they want to, and that the charging will start immediately. In worst case the owners will plug their vehicles at the same time. This situation may occur when the users come home from work, which are typically existing peak hours. The load from the vehicles will be added to the excising peak and this may result in a capacity problem. This approach is described as a non controlled strategy, leaves the power company to almost guess the production planning. In the dumb charging strategy the following assumption have

Strategy 2 - *"Smart charging"*

In the second approach, the smart charging strategy is introduced. It is assumed that there is an active control and manage system that continuously monitor all the elements connected to the grid. Then the charging schedules will be phased in. It is expected that the demand curve will be made more uniform. The vehicle will communicate to the grid when it is connected, and will start to charge when the demand is low. The smart charging strategy requires technology that can measure and communicate. It will also require a commitment from the vehicle owners.

This approach will provide a beneficial usage of available resources, and also prevent damaging the grid. The V2H can also be introduced as a part of the smart charge. Due to the continuously monitoring of the elements connected to the grid, the EVs can operate as ancillary services and support the grid. The EVs can both deliver and store electric energy from the battery to the supply in situation with surplus/deficit of energy.

Chapter 5

Results

5.1 Power analysis

The fist part of the analysis consisted of looking at the capacity of the system. This was primarily done in Excel. As mentioned, the dumb charging was added to the base demand as a direct function of figure 4.5. The dumb charging charging lasted for four hours and one EV consumed 6 kW each hour. In the second approach - the smart charging, the load from charging the vehicles, were added to the demand as a function of when the demand was low. It is expected that in a smart manage system, the vehicle can be charged at a lower power and over a longer time period, but to simplify this analysis, the smart charging will as the dumb charging last for four hours and each vehicle will consume 6 kW.

5.1.1 Scenario 1

The demand from the rest of the residences were calculated and a 24 hour demand profile for the system were made. This profile is shown in figure 5.1. The capacity of the substation is, as previous mentioned, exceeded in scenario 1. It is therefore chosen to set the capacity limit in this analysis as the cables thermal limit. The power capacity for each cable were calculated by the nominal voltage and I_{th}, the maximum continuous operating current. I_{th} was given from Quire for power grid, Technical data provided by SINTEF[3]. Further it was calculated for the entire system. The thermal limit was calculated to approximate 380 kW.

5.1.2 Scenario 2

The demand profile in scenario 2 is shown in figure 5.2. The extra demand of the six electrical vehicles does not exceed the capacity at any point. Figure 5.2 represent the worst case scenario, when all the vehicle is connected during peak hours. As seen in the figure, the highest peak of 366 kW occur at 15.00.

Except for the peak hours, the dumb charging, represented as the red line, is consistent with the base demand. The smart charging is, as shown in the figure with a blue line, slightly higher during the night. This represent the charging of the vehicles. It is assumed that all the vehicles are disconnected between 06.00 and 14.00.

As expected, the extra demand from charging in the dumb charging approach doe not exceed the limits of the system. It does however cause an extra strain during peak hours of 36 kW. Since the charging is moved to night-time in the smart approach, there are no additional strain in peak hours.

5.1.3 Scenario 3

In the third scenario, the load for charging 36 vehicle is added to the power profile. This is shown in figure 5.3. The demand for the dumb charging will, as figure 5.3 presents, follow the base demand until 14.00 - when the vehicles are connected to the grid. The consumption peak at 17.00 with a load of 454,5 kW, which exceed the limits of the system with 76,1 kW. The demand exceed the capacity limits between 15.00 and 19.00.

During the second approach, the smart charging, the charging is moved to late evening and night. The demand profile is consistent of the base demand during peak hours, leaving the highest peak to 330 kW at 15.00. The low demand between 05.00 and 07.00 is due to that the vehicle are done charging. In a case with a higher EV percentage this time could also been used for charging.

In scenario 2, the dumb charging represented the worst case scenario. In the figure shown here, this is not the case. The worst case scenario would occur if all 36 vehicles started to charge at 15.00. In that case the load would peak at 15.00

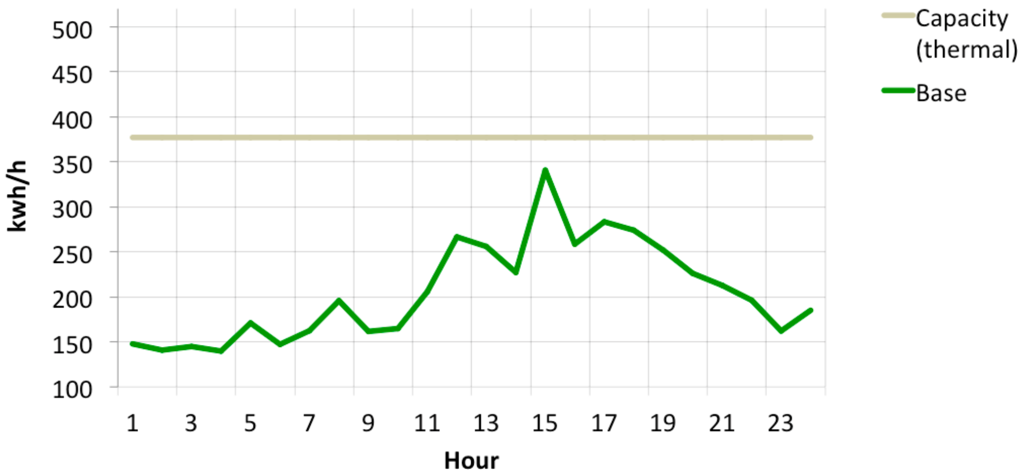


Figure 5.1: Scenario 1 - The scaled up demand

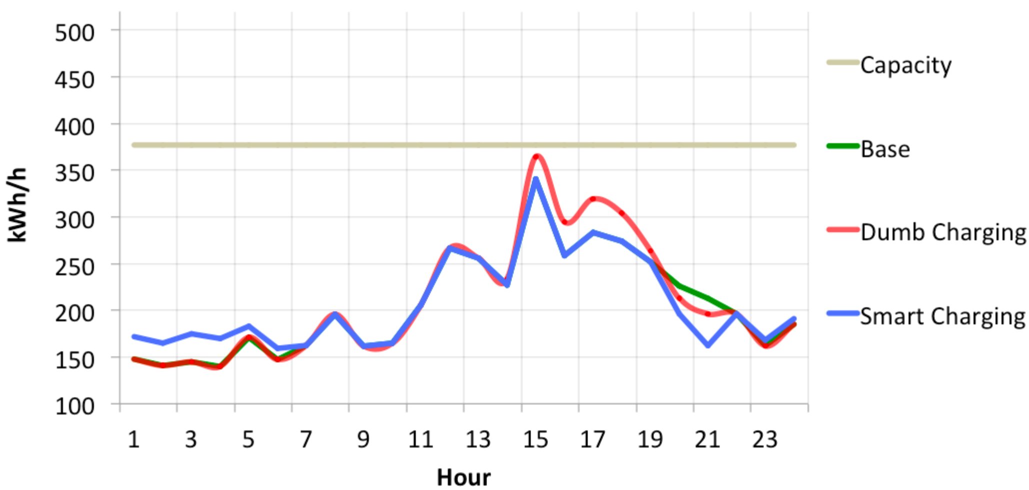


Figure 5.2: Scenario 2 - Demand with 10% EVs

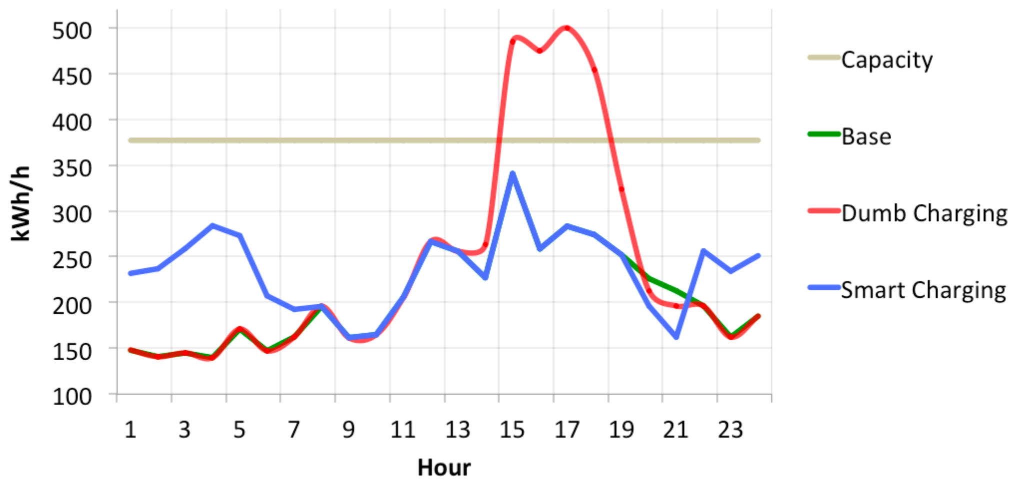


Figure 5.3: Scenario 3 - Demand with 63% EVs

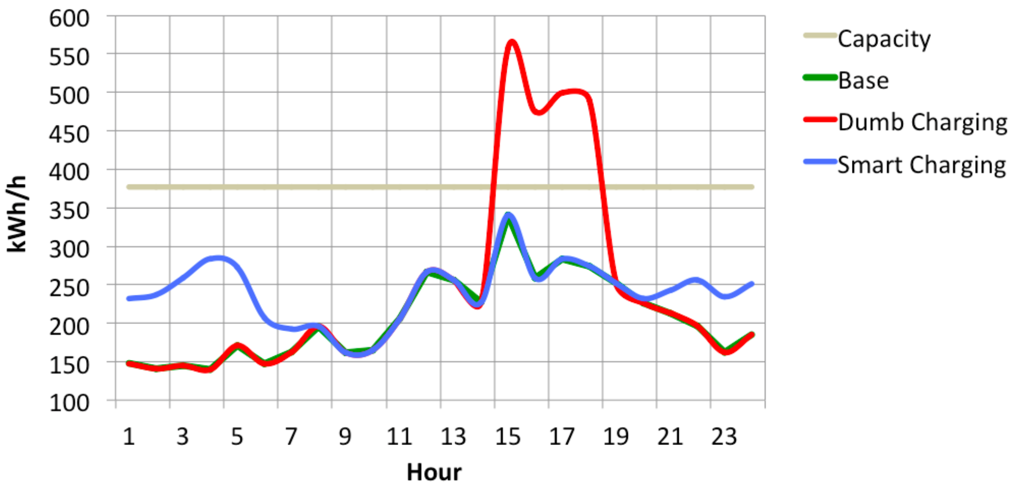


Figure 5.4: Scenario 3 - Worst Case Scenario

with a total load of 546 kW, an increase of 91,5 kW compared to scenario 3 (ref figure 5.3). This case is shown in figure 5.4. This is not simulated further since it was assumed that the percentage of EVs connected to the grid at that point is approximate 20% (ref: 4.5)

5.2 Voltage analysis

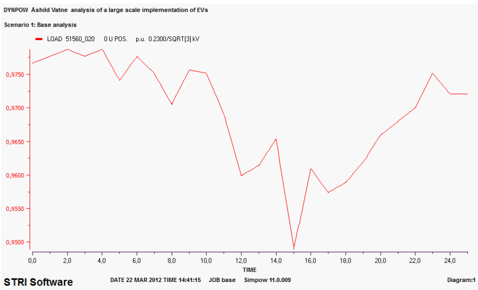
In the second part of the analysis, the voltages in the system were measured. This was done in Simpow. According to the govenrment's Regulations on Delivery Quality in the Electric System (*FOR-2004-11-30 nr 1557: Forskrift om leveringskvalitet i kraftsystemet* the voltage shall not exceed ±10%[13]. In addition to the general $U_n \pm 10\%$ requirement, the quality of voltage at the point of end user is also included in the regulations. The voltage at the point of end user shall not exceed the limits given in table 5.1 when the nominal voltage is $\leq 1kV$[1].

Table 5.1: Allowed voltage variation at point of end user ($U_n \leq 1kV$)[13]

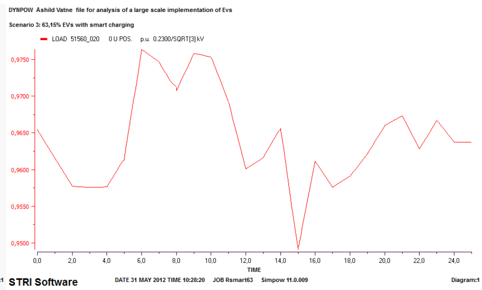
	Variation	Per Unit	Volt
Maximum voltage	$U_n + 8\%$	1.08	248.4 V
Minimum voltage	$U_n - 6,5\%$	0.935	215.05 V

Figure 5.5 shows the voltage during the different scenarios and charging approaches at residence 020 in the system. This was the point of measurement provided by NTE. Figure 5.5a present the voltage during scenario 1 - the base demand. The voltage is decreasing as the load is increasing. The lowest voltage dip measured in scenario 1 is 0.9491 p.u which occur at 15.00. Figure E.1a present the voltage at the residence in scenario 3 with smart charging. The lowest measured voltage is as for scenario 1, 0.9491 p.u. The only difference from figure 5.5a is a reduction in the voltage between midnight and 06.00 due to charging of the vehicles. The voltage measurement for smart charging in scenario 2 was not included here due to the result is the same as in scenario 3, just with smaller values. The measurement is however shown in figure E.2 in the appendices. In figure 5.5c, the voltage at the residence is scenario 2 during dumb charging is presented. As explained previous in this chapter, the value will follow the base demand until the vehicle is connected around 14.00. Due to the extra load caused by the charging the voltage dips, and the lowest measured voltage is 0,9424 p.u. This does not exceed the limits in table

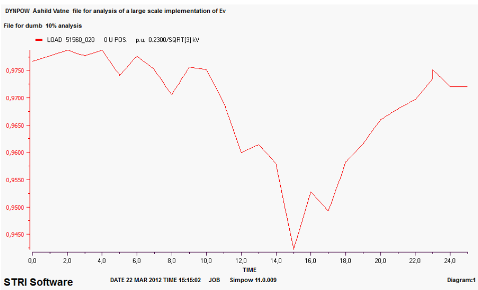
5.1.



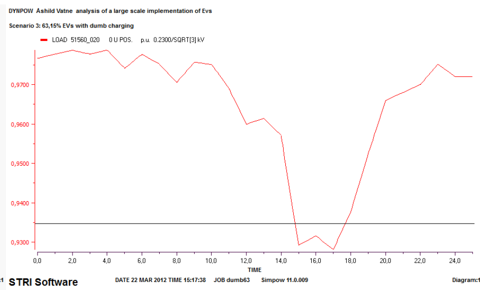
(a) Scenario 1 -Base demand



(b) Scenario 3 - Smart charging



(c) Scenario 2 -Dumb charging

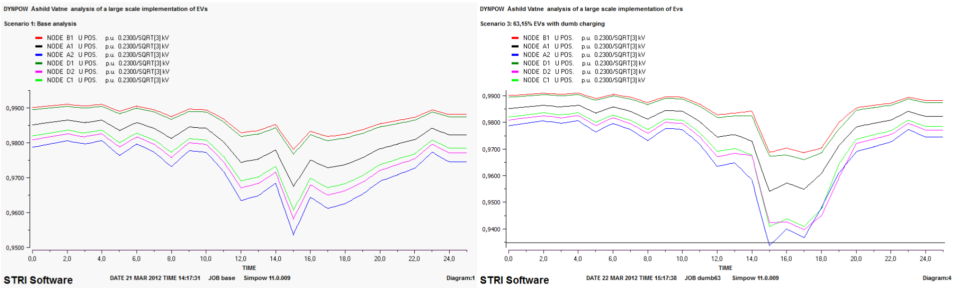


(d) Scenario 3 - Dumb charging

Figure 5.5: Voltage measured at the given residence - residence 020

Figure 5.5d shows voltage at residence in scenario 3 during dumb charge. As seen in the figure, there are no change in the voltage compared to scenario 1 between 22.00 and 13.00. During the charging of the vehicle the voltage dip below the limits of $U_n - 6,5\%$. The limit is marked in the figure. The voltage is below the limit between 15.00 and 18.00 as seen in 5.5d, with its lowest value at 17.00 when the voltage is 0,9283.

Figure 5.6 presents the voltage during the different scenarios at the outgoing feeders. The regulation require that voltage shall not exceed the respective limits of $\pm 10\%$ in this point. In the figures (ref:5.6) the requirements are kept. The different feeders are supplying 4-9 residences each. The voltage at these residences can not drop below 0.935 p.u according to the regulations of voltage variation at point of end user. Scenario 1 is shown in figure 5.6a. The two feeders with lowest value are D2 (pink line in 5.6a) and A2 (blue line in 5.6a). These feeders are located furthest away from the main supply and will therefore have a lower voltage value than nodes that are directly connected to the main supply. Figure 5.6b shows the voltage at



(a) Scenario 1 -Base demand (b) Scenario 3 - Dumb charging

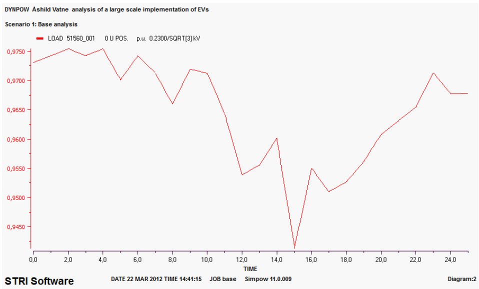
Figure 5.6: Voltage measured at the outgoing feeders

the feeders in scenario 3 - dumb charging. At approximate 15.00 the voltage at A2 drops below 0.935 p.u - which means that all the residences connected to A2 has also exceeded the limit. It it therefore interesting to look at the residences connected to this feeder.

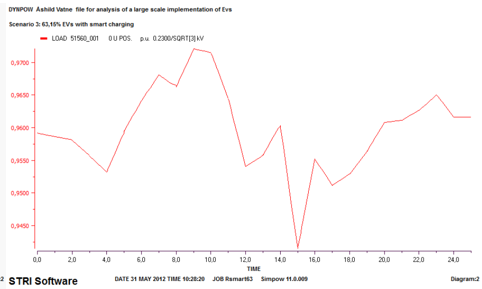
Residence 001 is the point furthest away from the main supply (ref: figure A.1 in appendices). It is therefore expected that this point will face voltage problem first. Figure 5.7 present the voltage measurement for residence 001. The voltage in scenario 1, the base demand, is shown in figure 5.7a. Due to the up scaling of the system from the consumption from residence 020, the consumption-curve for residence 001 will have the same form as the demand for residence 020, shown in figure 5.5. The lowest measured value is 0,09419 p.u. in scenario 1. The same for scenario 3 - smart charging, this can be seen in figure 5.7b. The dip in voltage from midnight to approximate 04.00 is due to the charging of the vehicles.

Figure 5.7c and 5.7c shows the voltage for respectively scenario 2 and 3 during the dumb charging. In this approach the demand is consisted with the base demand from scenario 1, with the exception of peak hours. In both figures, the voltage drops below the margin. The limit of $U_n - 6,5\%$ (0,935 p.u) is marked in both figures. In scenario 2 the voltage drops below the limit at 15.00, with the lowest measured voltage as 0,9332 pu.

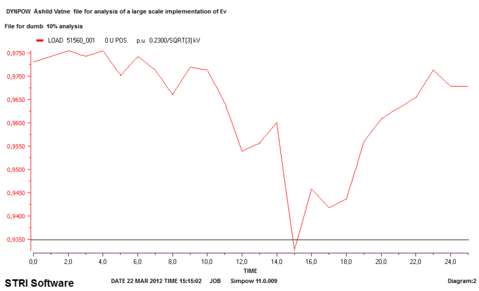
In the case of scenario 3, figure 5.7c shows that the limits is exceeded between 15.00 and 18.00. The lowest voltage is measured to be 0,9179 p.u., which occur at 15.00. This differs from the measurement from residence 020, that had the lowest voltage dip at 17.00 in scenario 3. The voltage in this case is 1,71 % bellow the limit.



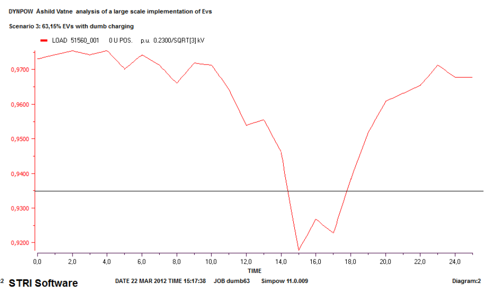
(a) Scenario 1 -Base demand



(b) Scenario 3 - Smart charging



(c) Scenario 2 -Dumb charging



(d) Scenario 3 - Dumb charging

Figure 5.7: Voltage measured at node farthest away - residence 001

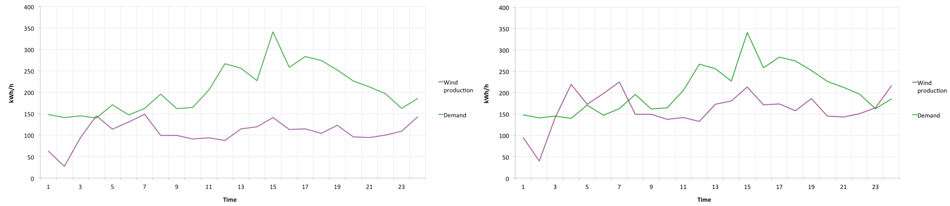
5.3 Wind power analysis

In the third part of the analysis, it was determined to look at the correlation between demand and wind power production in the distribution network in Nord-Trøndelag. Can wind power solely supply the low voltage network? What capacity of energy storage is needed?

It is assumed that smart charging will implement production as a parameter for the scheduling. In the scheduling shown previous in the report, the scheduling is based on low demand only. The charging of the vehicle has therefore been neglected in the following analysis.

Figure 5.8 shows the power flow for December 22nd 2010. The demand for the given low voltage system is presented as the green line. The produced power shown as the purple line in the figure, is the estimated wind power production, calculated as described in section 4.4.

Figure 5.9a present the case with the 330 kW turbine. The demand is higher than



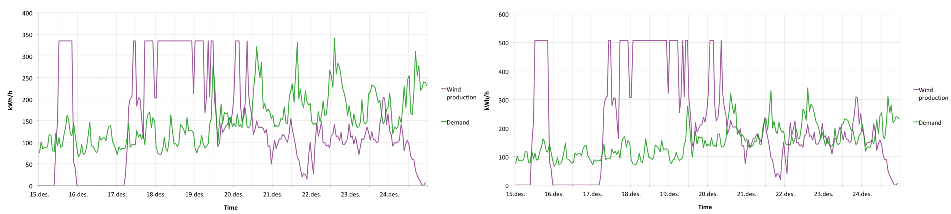
(a) 330 kW turbine (b) 500 kW turbine

Figure 5.8: Production and demand, December 22nd 2010

then production throughout the day. The deficit of energy is calculated to $\approx 2,46$ MWh. The only time the production curve reach the demand curve, is a 04:00, where the production peak with 5 kW over the demand curve. The case with the 500 kW turbine, is shown in figure 5.9b. The wind production is higher than demand from around 03:00 and until 08:00. This surplus can be used for smart charging/energy storing.

In order to be able to determine the available power in a storage before the 22nd, an analysis of data from the 15th and until the 25th were carried out. The production and demand for these days can be seen in figure 5.9, both for the 300 kW and the 500 kW.

The demand for the given days has a higher average value than the average value for the month. The value is 5,91 kW, while the average demand for the month of December is 5,52 kW. The demand in the winter of 2010 was, as mentioned in the other analysis, higher than usually due to an extreme cold winter. The wind measurement for the 10 days has also a higher average wind speed than for the rest of the month. The mean wind speed was 8,5 m/s in comparison to 7,5 m/s



(a) [330 kW turbine (b) 500 kW turbine

Figure 5.9: Production and demand for 10 days in December 2010

as it was for the month of December. The figure shows that there are production on the 15th, from noon and until midnight, and then there are not produced any energy until the morning of the 17th. The wind is steady until the middle of the day at the 20th, except for a period with lower wind speed the 19th. From noon the 20th, the demand increases some while the wind speed decreases. There are a small surplus of energy at the night of the 24th. During the day of the 24th, the wind goes below the cut-inn wind speed at there are no available wind power.

In figure 5.10 the green field represent the energy deficit in the case with a 500 kW turbine. In these periods, an external power supply or a local energy storage need to deliver energy to the system. The total area of the green field is calculated to

Figure 5.10: Deficit in energy for 10 days in December 2010

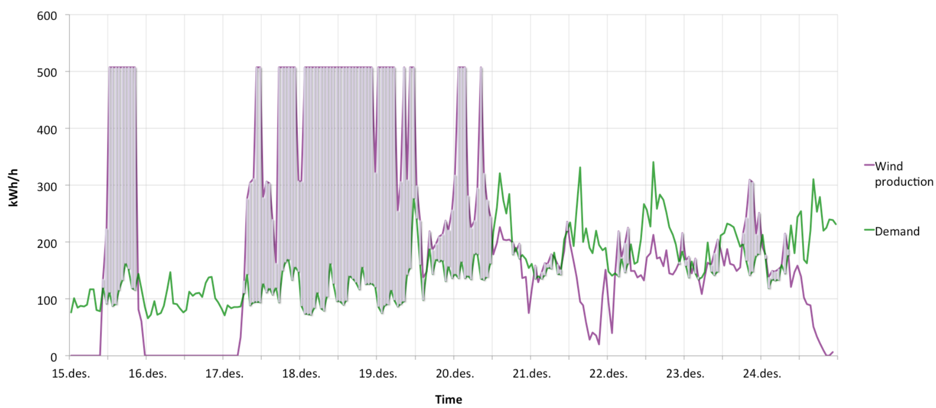
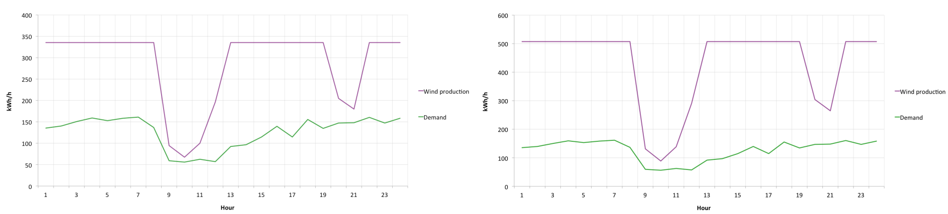


Figure 5.11: Surplus in energy for 10 days in December 2010

be 10,2 MWh, which is the sum of the deficit power. In the periods where then production is more than the demand, the surplus must be stored or delivered to the rest of the grid. The same value for the case with the 330 kW turbine, was 14,83 MWh.

The surplus is marked in purple in figure 5.11. The total amount of surplus energy is calculated to 25,5 MWh for the time period. This value represent the production with a 500 kW turbine. When calculating with a turbine size of 330 kW, the surplus energy is only 12,68 MWh. The production form the 330 kW turbine is not enough to cover the demand for the period. Calculations using a wind turbine of 500 kW, produce enough. Theoretical, this means that the wind production can cover the entire demand for the low voltage network. In addition, there will be an energy surplus of 15,3 MWh. However, this depends on the capacity and size of the designed energy storage.

NTE provided wind measurement and consumption data for the 9th March 2012. To be able to design the most suitable storage, the two different days were compared. The power flow for March 9th 2012 is presented in figure 5.12. For the case in figure 5.12a the 330 kW turbine is used, and the 500 kW is used in figure 5.12b. In contrast to December, the production curve is higher than the demand curve at all points for the time period. The wind turbine is producing at rated power at 75 % of the time. the calculated surplus of energy is 3,65 MWh when turbine is 330 kW, and 7,01 MWh with a 500 kW sized turbine.



(a) 330 kW turbine (b) 500 kW turbine

Figure 5.12: Production and demand, March 9th 2012

5.3.1 Energy Storage

Since the case study presented in this report is discussing a large scale adoption of electrical vehicle, it is therefore chosen to look at vehicle batteries as preferable storage. As previous stated, Nissan Leaf is delivered with a 24 kWh Li-ion battery pack. Tesla deliver their vehicles with larger battery-packs. Tesla S will be delivered with a Li-ion battery-pack of 42 kWh. Tesla Roadster can be delivered with 53 kWh. For Tesla's newest model, Tesla Model X, Tesla has developed state of the art battery-pack with the total capacity of 60 kWh and 85 kWh[44]. The energy storage is build up by a vehicle fleet. A fleet with 50 Tesla X - or other models with a Li-ion battery of 85 kWh, can have the total capacity of 4,25 MWh.

It was desirable to try to operate the low voltage network as a "island grid", when neglecting stability and power quality issues. Since the demand peaked the production from the 330 kW turbine, it was decided to use the production from the 500 kW turbine in the storage design. The deficit of energy is marked in green in

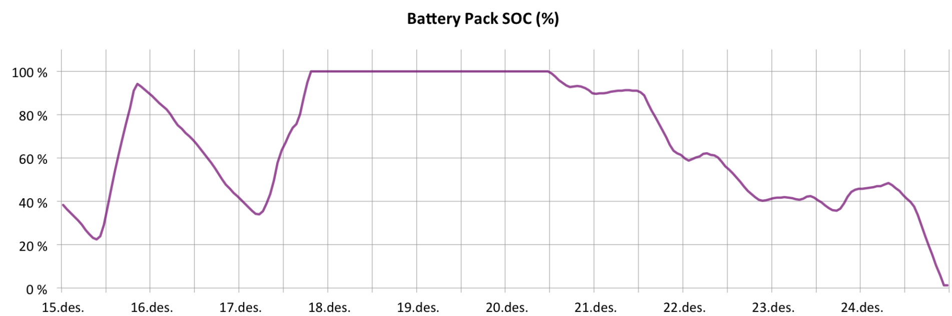


Figure 5.13: State of Charge with battery-pack of total 5 MWh

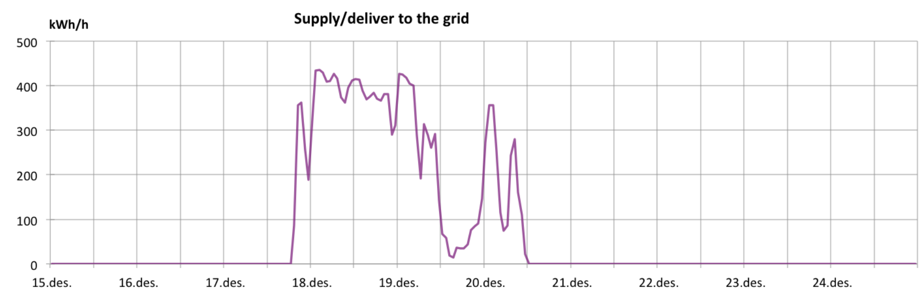


Figure 5.14: Surplus power delivered to the grid when storage is sized 5 MWh

figure 5.10. As seen in the figure, a large share of this deficit is due to the demand on the 15th and 16th. Therefore the required minimum SOC t the beginning of the time period, is 40%. In order to cover the total consumption for the time period, there need to a minimum capacity of 5,0 MWh. The lowest SOC will in that case be 1,2 %. This occur in the end of the time period, as shown in figure 5.13. It is expected that a longer analysis would require a larger storage. Figure 5.14 shows the surplus energy when the battery is charged to 100 %. This power can delivered out to the rest of the grid.

A total capacity of 5 MWh, require a huge number of vehicles. The Nissan Leaf fleet would consist of 209 vehicles, while a Tesla X fleet would require "only" 84 (60 kWh) or 59 (85 kWh) vehicles. For the given low voltage network, the vehicle fleet is 57 vehicles. If one consider a implementation of EVs as described in scenario 3, there are 36 battery-packs available. It is expected that the battery-pack in future EVs will be Li-ion batteries, with larger capacity for lower cost[14]. With that it mind, an energy storage consisting of 36x85 kWh Li-ion batteries, gives a total capacity of 3060 kWh.

With a total capacity of the vehicle fleet set to 3060 kWh, the state of charge (SOC) in percent would behave as shown in figure 5.15. The SOC is assumed to be 40% the morning of the 15th. The power delivered to and supplied from the grid, in the periods where the storage is not enough, is shown in figure 5.16.

The first part the storage deliver to the network, where the lowest SOC is 11,5 % which occur at 10:00 the morning of the 15th. Wind production charge to 100 % SOC, and a peak of 400 kW is delivered out to the grid. On the 16th the wind is below cut-inn, and the storage supplies until production starts on the 17th.

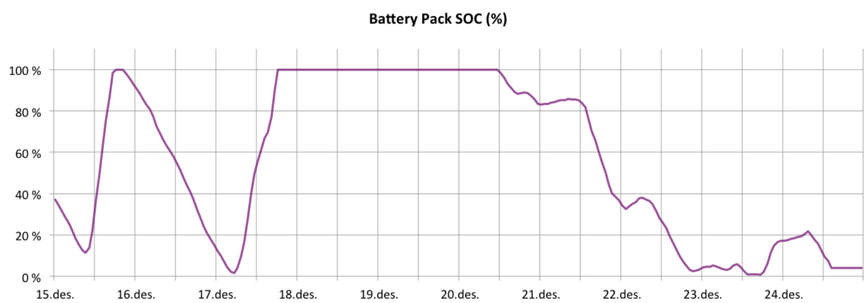


Figure 5.15: State of Charge with battery-pack: 36X85 kWh=3,06 MWh

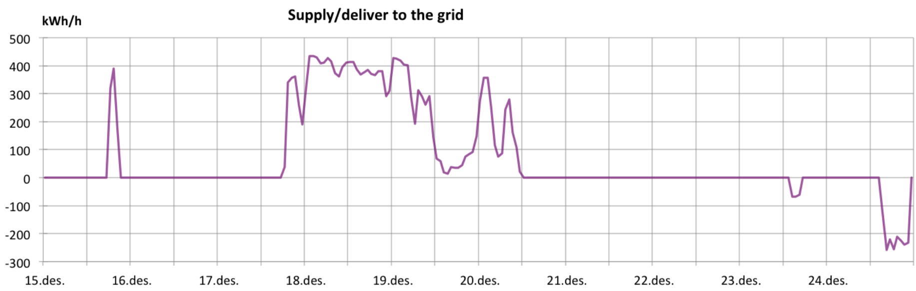


Figure 5.16: Surplus power delivered to the grid when storage is sized 3,06 MWh

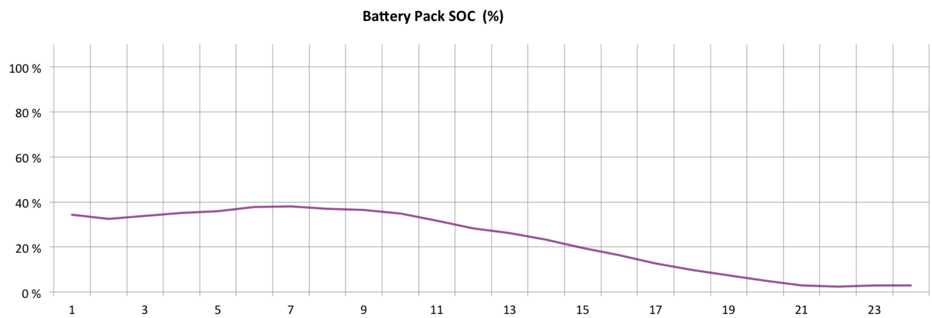


Figure 5.17: SOC for the 22nd of December 2010 with storage of 3,06 MWh

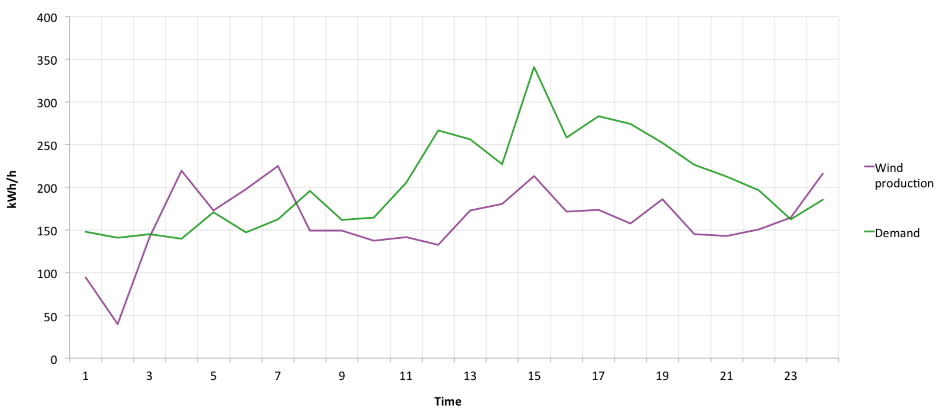


Figure 5.18: Production from a 500 kW turbine, and demand for the 22nd of December 2010

The lowest SOC is 1,7%. The windy days charge the batteries, and surplus power is delivered to the grid as shown in figure 5.16. Around noon at the 20th, the production decrease and the storage's SOC decreases gradual until the 23rd, where the SOC is 0,% - and the grid must deliver to the system (ref: figure 5.16. In the morning of the 24th, the production is higher than the demand, and storage is charged. After noon on the 24th, the SOC is zero and the grid must supply the the network. The SOC is $\approx$ 40% at the 22nd. A more detailed view of the SOC the 22nd of December 2010 is given in figure 5.17.

Figure 5.18 is the same as figure 5.9b, but included in this section to compare the state of charge (ref: figure 5.17). The SOC is initiated at 34 %, but is decreased to 32% due to low production the two first hours. After 03:00 the surplus production charge the batteries to 38%. From 07:00 the production is lower than the demand, and the storage supply some of the load. The lowest calculated SOC at 2,3% occurs at 22:00, before the production peaks the demand and the SOC is increased to 3%. The figures shows that a fleet of 38 vehicles with a 85 kWh Li-ion battery can work as the wind turbines back-up for the entire the 24 hour period. There are not any energy surplus for the time period.

The power production for March 9th is, as stated, higher at all times than the demand. In order to store the entire surplus of energy, there are need for a storage with a total capacity of 6,82 MWh. The SOC when using the energy storage designed above (3,06 MWh) is as shown in figure 5.19 when assuming a 0% SOC in the beginning of the period. It gradually increases until noon, were the batteries is fully charged. The surplus delivered to the grid is shown in figure 5.20. As seen in figure 5.12b, the production is at rated power except for between 08:00-12:00 and

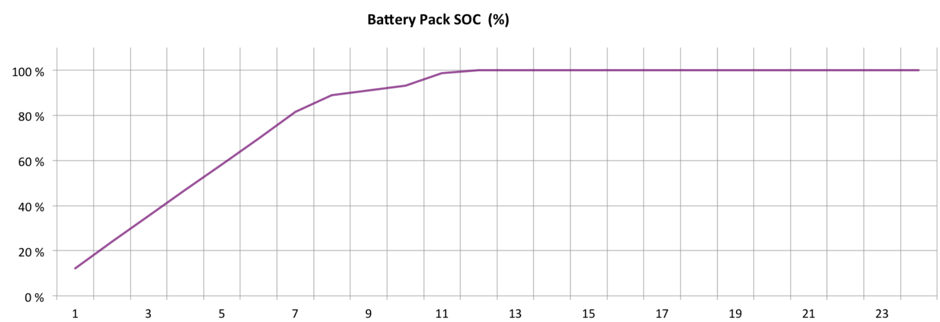


Figure 5.19: SOC for the 9th of March 2012

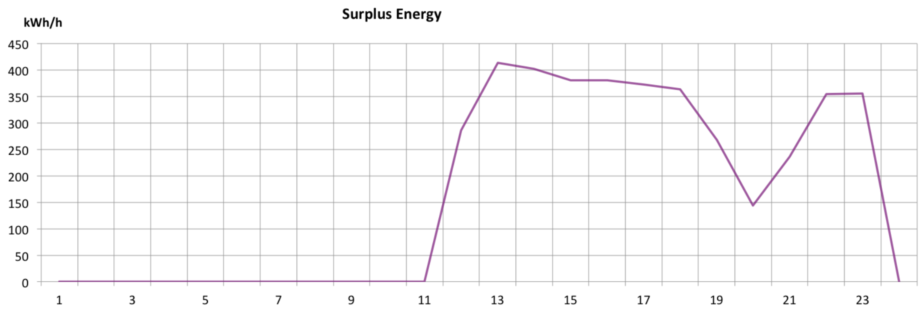


Figure 5.20: Surplus delivered to the grid, March 9th

19:00-21:00. The last production dip is seen in figure 5.20.

The designed energy storage described in the section above, consist of a 36 Li-ion 85 kWh batteries. The number of vehicles suit a medium sized parking lot in Norway. However, the battery is the state of art Li-ion battery and only delivered with Tesla X. The first Tesla X will be delivered late in 2013, and the price will vary between \$60.000 and \$100.000[44]. One can therefore assume that there is not possible to design this storage before 2020. The Nissan Leaf were chosen as the model for simulation - a energy storage consisting of a fleet of 36 Nissan Leafs would have a total capacity of 864 kWh.

The state of charge status for this storage is shown in figure 5.21. Due to a smaller storage, an external source must supply in the periods when demand is higher than the production and storage can deliver. This is marked in green in figure 5.22. It is in this case assumed that the 22 kV grid will match the power with supply and receive power as shown in figure 5.22. The purple field in the figure is surplus energy.

The SOC at the 22nd is $\approx$ 0%, as seen in figure 5.21. A more detailed state of charge is enclosed, and can be found as figure E.2a in appendices. A figure of the power matching from the grid is attached as well (ref: figure E.2b). The SOC is calculated to be 2,4% early morning of the 22nd. During the period where the production is higher than the demand, the batteries is charged to 22%. Except for that period, the grid have to supply the system throughout the day.

An energy storage of 36 Li-ion batteries with the capacity of 24 kWh, is not large enough to store the surplus power nor to supply the system in low production periods. In order for the vehicles to operate as storage, they must be part of an

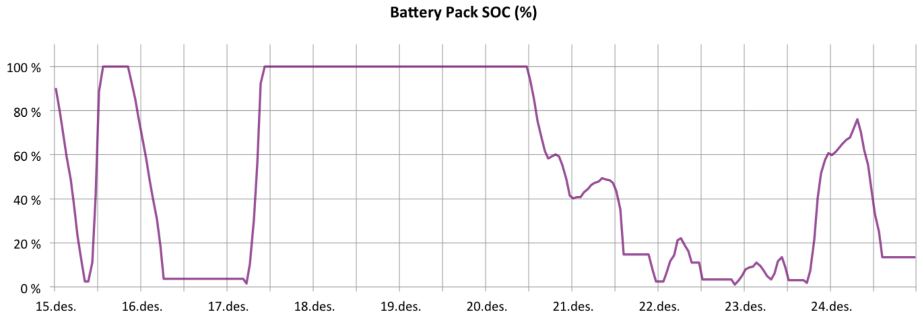


Figure 5.21: SOC for storage sized 864 kWh, 15th - 24th Dec 2010

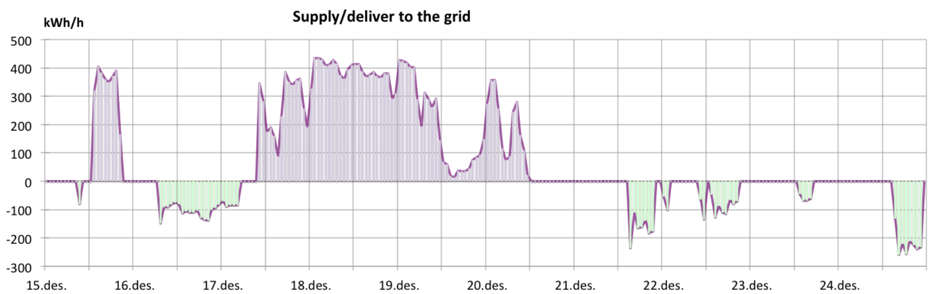


Figure 5.22: Grid support for storage sized 864 kWh, 15th - 24th Dec 2010

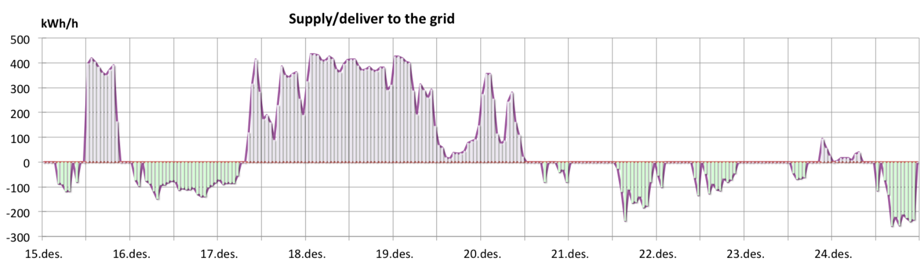


Figure 5.23: Grid support for storage sized 350 kWh, 15th - 24th Dec 2010

organized fleet, such as a taxi fleet or a parking-lot. This solution would be possible to conduct in larger cities, but is not suitable for Steinkjer and similar smaller cities. Figure 5.23 represents the power supplied from and delivered to the grid when the storage is set to 350 kWh. As seen in the figure, it does not differ significant from figure 5.22. The designed storage in figure 3.1 is a bank of 7 battery-packs with a capacity of 50 kWh each. The battery-packs consist of Li-ion batteries from old EVs (as meantioned in section 3.1).

5.4 Vehicle-to-Home

A different approach than one large energy storage is to use the solution of V2H. The vehicle will be charged from a mode 3 charger at the residence when the demand is low or available renewable production. The power flow shown in figure 5.24 shows the correlation between one Nissan Leaf and the consumption from residence 020.

The x-axis is the state of charge - and the hours of the day is in parenthesis. It is assumed that the vehicle will be charged from 22:00 and until 06:00, and it will be charged with 3 kW each hour. As previous, the vehicle is disconnected between 07:00 and 14:00, and the SOC is therefore applied as *not applicable* (NA). When the EV is connected to the charger again at 15:00, it is assumed a SOC of 50%. This is based on the average distance a person drives in Norway per day and the

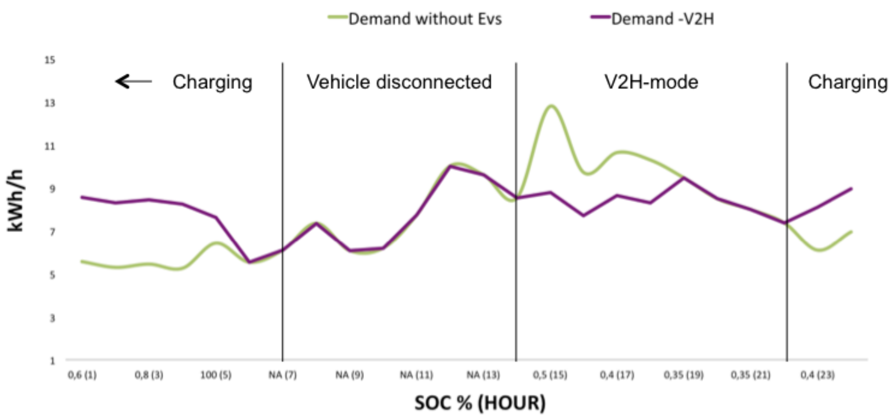


Figure 5.24: V2H - One EV connected to residence 020 at December 22nd 2010

range of the Leaf, it is also assumed some loss in the battery. During the peak hours the vehicles battery supply the home with power as seen from 14:00 until 19:00 in figure 5.24. The purple curve is the demand supplied from the grid when V2H solution is engaged. The load will be flatten and more even as seen in the figure.

It is assumed that the utility or a third party will continuously monitor all the elements in the grid, and phase in a charging schedule. One of the problem for this issue is that some of the vehicle manufacturers have indicated that they will not allow their vehicle to operate in V2H or V2G due to warranty, and other problem is the consumers willingness for peak shaving[32]. Are they willing to postpone charging or "loose" range at their vehicle?

5.5 Reactive compensating

EV chargers can provide several services that are included in the V2H, to the grid. Voltage support, harmonic filtering and reactive compensating, are some of the services. The reactive power on the nodes were controlled as the same way as the active power, where $Q = Q_{max} \cdot Q_{TAB}$.

Q_{max} was set to 0.002 p.u as a capacitive load in optpow, as $S_{ref} = 0.4$ MVA, the value of the reactive maximum power is 0.8 kVAr. Figure 5.25 shows the changing value of Q throughout the day of the 22nd of December 2010. The case simulated is scenario 3 with smart charging. Figure 5.26 and 5.27 shows the voltage at the

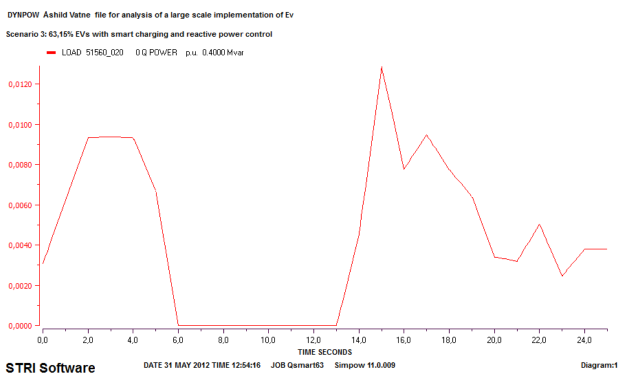


Figure 5.25: Reactive power at residence 020

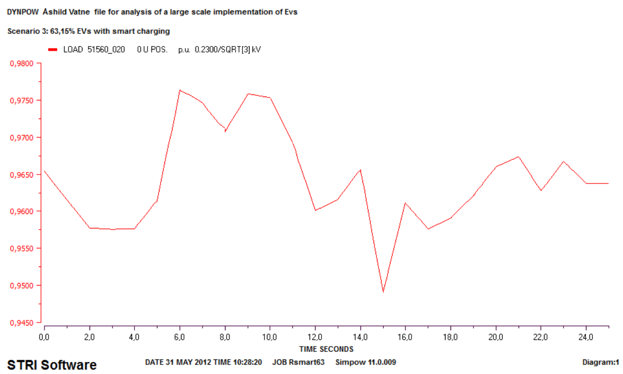


Figure 5.26: Voltage at residence 020 without Q-compensating

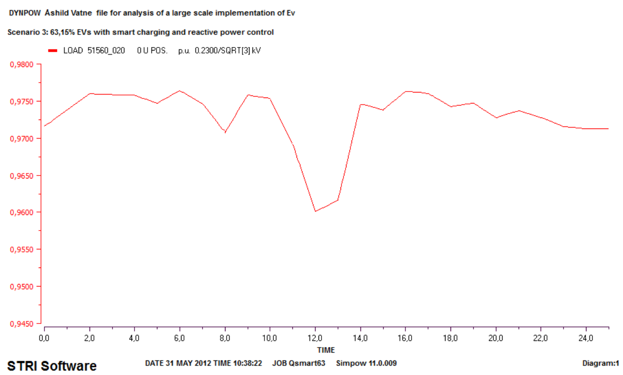


Figure 5.27: Voltage at residence 020 with Q-compensating

charger at residence 020. The voltage without Q-compensating is shown in figure 5.26. In figure 5.27, the voltage is more smooth.

The compensating shown here is a very simplified analysis, but the result show the trend of the possibility.

Chapter 6

Discussion

The purpose of the work addressed in this report was to show consequences of a large scale adoption of electrical vehicles. A low voltage network were chosen to be simulated. The specific network were provided by NTE, and was located in Steinkjer, Nord-Trøndelag. The network data is not compared with other network, but it is expected that the result of the report can be used for similar networks. The average annual consumption for a residence in Norway is 20 MWh. The average for the 38 residences in the system is 21,45 MWh. If one consider that the consumption was extremely high in 2010 with 130,4 TWH, the average value for the residence is a typically residence area in the Norwegian power-market. The annual consumption for 2009 is 123,7 TWh while the value was 121,8 TWh in 2011[34]. According to the Norwegian Meteorological Institute, December 2010 was the 4th coldest since 1900[18]. This caused a very high demand. One can expect that the analysis of December 2011, would give different results than stated here. Nevertheless, it is important and interesting to look at the worst case scenario as December 2010 represent.

The hourly consumption for each residence were scaled up from one residence. A power profile with hourly measurement from each residence may differ from the scaled version. The power profile used in the analysis, does however resemble a typical 24 hour load profile. The highest peak will normally occur later in the afternoon in a typically day, but as the simulation date is set to the 22nd of December one may assume that the peak occur earlier due to residents arrive earlier for Christmas.

The scaling of the systems demand profile, caused the demand to peak the substation. The substation were therefore set to 400 kVA. This is not a typical size in the Norwegian power-grid, but since the the cables thermal limit was calculated to 378 kW, it was decided that a 400 kVA substation would be suitable.

As described in section 4.1.1, the charging model for the electrical vehicles is very simplified. An simulation with a more detailed charging model may cause different results. Shouxiang Wang presented the difference between the actual charging and a simplified charging in *Hierarchical charging Management strategy of Plug.in Hybrid Electric Vehicles to Provide Regulation Service*[43]. The model is used for lithium batteries. Figure 6.1 indicate that the simplified charging is conformable for the work addressed in this report. The figure is remodelled to suit the study.

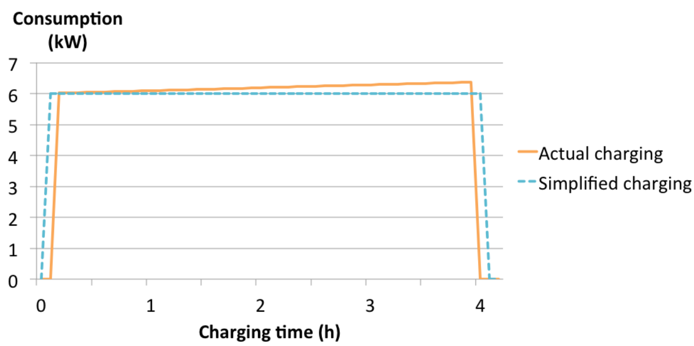


Figure 6.1: Simplified and actual charging process

It was assumed that all the EVs were charged during the 24 hours time period. According to the The Institute of Transport Economics (Transportøkonomisk institutt) the average distance a person drives each day in Norway is 43 km [42]. Considering that Nissan Leaf has a driving range of 150 km[29], the average charging frequency *could* be that the owners charged their vehicle every third night. However, the worst case scenarios where all the owners plug their vehicle in the grid at the same day will be analysed in this study due to the insecurity in the owners charging behaviour.

The power flow for the three different scenarios are the result of manual calculation. The charging scheduling were based only on low demand. A preferred method for the scheduling would be an smart algorithm based on price, low demand, available renewable production and available energy storage. Nevertheless, the manual scheduling show of the power flow and reflect a smarter charging. The power profile

Table 6.1: Lowest measured voltage in p.u.

		Scenario 1	Scenario 2	Scenario 3
Residence 020	Dumb charge	0.9491	0.9424	0.9283
	Smart charge	0.9491	0.9491	0.9491
Residence 001	Dumb charge	0.9419	0.9332	0.9179
	Smart charge	0.9419	0.9419	0.9419

for scenario 3 dumb charging exceed the systems limit. It was expected that the high power would cause a large voltage drop in the nodes far away from the supply. It was expected the voltage would drop below 0,9 p.u. Voltage simulations shows that dumb charging cause a voltage drop of 2,55% more than the smart charging. The LV-network is however connected to a relative stiff network. The 22 kV side had a $cos\Phi \approx 0,97$. It is therefore expected that in a low voltage network further away from production, would have larger voltage drops.

Even if the result did not give a voltage drop below 0,9 p.u, the dumb charging from scenario 2 showed some interesting found. Table 6.1 list the lowest measured voltage for each case. As seen in the table, the node furthers away from the supply, residence 001, will face voltage problems also in scenario 2 with only a 10% share of EVs. This means that the system is not capable to handle a share of 10% of electrical vehicles without any restrictions in charging.

The wind measurement was collected from a met-mast at 80 m high. The wind speeds were adjusted for 50 m with the power profile law. The power law exponent α was set to $\frac{1}{7}$. This assumption is not adequate if designing a wind farm, but due to the simplicity of the wind power analysis it is sufficient. Loss in the production has not been accounted for either. The Norwegian Water Resources and Energy Directorate (NVE) use a loss of 20% of the total production. Wake loss was given as the largest factor causing loss. Other factor is named as transmission loss, icing, etc[41]. Considering that the analysis only cover one turbine, the wake loss is neglected. The electrical loss is not included either. The resistance in the lines are very small - which gives small loss in active power. Reactive power have been neglected throughout the analysis.

Kjeller Vindteknikk developed an atlas showing the yearly mean wind speed for Norway and some of the North Sea. Figure 6.2 is extracted from the atlas. The circle in the figure is the area of the wind farm. This area is marked with a light

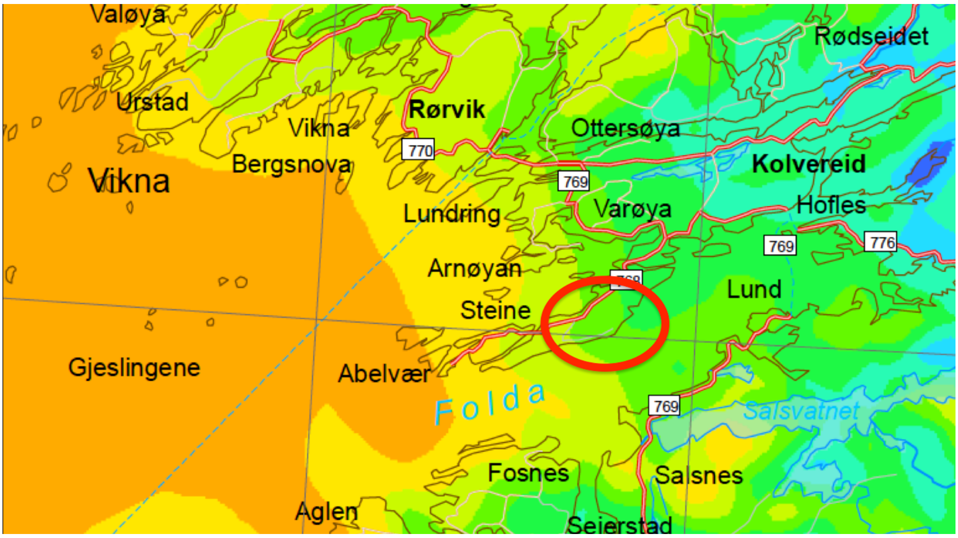


Figure 6.2: Wind map of the area[39]

green, which classify the areas with a yearly mean wind speed of 7.0 - 7.5 m/s at 50 m. The rest of the colour codes and the map is enclosed in appendix B. The adjusted speed for 50 m was respectively 7,26 m/s for December 2010 and 10,56 m/s for March 2012. In general, it is more windy during the winter. This indicates that the wind speed in December in 2010 is lower than average, causing a lower production. It is reasonable to assume that an analysis over a longer time period would result in a smaller storage design. The case simulated here represent the *worst* case scenario.

The storage were designed as a number of batteries in parallel. The total capacity of the storage were the sum of the capacity. The availability of the vehicles as a storage has not yet been discussed, but is an important factor for the solution. Can one secure the capacity of the storage when considering of the indeterminacy of the owners behaviour? It is not assumed that a storage will consist of several private vehicles due to this issues, but a taxi-fleet or a organized parking-lot connected to renewable power resources is reasonable choices. An other approach is also to use batteries from old vehicles. There are an ongoing project on turning the batteries from old Nissan Leafs into storages, as mentioned in section 3.1.

Even if the storage can both supply and receive the entire power flow, the system can not operate as a stand-alone system without power application storages or grid support. A common problem in wind power production is flicker and harmonic disturbances.

Harmonics are AC voltages or currents with a frequency that is in an integer multiple of the fundamental frequency (grid frequency). The harmonic disturbance or distortion is the effect on the fundamental waveform cased by electrical switches. In a circuit with several power electronic components, it i more likely to experience more harmonic disturbance. The harmonics are mainly caused by inverters, industrial motor drives, electronic appliances, light dimmers, fluorescent light ballasts and personal computers[21]. The harmonics disturbance is measured by THD (total harmonic distortion), the worse waveform, the higher THD. One can reduce these disturbances by placing a sinusoidal-filter after the inverter. In *Wind Energy Explained* by Manwell, flicker is defined as "disturbance to the network voltage that occur faster than the steady state voltage changes and which are fast enough and of a large enough magnitude that light noticeable change brightness"[21]. The disturbance occur due to the torque fluctuations in the turbine or when the turbine is connected/disconnected. Flicker is noticeable in weak grids.

There was not carried out a stability analysis in the case study. The wind power production needs to be balanced, both immediate balancing for fast response with propped inertia and load balancing as renewable back-up.

Chapter 7

Conclusion

In the study addressed in this thesis, an analysis of a large share adoption of EVs in a low voltage network has been carried out. The analysis was based on the worst case scenario, using demand from December 2010 - a month of extreme high demand. The result from the analysis shows that the utility companies need to forward a smart charging strategy. The system was not capable to handle a large share of EVs (>60%) without scheduling or restriction for charging. The smart charging did not cause any extra strain on the grid during peak hours. In order to reach the goal of 25% reduction in emission, it was stated that at least a share of 10% of the vehicles were electrical by 2020[9]. One can see in the result from the power flow, that the system provided here is capable to handle a 10% EV-share. However, the voltage simulations resulted in that the node furthest away from the supply, residence 001, will face voltage problems in this case, where only 10% of the vehicles is electrical. One can therefore conclude that system is not capable to handle a smaller implementation without charging scheduling or restrictions.

In the second part of the analysis, a series of wind measurement was added to the analysis. The results show that the system *can* operate as a stand-alone system when the designed storage consist of 59 Tesla X vehicles with 85 kWh batteries. A storage that would be extremely expensive, and accounted for as not realistic. A more realistic storage would consist of 24 kWh Li-ion batteries from ≈ 40 EVs. Due to the uncertainty of the private EV owner's behavior, the vehicles should be a part of a taxi fleet or an organized parking lot. Another storage possibility is the V2H, but as mentioned in section 5.3.1 the vehicle manufactures is not willing to engage this solution into their vehicles. It is therefore concluded to use battery-packs from old vehicles as storage in this low voltage network. It is also concluded that the storage will not be designed as the back-up for a stand-alone system. A storage bank of $\approx$ 7 battery-packs of 50 kWh each was designed as the most suitable storage based on availability of vehicles, cost of storage and location and size of network. The analysis from December 2010 was given as the worst case scenario, and the result from March 2012 shows that the area will be able to be self-supplied most of the time. Nevertheless, the connection to the grid is still needed to receive surplus energy and also supply stability services from the grid.

A large share adoption of EVs require a beneficial infrastructure. In addition to chargers, both from suitable docking station (mode 2/ mode 3) and fast chargers (mode 4), communication is essential in the implementation for smart charging. The smart charging and the smart grid in general, forwards large opportunities for new markets and new technology. The smart grid infrastructure gives opportunity for aggregation services, and it is therefore important to establish suitable standard for the equipment and solutions. There is also a need for further research on optimization algorithms and scheduling algorithms is essential in order to achieve smart charging.

Chapter 8

Further Work

The case study addressed in this thesis, is based on a short-time interval. A further analysis should compare several weeks and months. In order to carry out a longer analysis, there is a need for an smart charging algorithm. Further research on optimization algorithm is also very important in order to achieve smart charging. The algorithm could be based on several parameters in order to phase in the optimal charging schedule.

It would also be interesting to look at the new possibilities this solution and smart grids in general presents. Which technology that would be suitable in the EV. What services can an aggregator offer? Can there be one communication platform? Can some services cause a drawback in the EV-market?

In the analysis a small and simplified reactive compensation case was preformed to show how the system can benefit from such a service. As further work from this thesis, one could investigate this case more detailed. Data from an actual charger should be added into a simulation program, to compare it to the simplified case. Loss was neglected throughout the analysis, it is therefore important to see what result a more detailed analysis would give.

Bibliography

[1] T. Henriksen Ø. Håland A. Petterteig O. Mogstad. *Tekniske retningslinjer for tilknytning av produksjonsenheter*. Tech. rep. SINTEF Energiforskning AS, 2006.

[2] ABB. *Press release: Zurich January 18th 2012*. http://www.abb.com/cawp/seitp202/A2B2D2AFF96520BEC1257989004E62AE.aspx. Visited: May 29st 2012, 9:21.

[3] SINTEF Energi AS. *Planleggingsbok for kraftnett, Tekniske data*. Tech. rep. SINTEF AS, 2010.

[4] SAE Society of Automotive Engineers. *SAE J1772-2009*. http://standards.sae.org/j1772_201001/, year= 2010, note= Visited: 27 October 2011, 13:25,

[5] Grønn Bil. *Ladbare biler i Norge*. www.gronnbil.no. Visited: 5 December 2011, 11:09. 2011.

[6] Peter Van der Bossche. *Defining and Developing Standards*. http://www.park-charge.ch/documents/P_Van_den_Bossche1.pdf. Visited: 26 October 2011, 17:01. 2008.

[7] C. C. Chan. "The State of the Art of Electric, Hybrid, and Fuel Cell Vehicle". In: *IEEE*. Vol. 95. 4. 2007.

[8] conEdison. *Types of EVs*. www.coned.com/electricvehicles/index.asp. Visited: 20 September 2011, 15:37.

[9] EBL. *Handlingsplan for elektrifisering av veitransport*. 2009.

[10] Norsk Elbilforening. *En stayer i elbilbransjen*. http://www.elbil.no/mennesker/540-en-stayer-i-elbilbransjen. Visited: 9 December 2011, 09:42. 2011.

[11] *Electricity Storage Association*. http://www.electricitystorage.org. Visited: May 1st 2012, 15:30.

[12] ENERCON. *ENERCON Wind energy converters Product overview.* Provided by Enercon in Germany on a field trip in October 2011. 2010.

[13] Olje og energidepartementet. *Forskrift om leveringskvalitet i kraftsystemet.*

[14] Jayam Prabhakar Aditya Mehdi Ferdowsi. "Comparison of NiMH and Li-ion Batteries in Automotive Applications". In: Vehicle Power and Propulsion Conferance (VPPC), Harbin, China. Missouri University of Science and Technology. IEEE, 2008.

[15] Andrew McGordon Gareth Haines and Paul Jennings. "The Simulation of Vehicle-to-Home Systems - Using Electric Vehicle Battery Storage to Smooth Domestic Electricity Demand". In: *EVRE Monaco 2009*. EVRE. 2009.

[16] hybridCARS. `http://www.hybridcars.com/electric-car`. Visited: 12 October 2011, 19:10.

[17] *Information and data from the LV-grid from NTE.* recived as an e-mail from Jan A. Foosnæs at the 27th of October.

[18] Meteorologisk institutt. *Desember 2010 den 4. kaldeste.* `http://met.no/Desember+2010+den+4.+kaldeste.b7C_w7vSZm.ips`. Visited: November 16th 17:20.

[19] IEC International Standard. *IEC 61851-1.* Norsk Elektronisk Komite (NEK). Electric vehicle conductive charging system - Part 1: General requirements. 2010.

[20] P. M. Almeida M. Moreira da Silva J. A. Peças Lopes F. J. Soares. "Smart Charging Strategies for Electrical Vehicles: Enhancing Grid Performance and Maximizing the Use of Variable Renewable Energy Resorces". In: IINESC Porto and FEUP, Porto, Portugal. EVS24, Stavanger, 2009.

[21] A. L Rogers J. F Manwell J. G McGowan. "Wind Energy Explained". In: John Wiley & Sons, 2009. Chap. Wind Characterristics and Resources.

[22] James R. Bumbly Jan Machowski Janusz W. Bialek. "Power System Dynamics". In: vol. 2. John Wiley & Sons, Ltd, 2008. Chap. The Power System in the Steady State.

[23] Idaho National Laboratory. *The History of Electric Cars.* http://avt.inl.gov/pdf/fsev/history.pdf.

[24] Haruka CHAdeMO Association European Liaison. *CHAdeMO information.* e-mail at 29th September 2011, 10:33.

[25] Sue Kately Mark Rawson. "Electric Vehicle Charing Eqipment Design and Health and Safety Codes". In: *Energy System and Advanced Materials Research Group.* California Energy Commission, 1998.

[26] Leon M. Tolbert Mithat C. Kisacikoglu Burak Ozpineci. *Examination of a PHEV Bidirectional Charger System for V2G Reactive Power Compensating.* http://ieeexplore.ieee.org/ielx5/5426413/5433335/05433629.pdf?tp=&arnumber=5433629&isnumber=5433335. Visteted: June 8th 13:24.

[27] Marta Molinas. *Future Energy System and Smart Grid.*

[28] Energi Norge Norsk Vindkraftforening. *Infoside om vindkraft.* http://www.vindkraft.no. Visited: May 28st 2012, 13:39.

[29] Nissan Norway. *Nissan Leaf Teknologi.* http://www.nissan.no/NO/no/vehicles/electric-vehicles/electric-leaf/leaf.html. Visited: 11 November 2011, 17:00. 2011.

[30] Bengt Otterås. *Adviser at BKK Nett.* phonecall, 24 October 2011.

[31] E.C Bentley M.Narayana Ghanim A Putrus P. Suwanapingkarl D. Johnston. "Impact of Electric Vehicles on Power Distribution Networks". In: *Energy System and Advanced Materials Research Group.* IEEE, 2009.

[32] Helge Seljeseth. *Nettutfordringer (spenningskvalitet) ved storskala lading av elbiler.*

[33] Atatistisk Sentralbyrå. *Bilbestand of folkemengde (F).* http://www.ssb.no/bilreg. Visited: April 11th, 14.11.

[34] Statnett. *Nøkkeltall 1974-2011.* http://www.statnett.no/no/Kraftsystemet/Produksjon-og-forbruk/Historikk/. Visited: June 4st 2012, 11:19.

[35] Dr. G. J. Suppes. *Unviversity of Missouri.* http://web.missouri.edu/~suppesg/PHEV.htm. Visited: 25 October 2011, 11:21.

[36] Møre Trafo. *Technical data for a 315 kVA tranformator.* phonecall, 29 February 2012, 13.10.

[37] Keio University. http://www.eliica.com/English/project/eliica/spec.html. Visited: 13 October 2011, 11:15.

[38] Nissan USA. *Nissan Leaf Technology.* http://www.nissanusa.com/leaf-electric-car/index. Visited: 11 November 2011, 17:11. 2011.

[39] Kjeller Vindteknikk. *Vindkart for Norge.* Appendiks til rapport nummer. Kartbok 1c, Årsmiddelvind i 50m høyde. 2009.

[40] Kjeller Vindteknikk. *Vindkart for Norge.* Appendiks til rapport nummer. Kartbok 4ac, Produksjon i 80m høyde, fulllasttimer. 2009.

[41] Arvid Drivenes. Tale Eirum. Nils Henrik Johnson. Sigrun Kavli Mindeberg. Synnøve Lunde. Linn Silje Undern. Kirsti Veggeland. Brit Veie.Rosvoll. Astrid Voksø. *HAVVIND.* Tech. rep. NVE, 2010.

[42] Liva Vågane. *Bilhold og bilbruk i Norge.* 856th ed. TIØ. 2006.

[43] Liang; Wang Dan; Li Zuyi; Shahidehpour Wang Shouxiang; Han. “Hierchical Charging Management startegy og Plug-in Hybrid Electric Vehicles to Provide Regulation Service”. IEEE Transactions on Power Delivery. 2012.

[44] Zero. *Klimabiler*. `http://www.klimabiler.no`. Visited: June 1st 2012, 16:21.

[45] Zero Emission Resource Organization (ZERO). `http://www.zero.no/transport/batteribil`. Visited: 4 October 2011, 12:56.

[46] S. Tvedt Å. Vatne. *Ein smartare kvardag? Innføring av AMS i kraftforsyningen*. Tech. rep. Høgskulen i bergen, 2010.

Appendix A

Network data

List of data

Figure A.1	Data about cables provided by NTE
Figure A.2	Hourly consumption provided by NTE
Figure A.3	Data about consumption provided by NTE

Fra	Til	Typebetegnelse	Lengde km	Spenning kV
B1	07.51560.017	PFSP 1X3X25 AL	0,008	0,23
51560	07.51560.009	PFSP 1X3X4 CU	0,001	0,23
51560	TAMP	PFSP 1X3X4 CU	0,126	0,23
C1	07.51560.031	PFSP 1X3X25 AL	0,056	0,23
C1	07.51560.039	PFSP 1X3X6 CU	0,007	0,23
C1	07.51560.027	PFSP 1X3X25 AL	0,041	0,23
D1	07.51560.021	PFSP 1X3X25 AL	0,036	0,23
D2	07.51560.013	PFSP 1X3X25 AL	0,04	0,23
D2	07.51560.020	PFSP 1X3X25 AL	0,033	0,23
D2	07.51560.004	PFSP 1X3X25 AL	0,036	0,23
D2	07.51560.007	PFSP 1X3X25 AL	0,032	0,23
D2	07.51560.006	PFSP 1X3X25 AL	0,029	0,23
D1	D2	TFSP 1X3X95 AL	0,066	0,23
D1	07.51560.041	PFSP 1X3X25 CU	0,01	0,23
D1	07.51560.045	PFSP 1X3X25 CU	0,023	0,23
D1	07.51560.024	PFSP 1X3X25 AL	0,029	0,23
D1	07.51560.033	PFSP 1X3X25 AL	0,025	0,23
51560	D1	TFSP 1X3X240 AL	0,065	0,23
C1	07.51560.035	PFSP 1X3X25 AL	0,062	0,23
C1	07.51560.036	PFSP 1X3X25 AL	0,048	0,23
C1	07.51560.029	PFSP 1X3X25 AL	0,065	0,23
C1	07.51560.028	PFSP 1X3X25 AL	0,041	0,23
C1	07.51560.038	PFSP 1X3X25 AL	0,018	0,23
C1	07.51560.046	PFSP 1X3X25 AL	0,01	0,23
C1	07.51560.044	PFSP 1X3X25 AL	0,029	0,23
51560	C1	TFSP 1X3X150 AL	0,106	0,23
51560	07.51560.018	PFSP 1X3X2.5 CU	0,042	0,23
A2	07.51560.001	PFSP 1X3X25 AL	0,032	0,23
A2	07.51560.002	PFSP 1X3X25 AL	0,024	0,23
A2	07.51560.019	PFSP 1X3X25 AL	0,017	0,23
A2	07.51560.008	PFSP 1X3X25 AL	0,016	0,23
A1	A2	TFSP 1X3X95 AL	0,051	0,23
A1	07.51560.010	PFSP 1X3X25 AL	0,022	0,23
A1	07.51560.003	PFSP 1X3X25 AL	0,049	0,23
A1	07.51560.005	PFSP 1X3X25 AL	0,052	0,23
A1	07.51560.014	PFSP 1X3X25 AL	0,047	0,23
A1	07.51560.022	PFSP 1X3X25 AL	0,032	0,23
51560	A1	TFSP 1X3X150 AL	0,062	0,23
B1	07.51560.037	TFXP 1X4X50 AL	0,009	0,23
B1	07.51560.032	PFSP 1X3X25 AL	0,016	0,23
B1	07.51560.030	PFSP 1X3X25 AL	0,032	0,23
B1	07.51560.040	PFSP 1X3X25 AL	0,04	0,23
B1	07.51560.015	PFSP 1X3X25 AL	0,082	0,23
B1	07.51560.017	PFSP 1X3X25 AL	0,049	0,23
B1	07.51560.034	PFSP 1X3X25 AL	0,028	0,23
51560	B1	TFSP 1X3X150 AL	0,078	0,23
51560	07.51560.025	PFSP 1X3X25 AL	0,018	0,23
51560	51570	TXSP 3X1X25 AL	0,286	22
51560	51670	TXSP 3X1X95 AL	0,234	22

Figure A.1: Cables - provided by NTE

DATO	TIME 1	TIME 2	TIME 3	TIME 4	TIME 5	TIME 6	TIME 7	TIME 8	TIME 9	TIME 10	TIME 11	TIME 12	TIME 13	TIME 14	TIME 15	TIME 16	TIME 17	TIME 18	TIME 19	TIME 20	TIME 21	TIME 22	TIME 23	TIME 24
01.12.2010	5,16	6,62	5,71	5,7	5,48	5,36	6,33	7,56	6,14	5,65	5,52	6,74	6,15	7,05	5,62	5,79	5,98	6,54	7,43	6,58	6,9	7,06	7,15	6,48
02.12.2010	5,61	5,4	5,44	5,84	5,76	6,89	6,27	7,84	5,67	5,89	5,82	5,75	6,71	5,79	5,96	6,38	6,13	6,23	5,54	5,57	5,73	5,84	7,11	5,55
03.12.2010	5,58	5,51	4,95	6,14	5,36	5,59	6,34	8,37	5,79	5,69	5,69	5,73	6,41	5,58	5,61	6,66	6,26	7,12	7,14	7,73	7,67	7,04	6,06	5,49
04.12.2010	5,16	6,54	5,37	5,74	5,89	5,72	6,43	5,49	6,02	8,94	8,55	7,33	6,92	6,37	6,65	6,44	7,25	7,09	6,46	6,26	6,37	7,09	5,75	5,56
05.12.2010	5,52	5,64	6,04	5,31	5,45	5,35	5,27	5,87	5,07	5,11	7,2	5,82	5,95	7,34	7,69	9,29	7,5	7,28	7,7	7,87	5,87	6,26	5,65	2,72
06.12.2010	2,73	2,91	3,05	4,17	3,15	3,37	3,81	5,19	3,28	3,42	3,47	3,6	4,48	3,46	4,22	4,22	4,27	4,93	3,38	3,44	3,74	3,93	3,22	2,97
07.12.2010	2,78	2,84	3,69	3,03	3,18	3,27	4,64	5,14	3,29	3,43	3,49	4,29	3,31	3,22	3,06	3,72	4,91	3,97	4,5	6,06	5,02	4,03	3,97	3,32
08.12.2010	3,79	2,92	3,03	3,23	3,43	3,34	4,55	4,43	4,21	3,98	6,21	5,87	6,06	6,38	4,31	4,43	5,03	6,25	4,23	4,21	4,52	4,47	5,31	2,91
09.12.2010	2,85	2,92	3,27	4,02	3,49	3,27	3,89	5,58	3,26	3,66	3,62	3,63	3,61	4,59	4,16	6,41	6,07	6,15	5,58	3,75	3,66	3,43	3,48	4,38
10.12.2010	3,44	3,04	3,22	3,64	3,56	3,91	4,02	5,47	3,41	3,68	3,62	3,56	4,04	4,03	4,7	6,06	5,89	5,36	6,89	5,24	4,58	4,35	6,28	4,93
11.12.2010	2,71	2,77	3,44	3,66	3,2	3,26	2,89	2,78	4,52	5,85	7,16	4,53	3,41	3,36	4,38	5	5,32	6,02	6,16	5,36	6,87	6,61	6,5	4,55
12.12.2010	4,07	3,1	3,19	3,7	4,49	3,65	3,62	3,59	3,35	5,33	6,88	7,43	8,41	8,73	6,03	7,61	11,09	8,23	7,25	9,59	7,08	8,73	6,62	6,77
13.12.2010	3,97	3,01	3,1	3,17	3,2	3,71	3,63	6,22	4,5	4,4	4,36	4,44	5,19	4,63	4,62	5,67	5,24	6,47	4,79	4,59	5	4,6	4,94	3,7
14.12.2010	3,45	3,33	3,27	3,52	4,16	3,5	4,99	6,73	4,65	4,49	4,43	4,38	4,52	4,13	4,5	5,87	5,8	5,69	4,64	5,38	5,62	5,66	4,53	3,12
15.12.2010	2,86	3,79	3,19	3,28	3,27	3,36	4,4	4,38	3,04	2,96	4,51	3,46	4,18	3,31	3,41	4,34	5,03	6,1	5,76	4,45	4,34	5,42	4,42	3,21
16.12.2010	2,48	2,7	3,59	2,7	2,82	3,28	4,43	5,52	3,46	3,4	3,13	2,85	3,01	4,25	3,95	4,12	4,15	3,9	4,84	5,16	5,2	3,79	3,55	3,12
17.12.2010	2,69	3,34	3,14	3,22	3,22	3,27	4,14	5,39	3,33	3,54	3,56	3,52	4,77	4,2	4,47	4,02	4,5	3,54	5,63	6,19	6,37	5	5,89	5,55
18.12.2010	3,3	2,78	2,73	2,7	3,18	4,2	3,13	2,97	3,91	6,13	4,8	3,61	3,62	3,38	3,66	5,3	5,11	4,85	4,4	5,89	4,73	4,76	4,77	4,55
19.12.2010	3,25	2,83	3,32	3,41	4,36	3,67	3,27	3,41	3,62	5,35	5,79	10,4	9,09	6,02	3,68	5,62	7,07	5,39	6,38	6,23	6,31	4,93	5,93	5,12
20.12.2010	5,4	5,12	6,22	5,15	5,3	5,05	6,74	6,74	5,09	5,02	5,23	6,1	8,19	9,79	12,07	10,24	9,38	10,69	6,69	7,12	6,43	6,65	6,4	5,79
21.12.2010	6,07	5,09	5,24	5,1	5,33	5,82	5,74	6,83	5,42	5,37	7,66	8,25	8,81	7,23	9,68	12,45	7,52	8,41	7,14	6,76	8,25	7,33	6,99	7,13
22.12.2010	5,55	5,29	5,44	5,25	6,42	5,53	6,1	7,35	6,07	6,19	7,73	10,01	9,61	8,53	12,79	9,71	10,64	10,29	9,46	8,49	7,99	7,37	6,09	6,95
23.12.2010	5,94	5,17	6,22	5,46	5,04	5,17	5,54	7,46	5,57	5,34	5,57	7,95	8,11	8,74	8,67	8,51	7,89	7,19	7,4	6,31	5,34	5,58	6,61	6,72
24.12.2010	8	6,43	4,48	5,07	4,96	5,03	6	5,46	6,66	8,62	6,79	9,15	9,55	6,36	6,12	8,28	11,65	9,52	10,47	8,27	8,47	8,99	8,98	8,68
25.12.2010	7,62	7,44	8,76	6,75	6,27	6,29	6,25	7,21	6,33	6,55	8,28	7,58	8,35	8,07	7,98	6,54	6,32	7,32	8,16	7,47	7,83	7,96	8,78	8,15
26.12.2010	5,74	5,71	5,58	6,02	6,28	5,67	5,31	5,92	5,94	8,36	10,29	11,33	10,63	7,63	7,95	7,61	8,34	9,2	8,65	7,98	7,46	7,41	7,17	7,67
27.12.2010	5,76	5,3	6,31	5,46	5,52	5,77	6,02	4,79	4,81	5,83	6,55	5,95	6,4	7,08	7,47	6,41	6,53	9,27	7,82	9,61	7,36	5,67	7,68	4,94
28.12.2010	3,93	4,31	3,9	3,46	3,52	3,11	4,09	3,49	3,54	4,49	7,11	7,05	6,16	6,22	5,7	7,63	7,25	7,29	8,28	8,03	7,5	7,69	7,68	6,35
29.12.2010	5,18	4,08	4,01	5,17	4,35	4,42	4,5	4,33	5,24	3,97	6,35	6,81	6,89	7,08	6,02	4,79	4,92	5,68	4,8	4,91	6,52	5,39	5,74	4,38
30.12.2010	3,66	3,73	3,94	5,14	4,55	4,36	4,39	3,95	5,69	4,51	6,72	6,27	5,33	5,18	6,26	7,04	7,44	8,53	8,43	8,14	6,2	5,13	6,3	4,09
31.12.2010	3,33	3,55	3,78	4,74	4,15	4,13	3,92	3,62	4,13	6,37	5,43	6,36	6,4	7,18	7,71	7,98	6,92	8,35	7,11	7,31	7,25	6,73	7	5,23

Figure A.2: Hourly measurement a meeter - provided by NTE.

Anleggsnummer	Tariff	Energiforbruk kWh	Brukstid aktiv last t/år	Brukstid reaktiv last t/år	Velanderkoeffisient 2	Døgnvariasjon	Årsvariasjon	Referanseår	Sluttbrukergruppe
07.51560.034.001	NH4	15319	3600	3600	0,024	HUSHOLDNING	STANDARD	2010	35
07.51560.021.001	NH4	30052	3600	3600	0,024	HUSHOLDNING	STANDARD	2010	35
07.51560.046.001	NH4	16111	3600	3600	0,024	HUSHOLDNING	STANDARD	2010	35
07.51560.044.001	NH4	18317	3600	3600	0,024	HUSHOLDNING	STANDARD	2010	35
07.51560.037.001	NH4	31311	3600	3600	0,024	HUSHOLDNING	STANDARD	2010	35
07.51560.010.001	NH4	23118	3600	3600	0,024	HUSHOLDNING	STANDARD	2010	35
07.51560.025.001	NH4	20714	3600	3600	0,024	HUSHOLDNING	STANDARD	2010	35
07.51560.018.001	NS2F	800	3600	3600	0,024	STANDARD	STANDARD	2010	24
07.51560.006.001	NH4	29727	3600	3600	0,024	HUSHOLDNING	STANDARD	2010	35
07.51560.038.001	NH4	30234	3600	3600	0,024	HUSHOLDNING	STANDARD	2010	35
07.51560.039.001	NH4	1	3600	3600	0,024	HUSHOLDNING	STANDARD	2010	35
07.51560.041.001	NH4	21337	3600	3600	0,024	HUSHOLDNING	STANDARD	2010	35
07.51560.017.001	NH4	19033	3600	3600	0,024	HUSHOLDNING	STANDARD	2010	35
07.51560.001.001	NH4	42444	3600	3600	0,024	HUSHOLDNING	STANDARD	2010	35
07.51560.024.001	NH4	21286	3600	3600	0,024	HUSHOLDNING	STANDARD	2010	35
07.51560.032.001	NH4	10298	3600	3600	0,024	HUSHOLDNING	STANDARD	2010	35
07.51560.040.001	NH4	14342	3600	3600	0,024	HUSHOLDNING	STANDARD	2010	35
07.51560.035.001	NH4	24019	3600	3600	0,024	HUSHOLDNING	STANDARD	2010	35
07.51560.008.001	NH4	16901	3600	3600	0,024	HUSHOLDNING	STANDARD	2010	35
07.51560.005.001	NH4	30073	3600	3600	0,024	HUSHOLDNING	STANDARD	2010	35
07.51560.009.001	NS1	4858	3600	3600	0,024	STANDARD	STANDARD	2010	38
07.51560.033.001	NH4	18295	3600	3600	0,024	HUSHOLDNING	STANDARD	2010	35
07.51560.045.001	NH4	20534	3600	3600	0,024	HUSHOLDNING	STANDARD	2010	35
07.51560.020.001	NH4	30655	3600	3600	0,024	HUSHOLDNING	STANDARD	2010	35
07.51560.007.001	NH4	19926	3600	3600	0,024	HUSHOLDNING	STANDARD	2010	35
07.51560.029.001	NH4	24085	3600	3600	0,024	HUSHOLDNING	STANDARD	2010	35
07.51560.031.001	NH4	16252	3600	3600	0,024	HUSHOLDNING	STANDARD	2010	35
07.51560.028.001	NH4	20740	3600	3600	0,024	HUSHOLDNING	STANDARD	2010	35
07.51560.027.001	NH4	10039	3600	3600	0,024	HUSHOLDNING	STANDARD	2010	35
07.51560.036.001	NH4	23820	3600	3600	0,024	HUSHOLDNING	STANDARD	2010	35
07.51560.022.001	NH4	33097	3600	3600	0,024	HUSHOLDNING	STANDARD	2010	35
07.51560.019.001	NH4	15626	3600	3600	0,024	HUSHOLDNING	STANDARD	2010	35
07.51560.015.001	NH4	41906	3600	3600	0,024	HUSHOLDNING	STANDARD	2010	35
07.51560.014.001	NH4	24478	3600	3600	0,024	HUSHOLDNING	STANDARD	2010	35
07.51560.013.001	NH4	22673	3600	3600	0,024	HUSHOLDNING	STANDARD	2010	35
07.51560.003.001	NH4	19792	3600	3600	0,024	HUSHOLDNING	STANDARD	2010	35
07.51560.002.001	NH4	38533	3600	3600	0,024	HUSHOLDNING	STANDARD	2010	35
07.51560.004.001	NH4	14426	3600	3600	0,024	HUSHOLDNING	STANDARD	2010	35

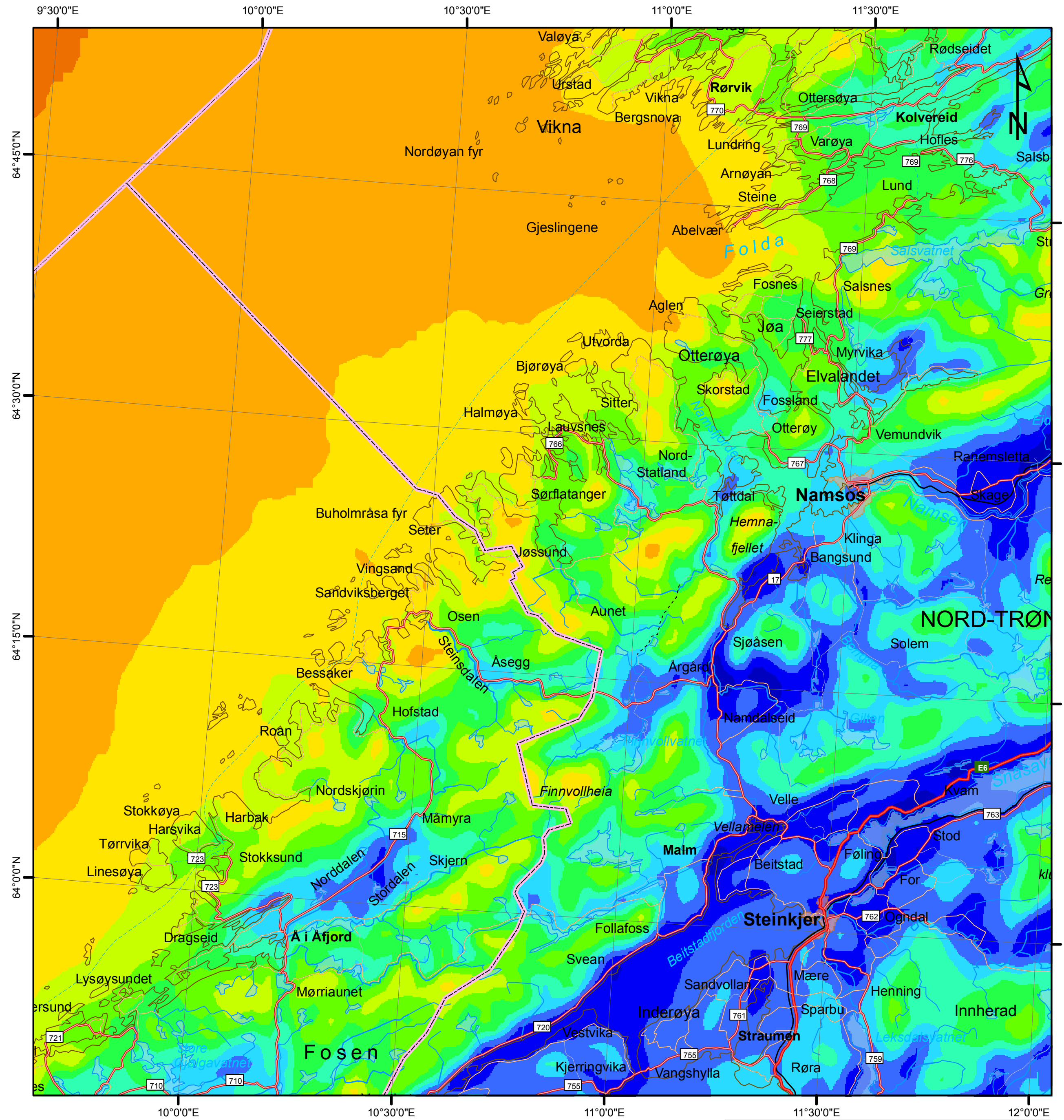
Figure A.3: Consumption - provided by NTE.

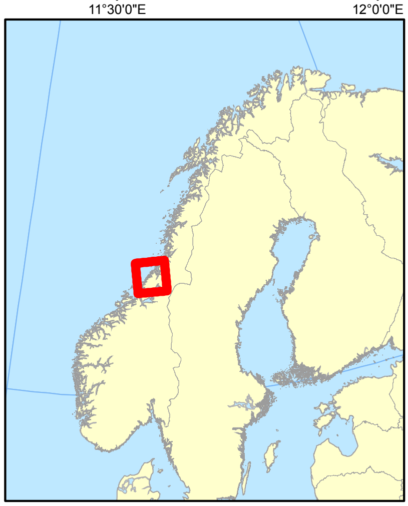
Appendix B

Wind data

The first page is a wind map over part of Nord Trøndelag. The map is collected from *Vindkart for Norge* by Kjeller Vindteknikk[39]. The data is the yearly mean wind for 50 m hight. The scale is 1 : 600.000. The map is page 30 in the book.

The second page is the correlative map with production[40]. This data is however for a hight of 80 m.





Årsmiddelvind [m/s]

3.5 - 4.0	7.5 - 8.0
4.0 - 4.5	8.0 - 8.5
4.5 - 5.0	8.5- 9.0
5.0 - 5.5	9.0 - 9.5
5.5 - 6.0	9.5 - 10.0
6.0 - 6.5	10.0 - 10.5
6.5 - 7.0	10.5 - 11.0
7.0 - 7.5	11.0 - 11.5

Landskap

- Innsjø
- Tettbebyggelse
- Snø/Isbre

0 5 10 20 30 km

NVE - Vindkart for Norge

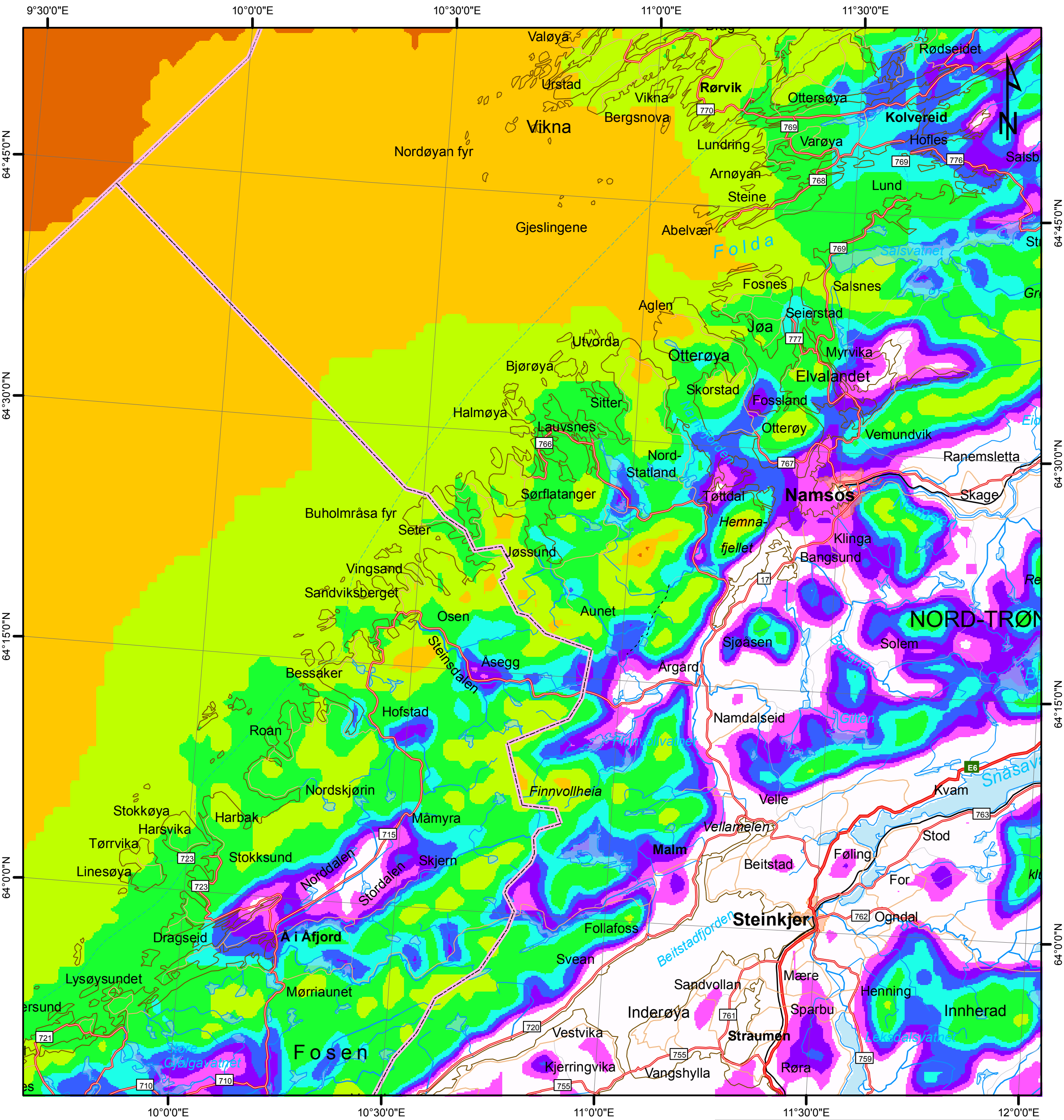
Figure/Drawing Title:

Årlig middelvind 50m

File Name: K:\NVE\Vindkart Norge\Vindkart Norge.mxd	Rev: 1
By: ØB · Date: sep 01, 2009	Checked: EB · Date: sep 01, 2009
Scale: 1:600 000	Paper Size: A4
Datum: WGS84	Projection: UTM sone33

KJELLER VINDTEKNIKK

NVE



Produksjon fullasttimer [timer]

0 - 2 000	2 800 - 3 000
2 000 - 2 200	3 000 - 3 200
2 200 - 2 400	3 200 - 3 400
2 400 - 2 600	3 400 - 3 600
2 600 - 2 800	3 600 - 3 800

Landskap

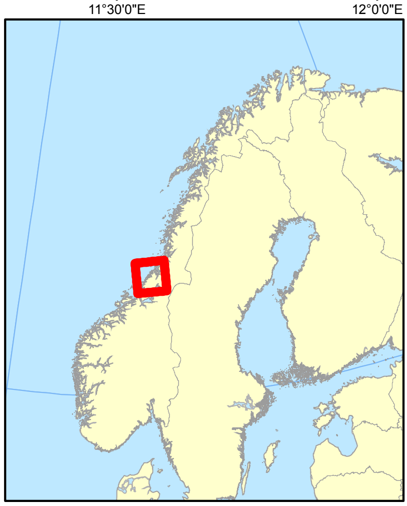
- Innsjø
- Tettbebyggelse
- Snø/Isbre

0 5 10 20 30 km

NVE - Vindkart for Norge			
Figure/Drawing Title: Fullasttimer 80m			
File Name: K:\NVE\Vindkart Norge\Vindkart Norge.mxd			Rev: 1
By: ØB	Date: okt 13, 2009	Checked: EB	Date: okt 13, 2009
Scale: 1:600 000		Paper Size: A4	
Datum: WGS84		Projection: UTM sone33	

KJELLER VINDTEKNIKK

NVE



Appendix C

Program codes

1. Simpow: Optpow file used for basic power flow simulations - general specifications
2. Simpow: Dynpow file used for time simulations - scenario 3 & smart charging
3. Matlab: m-file code is provided by supervisor for the thesis, Marta Molinas.

Åshild Vatne - optpow file for analysis of large scale adoption of EVs

```
**  SteinkjerOPT.optpow  **

GENERAL
        SN=0.4
END
NODES
        51570       UB=22
        51670       UB=22
        BUS1        UB=22
        BUS2        UB=0.23
        TAMP        UB=0.23
        51560.009           UB=0.23
        51560.018           UB=0.23
        51560.025           UB=0.23
        B1          UB=0.23
        51560.037           UB=0.23
        51560.017i          UB=0.23
        51560.032           UB=0.23
        51560.040           UB=0.23
        51560.015           UB=0.23
        51560.017ii         UB=0.23
        51560.034           UB=0.23
        A1          UB=0.23
        51560.022           UB=0.23
        51560.014           UB=0.23
        51560.005           UB=0.23
        51560.003           UB=0.23
        51560.010           UB=0.23
        A2          UB=0.23
        51560.001           UB=0.23
        51560.002           UB=0.23
        51560.019           UB=0.23
        51560.008           UB=0.23
        D1          UB=0.23
        51560.021           UB=0.23
        51560.041           UB=0.23
        51560.045           UB=0.23
        51560.024           UB=0.23
        51560.033           UB=0.23
        D2          UB=0.23
        51560.013           UB=0.23
        51560.020           UB=0.23
        51560.004           UB=0.23
        51560.007           UB=0.23
        51560.006           UB=0.23
        C1          UB=0.23
        51560.027           UB=0.23
        51560.038           UB=0.23
        51560.028           UB=0.23
        51560.029           UB=0.23
        51560.039           UB=0.23
        51560.031           UB=0.23
        51560.035           UB=0.23
        51560.036           UB=0.23
        51560.046           UB=0.23
        51560.044           UB=0.23
END
LINES
        B1      51560.017i          TYPE=2  R=1.2    X=0.082  B=0.0013 L=0.008
        BUS2    51560.009           TYPE=2  R=0.461  X=0.01   B=7.85E-6          L=0.001
        BUS2    TAMP     TYPE=2     R=0.461 X=0.01   B=7.85E-6          L=0.126
        C1      51560.031           TYPE=2  R=1.2    X=0.082  B=0.0013 L=0.056
        C1      51560.039           TYPE=2  R=0.308  X=0.094  B=8.64E-6          L=0.007
        C1      51560.027           TYPE=2  R=1.2    X=0.082  B=0.0013 L=0.041
        D1      51560.021           TYPE=2  R=1.2    X=0.082  B=0.0013 L=0.036
        D2      51560.013           TYPE=2  R=1.2    X=0.082  B=0.0013 L=0.04
        D2      51560.020           TYPE=2  R=1.2    X=0.082  B=0.0013 L=0.033
        D2      51560.004           TYPE=2  R=1.2    X=0.082  B=0.0013 L=0.036
        D2      51560.007           TYPE=2  R=1.2    X=0.082  B=0.0013 L=0.032
        D2      51560.006           TYPE=2  R=1.2    X=0.082  B=0.0013 L=0.029
        D1      D2       TYPE=2     R=0.32  X=0.076  B=0.000173         L=0.066
```

```
	D1	51560.041		TYPE=2	R=0.727	X=0.082	B=0.0013	L=0.01
	D1	51560.045		TYPE=2	R=0.727	X=0.082	B=0.0013	L=0.023
	D1	51560.024		TYPE=2	R=1.2	X=0.082	B=0.0013	L=0.029
	D1	51560.033		TYPE=2	R=1.2	X=0.082	B=0.0013	L=0.025
	BUS2	D1	TYPE=2	R=0.125	X=0.072	B=0.000198		L=0.065
	C1	51560.035		TYPE=2	R=1.2	X=0.082	B=0.0013	L=0.062
	C1	51560.036		TYPE=2	R=1.2	X=0.082	B=0.0013	L=0.048
	C1	51560.029		TYPE=2	R=1.2	X=0.082	B=0.0013	L=0.065
	C1	51560.028		TYPE=2	R=1.2	X=0.082	B=0.0013	L=0.041
	C1	51560.038		TYPE=2	R=1.2	X=0.082	B=0.0013	L=0.018
	C1	51560.046		TYPE=2	R=1.2	X=0.082	B=0.0013	L=0.01
	C1	51560.044		TYPE=2	R=1.2	X=0.082	B=0.0013	L=0.029
	BUS2	C1	TYPE=2	R=0.206	X=0.072	B=0.000187		L=0.106
	BUS2	51560.018		TYPE=2	R=0.741	X=0.0104	B=7.54E-6		L=0.042
	A2	51560.001		TYPE=2	R=1.2	X=0.082	B=0.0013	L=0.032
	A2	51560.002		TYPE=2	R=1.2	X=0.082	B=0.0013	L=0.024
	A2	51560.019		TYPE=2	R=1.2	X=0.082	B=0.0013	L=0.017
	A2	51560.008		TYPE=2	R=1.2	X=0.082	B=0.0013	L=0.016
	A1	A2	TYPE=2	R=0.32	X=0.076	B=0.000173		L=0.051
	A1	51560.010		TYPE=2	R=1.2	X=0.082	B=0.0013	L=0.022
	A1	51560.003		TYPE=2	R=1.2	X=0.082	B=0.0013	L=0.049
	A1	51560.005		TYPE=2	R=1.2	X=0.082	B=0.0013	L=0.052
	A1	51560.014		TYPE=2	R=1.2	X=0.082	B=0.0013	L=0.047
	A1	51560.022		TYPE=2	R=1.2	X=0.082	B=0.0013	L=0.032
	BUS2	A1	TYPE=2	R=0.206	X=0.072	B=0.000187		L=0.062
	B1	51560.037		TYPE=2	R=0.641	X=0.079	B=0.00017		L=0.009
	B1	51560.032		TYPE=2	R=1.2	X=0.082	B=0.0013	L=0.016
	B1	51560.040		TYPE=2	R=1.2	X=0.082	B=0.0013	L=0.04
	B1	51560.015		TYPE=2	R=1.2	X=0.082	B=0.0013	L=0.082
	B1	51560.017ii		TYPE=2	R=1.2	X=0.082	B=0.0013	L=0.049
	B1	51560.034		TYPE=2	R=1.2	X=0.082	B=0.0013	L=0.028
	BUS2	B1	TYPE=2	R=0.206	X=0.072	B=0.000187		L=0.078
	BUS2	51560.025		TYPE=2	R=1.2	X=0.082	B=0.0013	L=0.018
	BUS1	51570	TYPE=2	R=1.2	X=0.082	B=2.2E-5	L=0.286
	BUS1	51670	TYPE=2	R=0.32	X=0.12	B=3.61E-5		L=0.234
END
TRANSFORMERS
	BUS1	BUS2	SN=0.4	UN1=22	UN2=0.23	ER12=0.0106		EX12=0.0424
END
LOADS	51560.009		P=0.00200		MP=2
	51560.018		P=0.0003	MP=2
	51560.025		P=0.0084	MP=2
	51560.037		P=0.00131		MP=2
	51560.017i		P=0.0040	MP=2
	51560.032		P=0.0044	MP=2
	51560.040		P=0.0060	MP=2
	51560.015		P=0.0175	MP=2
	51560.017ii		P=0.0040	MP=2
	51560.034		P=0.0065	MP=2
	51560.022		P=0.0138	MP=2
	51560.014		P=0.0102	MP=2
	51560.005		P=0.0126	MP=2
	51560.003		P=0.0083	MP=2
	51560.010		P=0.0096	MP=2
	51560.001		P=0.0178	MP=2
	51560.002		P=0.0161	MP=2
	51560.019		P=0.0065	MP=2
	51560.008		P=0.0071	MP=2
	51560.021		P=0.0125	MP=2
	51560.041		P=0.0089	MP=2
	51560.045		P=0.0086	MP=2
	51560.024		P=0.0089	MP=2
	51560.033		P=0.0077	MP=2
	51560.013		P=0.0095	MP=2
	51560.020		P=0.0128	MP=2
	51560.004		P=0.0060	MP=2
	51560.007		P=0.0083	MP=2
	51560.006		P=0.0125	MP=2
	51560.027		P=0.0042	MP=2
	51560.038		P=0.0126	MP=2
	51560.028		P=0.0087	MP=2
	51560.029		P=0.0101	MP=2
	51560.031		P=0.0068	MP=2
	51560.035		P=0.0101	MP=2
```

```
            51560.036           P=0.0099 MP=2
            51560.046           P=0.0068 MP=2
            51560.044           P=0.0077 MP=2

END
POWER CONTROL
            BUS1        TYPE=NODE           RTYPE=SW            U=22        FI=14.9836          NAME=MYGRID1
END
END
```

DYNPOW – Åshild Vatne – file for analysis of a large scale implementation of Evs

Scenario 3: 63,15% EVs with smart charging

```
**

CONTROL DATA
 TEND=25.0
END
GENERAL
 FN=50
END
NODES
 BUS1 TYPE=1
END
LOADS
51560.009           MP=2 MQ=2 QTAB=867          PTAB=209
            51560.025           MP=2 MQ=2 QTAB=867          PTAB=225
            51560.037           MP=2 MQ=2 QTAB=867          PTAB=237
            51560.017i          MP=2 MQ=2 QTAB=867          PTAB=12
            51560.032           MP=2 MQ=2 QTAB=867          PTAB=232
            51560.040           MP=2 MQ=2 QTAB=867          PTAB=240
            51560.015           MP=2 MQ=2 QTAB=867          PTAB=215
            51560.017ii         MP=2 MQ=2 QTAB=867          PTAB=12
            51560.034           MP=2 MQ=2 QTAB=867          PTAB=234
            51560.022           MP=2 MQ=2 QTAB=867          PTAB=222
            51560.014           MP=2 MQ=2 QTAB=867          PTAB=214
            51560.005           MP=2 MQ=2 QTAB=867          PTAB=205
            51560.003           MP=2 MQ=2 QTAB=867          PTAB=203
            51560.010           MP=2 MQ=2 QTAB=867          PTAB=210
            51560.001           MP=2 MQ=2 QTAB=867          PTAB=201
            51560.002           MP=2 MQ=2 QTAB=867          PTAB=202
            51560.019           MP=2 MQ=2 QTAB=867          PTAB=219
            51560.008           MP=2 MQ=2 QTAB=867          PTAB=208
            51560.021           MP=2 MQ=2 QTAB=867          PTAB=221
            51560.041           MP=2 MQ=2 QTAB=867          PTAB=241
            51560.045           MP=2 MQ=2 QTAB=867          PTAB=245
            51560.024           MP=2 MQ=2 QTAB=867          PTAB=224
            51560.033           MP=2 MQ=2 QTAB=867          PTAB=233
            51560.013           MP=2 MQ=2 QTAB=867          PTAB=213
            51560.020           MP=2 MQ=2 QTAB=867          PTAB=220
            51560.004           MP=2 MQ=2 QTAB=867          PTAB=204
            51560.007           MP=2 MQ=2 QTAB=867          PTAB=207
            51560.006           MP=2 MQ=2 QTAB=867          PTAB=206
            51560.027           MP=2 MQ=2 QTAB=867          PTAB=227
            51560.038           MP=2 MQ=2 QTAB=867          PTAB=238
            51560.028           MP=2 MQ=2 QTAB=867          PTAB=228
            51560.029           MP=2 MQ=2 QTAB=867          PTAB=229
            51560.031           MP=2 MQ=2 QTAB=867          PTAB=231
            51560.035           MP=2 MQ=2 QTAB=867          PTAB=235
            51560.036           MP=2 MQ=2 QTAB=867          PTAB=236
            51560.046           MP=2 MQ=2 QTAB=867          PTAB=246
            51560.044           MP=2 MQ=2 QTAB=867          PTAB=244

END
TABLES
12 TYPE=0 F 1 0.4300 2 0.410 3 0.430 4 0.410 5 0.500 6 0.430 7 0.480 8 0.57 9 0.470 10 0.480 11 0.600 12 0.780 13 0.750 14 0.670
15 1.000 16 0.760 17 0.830 18 0.800 19 0.74 20 0.66 21 0.620 22 0.580 23 0.480 24 0.540 25 0.540
209 TYPE=0 F 1 0.430 2 0.410 3 3.380 4 3.360 5 3.460 6 3.390 7 0.480 8 0.57 9 0.470 10 0.480 11 0.600 12 0.780 13 0.750 14 0.670
15 1.000 16 0.760 17 0.830 18 0.800 19 0.74 20 0.66 21 0.620 22 0.580 23 0.480 24 0.540 25 0.540
```

218 TYPE=0 F 1 0.430 2 0.410 3 0.430 4 18.54 5 18.63 6 18.56 7 18.60 8 0.57 9 0.470 10 0.480 11 0.600 12 0.780 13 0.750 14 0.670
15 1.000 16 0.760 17 0.830 18 0.800 19 0.74 20 0.66 21 0.620 22 0.580 23 0.480 24 0.540 25 0.540
225 TYPE=0 F 1 1.150 2 1.130 3 1.140 4 1.120 5 0.500 6 0.430 7 0.480 8 0.57 9 0.470 10 0.480 11 0.600 12 0.780 13 0.750 14 0.670
15 1.000 16 0.760 17 0.830 18 0.800 19 0.74 20 0.66 21 0.620 22 0.580 23 0.480 24 0.540 25 0.540
237 TYPE=0 F 1 0.890 2 0.870 3 0.880 4 0.870 5 0.500 6 0.430 7 0.480 8 0.57 9 0.470 10 0.480 11 0.600 12 0.780 13 0.750 14 0.670
15 1.000 16 0.760 17 0.830 18 0.800 19 0.74 20 0.66 21 0.620 22 0.580 23 0.480 24 0.540 25 0.540
232 TYPE=0 F 1 0.430 2 1.790 3 1.800 4 1.790 5 1.880 6 0.430 7 0.480 8 0.57 9 0.470 10 0.480 11 0.600 12 0.780 13 0.750 14 0.670
15 1.000 16 0.760 17 0.830 18 0.800 19 0.74 20 0.66 21 0.620 22 0.580 23 0.480 24 0.540 25 0.540
240 TYPE=0 F 1 0.430 2 0.410 3 0.430 4 0.410 5 0.500 6 0.430 7 0.480 8 0.57 9 0.470 10 0.480 11 0.600 12 0.780 13 0.750 14 0.670
15 1.000 16 0.760 17 0.830 18 0.800 19 0.74 20 0.66 21 1.620 22 1.570 23 1.470 24 1.540 25 1.540
215 TYPE=0 F 1 0.430 2 0.410 3 0.430 4 0.750 5 0.850 6 0.780 7 0.820 8 0.57 9 0.470 10 0.480 11 0.600 12 0.780 13 0.750 14 0.670
15 1.000 16 0.760 17 0.830 18 0.800 19 0.74 20 0.66 21 0.620 22 0.580 23 0.480 24 0.540 25 0.540
234 TYPE=0 F 1 0.430 2 0.410 3 0.430 4 1.340 5 1.430 6 1.360 7 1.480 8 0.57 9 0.470 10 0.480 11 0.600 12 0.780 13 0.750 14 0.670
15 1.000 16 0.760 17 0.830 18 0.800 19 0.74 20 0.66 21 0.620 22 0.580 23 0.480 24 0.540 25 0.540
222 TYPE=0 F 1 0.430 2 0.410 3 0.430 4 0.840 5 0.940 6 0.870 7 0.910 8 0.57 9 0.470 10 0.480 11 0.600 12 0.780 13 0.750 14 0.670
15 1.000 16 0.760 17 0.830 18 0.800 19 0.74 20 0.66 21 0.620 22 0.580 23 0.480 24 0.540 25 0.540
214 TYPE=0 F 1 0.430 2 1.000 3 1.010 4 1.000 5 1.000 6 1.090 7 0.480 8 0.57 9 0.470 10 0.480 11 0.600 12 0.780 13 0.750 14 0.670
15 1.000 16 0.760 17 0.830 18 0.800 19 0.74 20 0.66 21 0.620 22 0.580 23 0.480 24 0.540 25 0.540
205 TYPE=0 F 1 0.430 2 0.410 3 0.430 4 0.410 5 0.500 6 0.430 7 0.480 8 0.57 9 0.470 10 0.480 11 0.600 12 0.780 13 0.750 14 0.670
15 1.000 16 0.760 17 0.830 18 0.800 19 0.74 20 0.66 21 1.100 22 1.050 23 0.950 24 1.020 25 1.020
203 TYPE=0 F 1 0.430 2 0.410 3 1.150 4 1.140 5 1.230 6 1.160 7 0.480 8 0.57 9 0.470 10 0.480 11 0.600 12 0.780 13 0.750 14 0.670
15 1.000 16 0.760 17 0.830 18 0.800 19 0.74 20 0.66 21 0.620 22 0.580 23 0.480 24 0.540 25 0.540
210 TYPE=0 F 1 0.430 2 0.410 3 0.430 4 1.030 5 1.130 6 1.060 7 1.100 8 0.57 9 0.470 10 0.480 11 0.600 12 0.780 13 0.750 14 0.670
15 1.000 16 0.760 17 0.830 18 0.800 19 0.74 20 0.66 21 0.620 22 0.580 23 0.480 24 0.540 25 0.540
201 TYPE=0 F 1 0.770 2 0.750 3 0.760 4 0.750 5 0.500 6 0.430 7 0.480 8 0.57 9 0.470 10 0.480 11 0.600 12 0.780 13 0.750 14 0.670
15 1.000 16 0.760 17 0.830 18 0.800 19 0.74 20 0.66 21 0.620 22 0.580 23 0.480 24 0.540 25 0.540
202 TYPE=0 F 1 0.810 2 0.790 3 0.800 4 0.780 5 0.500 6 0.430 7 0.480 8 0.57 9 0.470 10 0.480 11 0.600 12 0.780 13 0.750 14 0.670
15 1.000 16 0.760 17 0.830 18 0.800 19 0.74 20 0.66 21 0.620 22 0.580 23 0.480 24 0.540 25 0.540
219 TYPE=0 F 1 0.430 2 0.410 3 1.340 4 1.330 5 1.420 6 1.350 7 0.480 8 0.57 9 0.470 10 0.480 11 0.600 12 0.780 13 0.750 14 0.670
15 1.000 16 0.760 17 0.830 18 0.800 19 0.74 20 0.66 21 0.620 22 0.580 23 0.480 24 0.540 25 0.540
208 TYPE=0 F 1 1.280 2 1.260 3 0.430 4 0.410 5 0.500 6 0.430 7 0.480 8 0.57 9 0.470 10 0.480 11 0.600 12 0.780 13 0.750 14 0.670
15 1.000 16 0.760 17 0.830 18 0.800 19 0.74 20 0.66 21 0.620 22 0.580 23 1.320 24 1.390 25 1.390
221 TYPE=0 F 1 0.910 2 0.410 3 0.430 4 0.410 5 0.500 6 0.430 7 0.480 8 0.57 9 0.470 10 0.480 11 0.600 12 0.780 13 0.750 14 0.670
15 1.000 16 0.760 17 0.830 18 0.800 19 0.74 20 0.66 21 0.620 22 1.060 23 0.960 24 1.020 25 1.020
241 TYPE=0 F 1 0.430 2 1.090 3 1.100 4 1.090 5 1.180 6 0.430 7 0.480 8 0.57 9 0.470 10 0.480 11 0.600 12 0.780 13 0.750 14 0.670
15 1.000 16 0.760 17 0.830 18 0.800 19 0.74 20 0.66 21 0.620 22 0.580 23 0.480 24 0.540 25 0.540
245 TYPE=0 F 1 1.130 2 0.410 3 0.430 4 0.410 5 0.500 6 0.430 7 0.480 8 0.57 9 0.470 10 0.480 11 0.600 12 0.780 13 0.750 14 0.670
15 1.000 16 0.760 17 0.830 18 0.800 19 0.74 20 0.66 21 0.620 22 1.280 23 1.180 24 1.240 25 1.240
224 TYPE=0 F 1 1.110 2 0.410 3 0.430 4 0.410 5 0.500 6 0.430 7 0.480 8 0.57 9 0.470 10 0.480 11 0.600 12 0.780 13 0.750 14 0.670
15 1.000 16 0.760 17 0.830 18 0.800 19 0.74 20 0.66 21 0.620 22 1.250 23 1.150 24 1.220 25 1.220
233 TYPE=0 F 1 1.220 2 1.200 3 0.430 4 0.410 5 0.500 6 0.430 7 0.480 8 0.57 9 0.470 10 0.480 11 0.600 12 0.780 13 0.750 14 0.670
15 1.000 16 0.760 17 0.830 18 0.800 19 0.74 20 0.66 21 0.620 22 0.580 23 1.260 24 1.330 25 1.330
213 TYPE=0 F 1 1.070 2 0.410 3 0.430 4 0.410 5 0.500 6 0.430 7 0.480 8 0.57 9 0.470 10 0.480 11 0.600 12 0.780 13 0.750 14 0.670
15 1.000 16 0.760 17 0.830 18 0.800 19 0.74 20 0.66 21 0.620 22 1.210 23 1.110 24 1.180 25 1.180
220 TYPE=0 F 1 0.900 2 0.880 3 0.890 4 0.880 5 0.500 6 0.430 7 0.480 8 0.57 9 0.470 10 0.480 11 0.600 12 0.780 13 0.750 14 0.670
15 1.000 16 0.760 17 0.830 18 0.800 19 0.74 20 0.66 21 0.620 22 0.580 23 0.480 24 0.540 25 0.540
204 TYPE=0 F 1 0.430 2 1.410 3 1.420 4 1.410 5 1.500 6 0.430 7 0.480 8 0.57 9 0.470 10 0.480 11 0.600 12 0.780 13 0.750 14 0.670
15 1.000 16 0.760 17 0.830 18 0.800 19 0.74 20 0.66 21 0.620 22 0.580 23 0.480 24 0.540 25 0.540
207 TYPE=0 F 1 0.430 2 1.140 3 1.150 4 1.140 5 1.230 6 0.430 7 0.480 8 0.57 9 0.470 10 0.480 11 0.600 12 0.780 13 0.750 14 0.670
15 1.000 16 0.760 17 0.830 18 0.800 19 0.74 20 0.66 21 0.620 22 0.580 23 0.480 24 0.540 25 0.540
206 TYPE=0 F 1 0.430 2 0.890 3 0.910 4 0.890 5 0.980 6 0.430 7 0.480 8 0.57 9 0.470 10 0.480 11 0.600 12 0.780 13 0.750 14 0.670
15 1.000 16 0.760 17 0.830 18 0.800 19 0.74 20 0.66 21 0.620 22 0.580 23 0.480 24 0.540 25 0.540
227 TYPE=0 F 1 0.430 2 0.410 3 0.430 4 0.410 5 0.500 6 0.430 7 0.480 8 0.57 9 0.470 10 0.480 11 0.600 12 0.780 13 0.750 14 0.670
15 1.000 16 0.760 17 0.830 18 0.800 19 0.74 20 2.090 21 2.050 22 2.010 23 1.910 24 0.540 25 0.540
238 TYPE=0 F 1 0.910 2 0.410 3 0.430 4 0.410 5 0.500 6 0.430 7 0.480 8 0.57 9 0.470 10 0.480 11 0.600 12 0.780 13 0.750 14 0.670
15 1.000 16 0.760 17 0.830 18 0.800 19 0.74 20 0.660 21 0.620 22 1.050 23 0.950 24 1.020 25 1.020
228 TYPE=0 F 1 0.430 2 0.410 3 0.430 4 0.410 5 0.500 6 0.430 7 0.480 8 0.57 9 0.470 10 0.480 11 0.600 12 0.780 13 0.750 14 0.670
15 1.000 16 0.760 17 0.830 18 0.800 19 0.74 20 0.66 21 1.310 22 1.260 23 1.160 24 1.230 25 1.230
229 TYPE=0 F 1 0.430 2 1.010 3 1.020 4 1.010 5 1.100 6 0.430 7 0.480 8 0.57 9 0.470 10 0.480 11 0.600 12 0.780 13 0.750 14 0.670
15 1.000 16 0.760 17 0.830 18 0.800 19 0.74 20 0.66 21 0.620 22 0.580 23 0.480 24 0.540 25 0.540
231 TYPE=0 F 1 0.430 2 0.410 3 1.310 4 1.300 5 1.390 6 1.320 7 0.480 8 0.57 9 0.470 10 0.480 11 0.600 12 0.780 13 0.750 14 0.670
15 1.000 16 0.760 17 0.830 18 0.800 19 0.74 20 0.66 21 0.620 22 0.580 23 0.480 24 0.540 25 0.540
235 TYPE=0 F 1 0.430 2 0.410 3 1.020 4 1.010 5 1.100 6 1.030 7 0.480 8 0.57 9 0.470 10 0.480 11 0.600 12 0.780 13 0.750 14 0.670
15 1.000 16 0.760 17 0.830 18 0.800 19 0.74 20 0.66 21 0.620 22 0.580 23 0.480 24 0.540 25 0.540
236 TYPE=0 F 1 1.040 2 1.020 3 1.030 4 1.010 5 0.500 6 0.430 7 0.480 8 0.57 9 0.470 10 0.480 11 0.600 12 0.780 13 0.750 14 0.670
15 1.000 16 0.760 17 0.830 18 0.800 19 0.74 20 0.66 21 0.620 22 0.580 23 0.480 24 0.540 25 0.540
246 TYPE=0 F 1 0.430 2 0.410 3 0.430 4 0.410 5 0.500 6 0.430 7 0.480 8 0.57 9 0.470 10 0.480 11 0.600 12 0.780 13 0.750 14 0.670
15 1.000 16 0.760 17 0.830 18 0.800 19 0.74 20 0.66 21 1.510 22 1.460 23 1.360 24 1.430 25 1.430
244 TYPE=0 F 1 1.220 2 1.200 3 1.210 4 1.190 5 0.500 6 0.430 7 0.480 8 0.57 9 0.470 10 0.480 11 0.600 12 0.780 13 0.750 14 0.670
15 1.000 16 0.760 17 0.830 18 0.800 19 0.74 20 0.66 21 0.620 22 0.580 23 0.480 24 0.540 25 0.540
867 TYPE=0 F 1 0.000 2 00 3 00 4 000 5 00 6 0.000 7 0.000 8 0.00 9 0.000 10 0.000 11 0.000 12 0.000 13 0.000 14 0.0 15 000 16
000 17 0.0 18 0.00 19 0.0 20 0.0 21 0.0 22 0.0 23 0.00 24 0.0 25 0.0
END
END

```
%clear all
close all
load data
%load data2
load Load_data
load smart_load

% Input data hints   (input data imported as variable "data")
% Column 7 = Wind speed
% Column 9 = Wave height
% Column 11 = Wave average period (of the 1/3 highest waves)


% Input data adjusting
%for j =1:size(data,1)
 %   if data(j, 9) == 99
  %       data(j, 9) = 0;
   % end
%end

for j =1:size(data,1)
    if data(j, 7) == 99
        data(j, 7) = 0;
    end
end

%Normalization of wind speed data  (Wind profile power law)
zr= 50;   %m ref height  of wind measures
z = 82.6; % real turbine height
for j =1:size(data,1)
    data(j,7) = data(j,7)*(z/z)^0.143;
end

% Input data adjusting
%for j =1:size(data,1)
 %   if data(j, 11) == 99
  %       data(j, 11) = 0;
   % end
%end


figure(1)
plot(1:size(data,1), data(1:size(data,1),7))
xlim([0 size(data,1)])
title('wind speed')


%% ANALYSIS WIND ENERGY CONVERTER

vmin = 3;   %3   min wind velocity allowed
vmax = 25;  %25  max wind velocity allowed
vn = 13;     %7  rated wind velocity of the turbine
Pn = 0.33e6;  % Hp Pn = 0.33 MW   rated power for the wind turbine
for k =1:size(data,1)
   if data(k,7) < vmin
       Pwind(k) = 0;
```

```
    elseif (vmin <= data(k,7))&&(data(k,7)<vn)
        Pwind(k) =Pn*(data(k,7)/vn)^3;
    elseif ( data(k,7)>= vn)&&(data(k,7)<vmax)
        Pwind(k) =Pn;
    else
        Pwind(k) = 0;
    end
end

figure(3)
plot(1:size(data,1), Pwind/1000)
hold on
plot(Load_data)
hold on
plot (smart_load)
ylim([0 600])
xlim([0 size(data,1)])
title('Power wind in kW')
```

Appendix D

Technoport paper

The following paper was published and presented at Technoport RERC Research conference in Trondheim April 2012. The study presented in the paper is based on the work done in the specialization project (TET 4510) at NTNU during fall 2011, and was used as a background project for the work described here.

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Technoport RERC Research

Analysis of a Scenario of Large Scale Adoption of Electrical Vehicles in Nord-Trøndelag

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Abstract

With the Klimaforliket (Agreement on climate policy) signed by the Norwegian government on January 17th 2008, Norway has set a goal to reduce emission caused by transportation with 2,5 – 4 million tons CO2 equivalents compared with the reference for 2020[1]. To reach this goal, a high penetration of electrical vehicles is essential, and new technologies and solutions for the infrastructure must be cleared early in the process. With the aim of triggering and stimulating a discussion in the topic, this paper will present a methodology for the analysis of the impact of large scale adoption of EVs on the electrical grid. A specific portion of a real network will be selected and two charging modalities for the electric vehicles will be investigated.

Keywords: Electric vehicles, charging, distribution network, Smart Grids

1. Introduction

The transport sector is accountable for more than half of the worlds consumption of oil, and a large amount of this is consumed by passenger cars.[2] A large scale adoption of electric vehicles would reduce the greenhouse gas emissions, and also reduce the dependency of oil. Nevertheless, the environment benefit is dependent of the generation mix. The higher percentage of renewable in the generation mix, the more beneficial the integration of EVs is. Renewable resources, such as wind energy, tends to have a stochastic production and will cause surplus energy in certain periods. To have the most efficient usage of the power, a good solution is to implement EVs in the grid. The EVs can also provide ancillary service and support

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the network with supply/demand matching and reactive power support[2].The solution where the vehicle delivers power back to the grid is called Vehicle-to-grid (V2G). Vehicle-to-home (V2H) is the solution where the vehicle deliver power to the owners home. All thought the integration of EVs is an intelligent solution to use the energy surplus, the implementation of a large EV fleet causes a lot of challenges. This paper questions the impact on the distribution grid, where the first bottlenecks are likely to occur. To be able to determine the impact on the distribution grid caused by a increasing number of EVs, a real data analysis of a low voltage network in the middle of Norway will be carried out. The grid is located in Steinkjer, outside Trondheim and is provided by NTE[3]. The analysis will start with chargers located at residences, to then explore how the utility can put forward a system for smarter charging strategies ("dumb" vs "smart" charging). In the first part of the paper, different charging technologies will be discussed. The second part will focus on the consequences a large scale adoption will cause on the selected grid in Steinkjer.

1.1. *Ambitions and driving forces*

The 17th of January 2008 the Norwegian government signed Klimaforliket (Agreement on climate policy) declaring that the state of Norway will be carbon-neutral no later than 2030. This agreement stated that Norway have to reduce the emission with 15-17 million tons CO_2 equivalents, a reduction of 25% compared with the 2007 reference [1]. It was also stated that the transport sector need to reduce the emission with 2.5 - 4 million tons CO_2 by the year 2020. The transport sector in Norway is accountable for 19% of the emissions. As a part of the obligation given in Klimaforliket a resource group was formed in December 2008 to elaborate a plan for electrification of the transport sector in Norway. The result from this project was presented in *Handlingsplan for elektrifisering av veitransport* (Plan of action to electrification of the road transportation)[1]. To reach the goal of a 25% reduction in emission, the resource group suggests that the traditional vehicle becomes more efficient as well as an integration of EV and vehicles that run on biofuel. A share of at least 10% electric vehicles is adequate by 2020. It was also stated in the same report that a share of 50% of EVs would cause a reduction of 36% compared to a vehicle-fleet with only efficient traditional gasoline vehicle. An efficient vehicle is calculated with 95 g CO_2 per km. If Norway wants to achieve the ambition of being carbon-neutral, the report propose a large implementation of EVs by 2030[1].

1.2. *Electric Vehicle in Norway 2011*

As of September 2011, there are according to Grønn Bil 4715 electric vehicles in Norway. The estimated number for November 2011 is 5301[4]. The electric vehicles are mainly located in and around the big cities. Oslo has the largest share with 1223 vehicles. This value is from September 2011. For the same period Bergen had the second largest share with 242 vehicles. In Trondheim the number of vehicles were 228[4]. Grønn bil has also a geographical presentation of where the charging stations in Norway are located on their web page. There are currently 3067 regular and 24 fast charging points in Norway. 4 of these are located in Oslo, 4 is located outside Stavanger, 2 in Bergen and 1 in Trondheim[4]. There are several EV models available at the Norwegian market today. The Norwegian EVs, Think and Buddy are according to the statistics they are the most popular EVs in Norway. 25% of the EV owners in Norway chose Think, while 23% chose Buddy. Mitsubishi is also a popular vehicle, and their EV, i-MIEV, is represented with 17% of the Norwegian market. Both Buddy and Think were produced in Norway, but currently there are no production of EVs in Norway. The production of Think stopped in March 2011. The company was liquidated in May 2011, and the estate was bought by Boris Zingarevish from Russia. Pure mobility, the company that produced Buddy in Økren, was liquidated as of November 1st 2011. Buddy is now owned by Buddy Electric AS that wish to continue production in Norway[5]. For the case study addressed in this paper, Nissan Leaf will be used as the simulation model. Nissan Leaf was selected Car of the Year 2010. According to the sales revenues for November 2011 in Norway, 64% of the models bought in November was Nissan Leaf[4]. Mitsubishi's i-miev which is also very popular in Norway were considered, but according to Bengt Otterås from BKK Nett AS, future charging system in EVs will as the Nissan Leaf have a charging current close up to the limits for the different charging modes[6]. These modes are explained in section 2.1.

2. Charging Technology

There are many different types of EVs. Essentially, an EV is a vehicle that uses electric motor for propulsion. The term *Grid Enabled Vehicle* (GEV) represent the vehicles that is directly implemented in the grid. The *Plug-in Hybrid Electric Vehicle* (PHEV) and the *Battery Electric Vehicle* (BEV) are included in this term. For the purpose of this paper, the term EV will be used for BEVs when not mentioned otherwise.

2.1. Charging standards

There are several standards for charging electric vehicle. In this paper it is chosen to look at the European standard IEC 61851-1. The charging modes are defined as;[7]

1. Mode 1, (AC) slow charging from a standard household-type socket-outlet not exceeding 16 A and not exceeding 250 VAC single-phase or 480 VAC three-phase, at the supply side, and utilizing the power and protective earth conductors. Mode 1 is the most widely used system today.
2. Mode 2, (AC) slow charging from a standard household-type socket-outlet with an in-cable protection device, not exceeding 32 A and not exceeding 250 VAC single-phase or 480VAC three-phase, utilizing standardized single-phase or three-phase socket-outlets, and utilizing the power and protective earth conductors together with a control pilot function and system of personnel protection against electric shock (RCD) between the EV and the plug or as a part of the in-cable control box. The inline control box shall be located within 0,3 m of the plug or the EVSE or in the plug. Mode 2 requires a control pin, but only on the vehicle side. The supply side does not need a control pin. The control is governed by the control box in the cable.
3. Mode 3, (AC) slow or fast charging using a specific EV socket-outlet and plug with control and protection function permanently installed. Mode 3 connectors require, according to IEC 61851-1, a range of control and signals pins for both sides of the cable. If the there is no vehicle present, the station socket is dead. The pilot pin in the plug on the charger side controls the circuit breaker.
4. Mode 4, (DC) fast charging using an external charger. Mode 4 charging is a solution where the power from the supply is converted in the charging station to DC. Mode 4 allows DC fast charging with currents up to 400 A. As for mode 3, mode 4 connectors require a range of control and signals pins to ensure a safe operation.

Mode 1 is the solution that is widely used today. As for the future, it is expected to use the other modes. Mode 4 defines the fast DC chargers. To be able to replace a large share of the traditional ICE vehicles with EVs, there is necessary to build the infrastructure for it. This include fast chargers at shopping malls, at gas stations and in the streets and at rest stops along the highway. Mode 4 will not be further discussed in this paper. Mode 2 and 3 chargers are the solution that will be the most common modes. The chargers will be stationed at residents, workplace and public sites. The difference between mode 2 and 3 is that mode 3 requires more communication and control in on the vehicle side. One can expect that mode 3 will become the standard solution for resident chargers if the V2H is introduced.

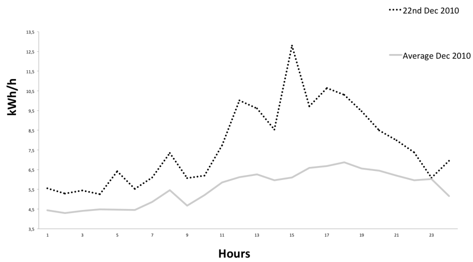
3. Vehicle to Grid (V2G) and Vehicle to Home (V2H)

The terms Vehicle to Grid and Vehicle to Home cover the solution were the battery in the electric vehicle delivers power back to the source. The intention is to save renewable unregulated energy in the battery and feed it back to the grid during peak hours. The introduction of electrical energy storage, such as the EV, could improve the efficiency and reliability in the power supply. The demand on the grid will be smoothed. However, V2G is associated with challenges such as state of charge (SOC) and the availability of the vehicle. How many vehicles are required to stand by as storage? How can we obtain the reliability, and at the same time the EV owners satisfied? Due to the fact that the V2H solution avoid some of the infrastructure and tariff problems raised by the V2G solution, the V2G solution has been neglected from this project[8]. In the V2H solution, the load is geographically close to the source that makes transmission minimal, reducing losses. The EV supplies the home with electricity during peak hours, causing less load on the grid. This may reduce the cost of the transmission grid, and may prevent building new lines. A study made by Gareth Haines, Andrew McGordon and Paul Jennings at this topic presents that the V2H solution reduces the peak demand. The work is presented in *The Simulation of Vehicle-to-Home System – Using Electric Vehicle Battery Storage to Smooth Domestic Electricity Demand.* [8]. The V2H requires smart solutions. In light of the Smart Grid vision the opportunities for a third-party to offer add-ons are huge. What type of services do the different consumers want? Some consumers want to control the flow themselves, while others want it to go automatically. Can this be a part of the Smart Metering infrastructure or do we need new infrastructure for communication?

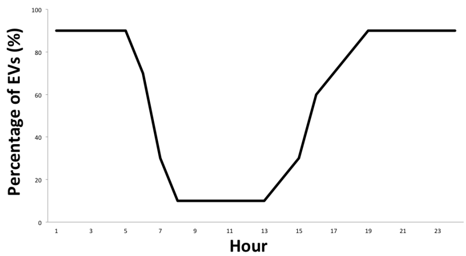
4. Network Description

For the purpose of this case, a low voltage distribution network was chosen to be simulated. The real data is provided by NTE[3]. This low voltage network is located in Steinkjer, outside Trondheim. The provided system includes a distribution network with primary voltage level of 22 kV transfer down to the low voltage level of 230 V. From the substation there are six outgoing feeders, supplying together the load from 35 residents. There are also 3 residential loads that are supplied directly from the substation. This gives a total load of 38 residents. NTE provided the hourly consumption from one resident in the network in Steinkjer. Due to the demand is highest in the winter, it is beneficial to analyse this case. It is therefore chosen to use the load in December 2010 from the given resident as the simulation data. Yearly consumption for the other residents in the network was also provided by NTE. The hourly real time data from December 2010 for the resident in Steinkjer was used to calculate the daily hourly average demand for the resident. Based on these data, a 24 hour load profile were calculated and designed in PSCAD. Due to some limitation in PSCAD, the residents were lumped together as one load. The cables were connected in parallel, and the line impedances were calculated from data given in *Planleggingsbok for kraftnett, Tekniske data* (Quire for power grid, Technical data) provided by SINTEF[9]. To be able to calculate the total consumption a power coefficient was introduced. This coefficient is the relation between the yearly consumption for the given resident and the total yearly consumption. Further it was decided to use the 22nd of December 2010 as the "simulation date". This was done to look at the worst case scenario, and the 22nd had the highest demand. Figure 1a shows the difference between the average demand and the demand on the simulation date. The demand peaks are, as expected, in the afternoon. For the chosen simulation date, the highest peak occurs at 15.00. It was expected that this peak would occur later, like shown on the average where the peak occur around 18.00. It is also expected that the EVs will be connected and charged during this time and cause higher peaks. To be able to simulate these peaks it was determined the average number of EVs connected to the grid during the day. This was made on general assumptions, and is only a calculated value. It is, however, used in other analysis [10] and will correspond to the real situation. These values are shown in figure 1b.

As seen on figure 1b, the electric vehicles are connected from approximate 16.00 until 06.00. However, the recharge time is assumed to be less than the connection time. To determine the recharge time for the EVs, data from Nissan's EV, *Nissan Leaf* is used as a basic for the following calculations. The Nissan Leaf has a Li-ion battery with a capacity of 24kWh. The recharge time depends on which level or mode is used. For a charging dock 220/240V and 40A the recharge time is 3.5 hours[11], while a 220/240V and 16 A the recharge time will be 6.5 hours[12]. Due to the fact that mode 2 will be more commercialized in the future, it is then assumed that the recharge time will be approximate 4 hours. This assumption is also used in the Portuguese publication *Smart Charging Strategies for Electric Vehicles: Enhancing Grid Performance and Maximizing the Use of Variable Renewable Energy Resources* by J. A. Peças Lopes[10]. It is further determined that average value of vehicle per household is equal to 1.5 vehicle, which gives a total of 57 vehicles enclosed in the area of the network. This was based on that the vehicle density in Trondheim is



(a) Average daily load for a resident in December 2010



(b) Percentage of EVs connected to the grid

Fig. 1. Network description

over 500 per 1000 citizen[13]. As mentioned, the Nissan Leaf will represent the EV fleet, this gives the modelled vehicle a rated power of 6 kW. This value is calculated from equation 3.

$$E_{batt} = 24\ kWh \tag{1}$$

$$T_{charge} = 4\ h \tag{2}$$

$$P_{EV} = \frac{W_{batt}}{T_{charge}} = \frac{24}{4} = 6\ kW \tag{3}$$

According to the The Institute of Transport Economics (Transportøkonomisk institutt) the average distance a person drives each day in Norway is 43 km [14]. Considering that Nissan Leaf has a driving range at 150 km[12], the average charging frequency could be that the owners charged their vehicle every third night. However, this analysis cover the worst case scenario where all the owners plug their vehicle in the grid at the same day will be analysed in this study due to the insecurity in the owners charging behaviour.

5. Scenarios

According to the Norwegian government's plan for electrifying the transport sector, it is determined that at least 10% of the passenger cars is chargeable in 2020. It is also stated in the same rapport, that if the share of chargeable passenger cars reached 50% towards 2050, it would cause a reduction of 36% in emission[1]. In consideration to this, the different scenarios were determined. The simulation includes three different scenarios, which are presented in table 1. This numbers are based on assumption made in section Network Description and consumption provided by NTE[3]. The first scenario is a simulation of the system without EVs, to have it as a base for comparing the scenarios with EVs. The second scenario was made to reflect the governments goal for 2020. A percentage of 10% in this area equal $5,7 \approx 6$ vehicles, resulting in a percentage of 10.53. For the third scenario is was decided to exceed the government's ambition of 50% by 2050. It was chosen to see what a 60% share of EVs would cause in this LV-gird. The number of EVs in the third scenario was decided to by 36 vehicles, leaving the percentage to be 63,16.

Table 1. Scenario Overview

Scenario	1	2	3
N of vehicle	57	57	57
N of EVs	0	6	36
Percentage of EVs[%]	0	10.53	63.16
Total demand [MW]	4.77	4.91	5.63

6. Charging Strategies

As it is previously mentioned, this paper will focus on the impact on the distribution network caused by EVs. Figure 1a and 1b in section 4 illustrate that implementation of EVs in the grid *can* cause a capacity problem in the afternoon. There is an existing peak in the afternoon and when a large share of EVs is implemented, the peak will increase. That may result in a capacity problem, a situation where the grid is not able to handle the heavy load. For the case study addressed in this work, two different charging strategies for EV charging were analysed:

Strategy 1 - "Dumb charging"

In the first approach it is assumed that the electric vehicle owners can connect to the grid whenever they want to, and that the charging will start immediately. In worst case the owners will plug their vehicles at the same time. This situation may occur when the users get home from work, which are typically existing peak hours. In the dumb charging strategy the charging start immediately and last for four hours. This approach is described as a non controlled strategy, leaves the power company to almost guess the production planning.

Strategy 2 - "Smart charging"

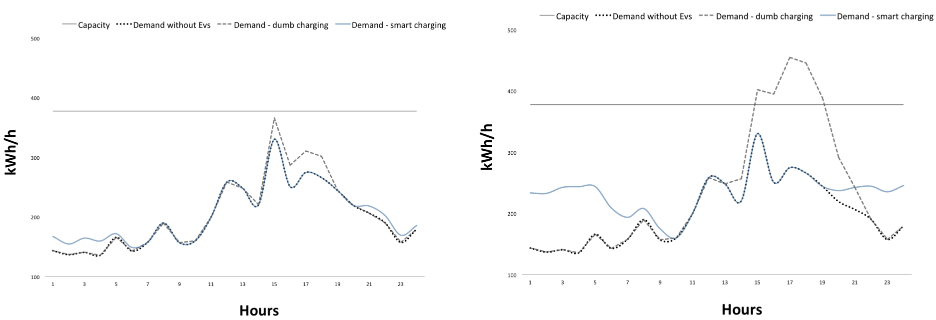
In the second approach, the smart charging strategy is introduced. It is assumed that there is an active control and manage system that continuously monitor all the elements connected to the grid. Then the charging schedules will be phased in. It is expected that the demand curve will be made more uniform. The vehicle will communicate with the grid when it is connected, and will start to charge when the demand is low. The smart charging strategy requires technology that can measure and communicate. It will also require a commitment from the vehicle owners. This approach will provide a beneficial usage of available resources, and also prevent damaging the grid. The V2H can also be introduced as a part of the smart charge. Due to the continuously monitoring of the elements connected to the grid, the EVs can operate as ancillary services and support the grid. The EVs can both deliver and store electric energy from the battery to the supply in situation with surplus/deficit of energy.

7. Result and Analysis

The hourly demand from the EV was calculated to be 6 kW. Due to the fact that there are no real data of an implementation of EVs, the extra demand caused by the vehicles were added to the load curve in Excel. It was done for both of the different charging strategies and both of the scenarios. As a starting point, the demand from the EVs were added as a function of when the vehicle were connected to the grid with references to figure 1b. For the dumb charging, the vehicle started to charge immediately when connected in the afternoon and charged for four hours. In the smart charging approach, the extra demand was added manually as a function of available vehicle and low demand. That resulted in charging late in the evening and at night. For a proper comparison between the dumb and the smart charging, the load profiles are presented in the same graph, as well as the base demand. A total capacity limit was added as a demand limitation, an indication on how much the system could handle. This limit were calculated to 378,4 kW and was based on the cables thermal limit. The power capacity for each cable were calculated by the nominal voltage and I_{th}, the maximum continuous operating current, found in *Planleggingsbok for kraftnett, Tekniske data* from SINTEF [9]. These values were added together to represent the capacity limit for the system.

In scenario 2, six EVs were implemented in the system. Figure 2a show the consequences an implementation of 10% will cause on the load profile. As seen on the figure, the extra demand does not exceed the capacity limit. The highest peak for the dumb charging is 366,01 kW. The figure shows the worst case scenario, when all the EV owners connect their vehicle at 15.00. The curve for the dumb charging and the base is consistent until the vehicles in connected in the afternoon, and then the curves "melt" together after the vehicles is done charging at 19.00. The curve for the smart charging is higher during the nigh when the vehicles is charging, and starts to follow the base demand from 06.00 when the vehicles is disconnected until 20.00 in the evening, when some of the vehicles start to charge. Nevertheless, figure 2a show that the dumb charging strategy will strain the system with extra 36 kW in the existing peak. In the third scenario, 36 vehicles were added. The change in the load profile is shown in figure 2b. The demand for the dumb charging will, as figure 2b presents, follow the base load until 15.00. At this point it is assumed that some of the EVs are connected to the grid. Between 15.00 and 19.00 the dumb charge exceed the capacity limit. The demand for the dumb charging will peak around 17.00 with a load of 454,5 kW, which exceed the capacity with 76,1 kW. The charging will end four hours later, around 22.00. In the smart charging approach the charging is moved, as one can see in figure 2b, to late night and early morning. The load profile in this approach will cause no extra demand during peak hours. The highest peak in in the smart charging approach is the same value as the base demand. The peak of 330,01 kW occur at 15.00. The low demand between 5 and 7 is due to that the vehicles are done charging. In a scenario with a higher EV percentage this period may also be used for charging. Since it is assumed that most of the vehicles is not connected in the grid between 06.00 and 16.00, the low demand will be unchanged in this period.

Scenario 3 was simulated in PSCAD to analyse if the voltage on the load exceeded its limits. As a starting point, the respective limit given from *Forskrift for leveringskvalitet* that state that the voltage should not exceed ±10%[15]. The per unit value were measured from the phase voltages in PSCAD. The two different charging approaches were simulated, as well as the base. Figure 3 shows how the voltages decreases as the load increases. The figure shows the voltage between 13.00 and 20.00, when the highest demand occurs. The purple line in the figure is the voltage during the dumb charging. As expected this approach causes a dip in the voltage around 17.00 when the system's demand peaks. From figure 2b one could see that the smart charging does not cause any extra demand than the residential load during peak hours, therefore there are no extra drop in the voltage either. The curve follows each other up until 19.00 when the base voltage increase more than the smart charge voltage. This reason for the lower voltage in the smart charge, is because the vehicles are starting to charge at that point, causing a higher load. The lowest measured voltages for the different approaches, are presented in table 2. The lowest measured voltage in the dumb charging is measured to 0.984 p.u. - a deviation of 1,6 %. The voltage drop during the dumb charge, were expected to be severe.



(a) Scenario 2 - 10.5% EVs.

(b) Scenario 3 - 63% EVs.

Fig. 2. Result - daily demand on substation

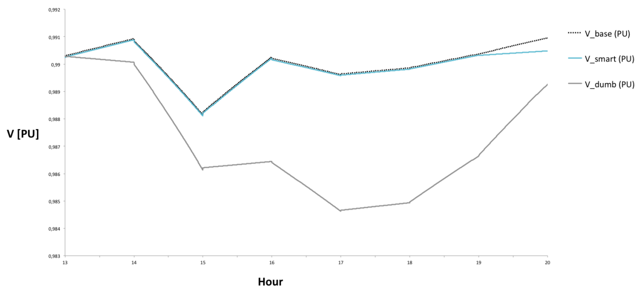


Fig. 3. Measured voltage in p.u.

Table 2. Result from scenario 3

Measurement	Peak Hour	Voltage (p.u.)
Base (no EVs)	15.00	0.988
Dumb charging	17.00	0.984
Smart charging	15.00	0.988

V2H

As a part of the project discussed in this report, a V2H solution was simulated. In this case, the analysis focused on only one EV and the given residential load. The result of this analysis is presented in figure 4. The x-axis on the figure shows the state of charge (SOC), and the hours of the day in shown in parentheses. Between 07.00 and 14.00 the EV is not connected to the supply, and the state of charge is therefore applied as NA (not applicable). It is further assumed that the SOC is 50% when the vehicle is connected to the supply at 15.00. This is based on the average distance a person drives each day in Norway and Nissan Leafs driving range, and an assumption that there will be some losses in the battery during the conversion of energy. The purple line indicates the demand in the V2H solution, while the green indicate the base demand. The EV is charged late at night and early in the morning.

In the afternoon, the load from the resident peak and the battery in the vehicle can provide some of the

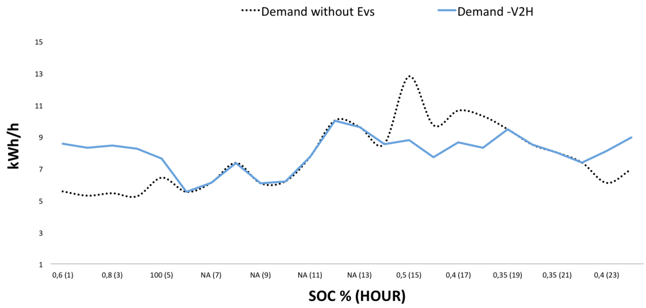


Fig. 4. Residential demand with Vehicle-to-Home.

demand. This causes less strain on the grid. One can see on figure 4 that this solution makes the load curve more smooth. For the case of the V2H, the peak occur at noon with a load of 10,01 kW. One can expect that the voltage would be smoother, and that the voltage-drop around 15.00 would have been reduced.

8. Discussion

The purpose of the work addressed in this report was to show the strain on the grid by implementing a large share of EVs. The result from the manually simulations shows that the system in not capable to handle a dumb charging approach when the share of EVs are 63%, while the simulations from PSCAD show that the voltage limits is not exceeded. The lowest measured voltage in the dumb charging is measured to 0.984 p.u. This is a voltage drop of 1,6% and therefore does not exceed the limits of ±10%. It was expected that the voltage drop in the dumb charging approach would be larger. The sources of error has not yet been located. The trend of the results does however, show that a smart charge approach will cause less strain on the grid. A large scale adoption of EVs is an intelligent way to reach this goal and addition have a more efficient usage of the available power, and especially in a network with a high share of renewable resources. The result from the analysis shows that the smart charging approach did not causes any extra strain on the demand during the peak hours. A large share adoption of EVs requires beneficial infrastructure. In addition to slow charging from a suitable docking station (mode 2/ mode 3), fast chargers (mode 4) need to be included in the infrastructure. Mode 1, which is the most used charging mode today, will fade out and be replaced. The chargers at residents and workplaces will mainly consist of mode 2 and mode 3 chargers. To be able to introduce the V2H solution, the charging technologies need to be based on mode 3 charging described in IEC 61851-1. Mode 3 requires control and signal pins for both the charger side and the vehicle side. An introduction of V2H and generally smart charging forward a huge opportunity for a third-party to offer add-ons and other business ideas.

9. Further work

The simplifications made in this project make it impossible to look at the different buses in the system. It is expected that the buses far away from the feeder would face large voltage drops. In a further analysis a more detailed simulation should be carried out. A further analysis could also use other areas and time for simulation.

10. Acknowledgement

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References

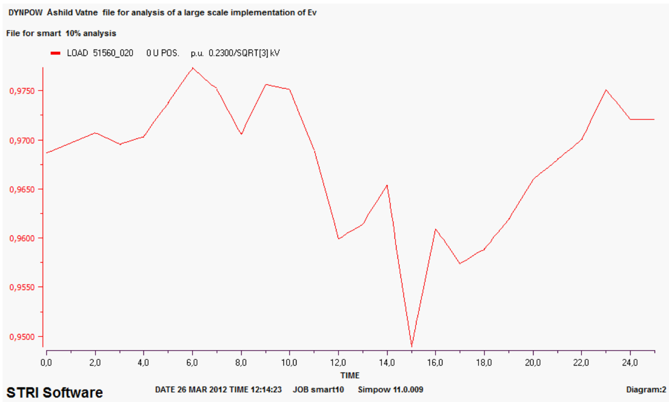
[1] EBL, Handlingsplan for elektrifisering av veitransport (May 2009).
[2] E. B. M. G. A. P. P. Suwanapingkarl, D. Johnston, Impact of electric vehicles on power distribution networks, in: Energy System and Advanced Materials Research Group, IEEE, 2009.
[3] Information and data from the lv-grid from nte, recived as an e-mail from Jan A. Foosnæs at the 27th of October.
[4] G. Bil, Ladbare biler i norge, www.gronnbil.no, visited: 5 December 2011, 11:09 (September 2011).
[5] N. Elbilforening, En stayer i elbilbransjen, http://www.elbil.no/mennesker/540-en-stayer-i-elbilbransjen, visited: 9 December 2011, 09:42 (November 2011).
[6] B. Otterås, Adviser at bkk nett, phonecall, 24 October 2011.
[7] I. International Standard, Iec 61851-1, Norsk Elektronisk Komite (NEK), electric vehicle conductive charging system - Part 1: General requirements (2010).
[8] A. M. Gareth Haines, P. Jennings, The simulation of vehicle-to-home systems - using electric vehicle battery storage to smooth domestic electricity demand, in: EVRE Monaco 2009, EVRE, 2009.
[9] S. E. AS, Planleggingsbok for kraftnett, tekniske data, Tech. rep., SINTEF AS (2010).
[10] P. M. A. M. M. d. S. J. A. Peças Lopes, F. J. Soares, Smart charging strategies for electrical vehicles: Enhancing grid performance and maximizing the use of variable renewable energy resorces, IINESC Porto and FEUP, Porto, Portugal, EVS24, Stavanger, 2009.
[11] N. USA, Nissan leaf technology, http://www.nissanusa.com/leaf-electric-car/index, visited: 11 November 2011, 17:11 (2011).
[12] N. Norway, Nissan leaf teknologi, http://www.nissan.no/NO/no/vehicles/electric-vehicles/electric-leaf/leaf.html, visited: 11 November 2011, 17:00 (2011).
[13] T. kommune, Bymiljørapport, http://www.trondheim.kommune.no/content/1117700102/Bymiljorapport:-Trondheim-best-i-Norge-pa-avfall, visited: November 4th 14:27.
[14] L. Vågane, Bilhold og bilbruk i Norge, TIØ, 856th Edition (October 2006).
[15] O. og energidepartementet, Forskrift om leveringskvalitet i kraftsystemet (2004).

Appendix E

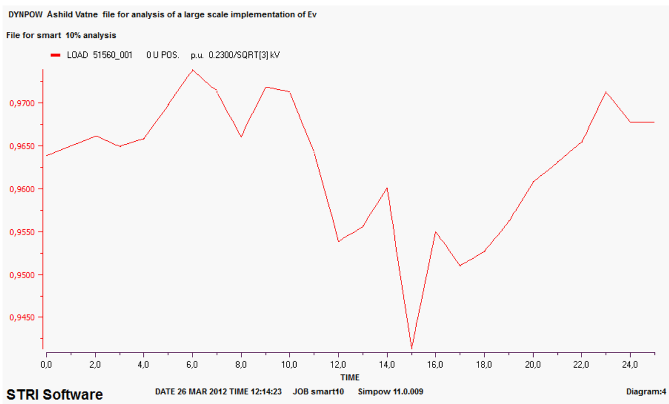
Results

Additional results from the simulations:

Figure E.2 Voltage measurement for smart charging scenario 2

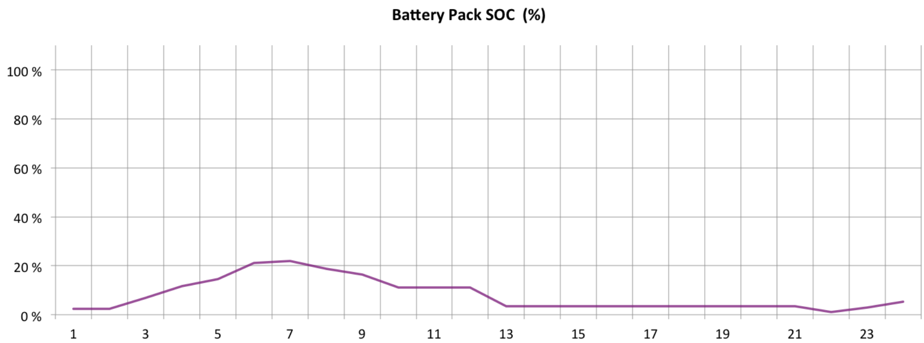


(a) Residence 020

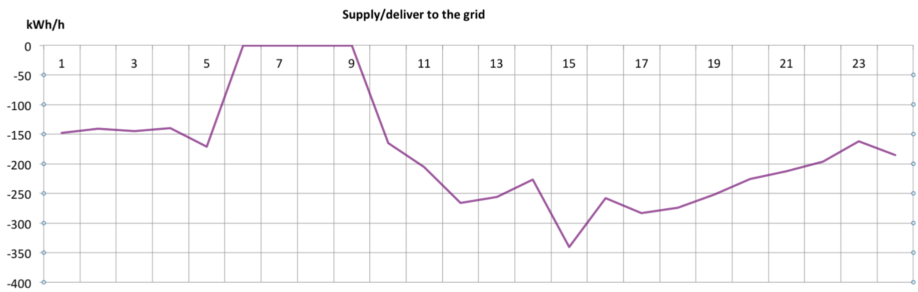


(b) Residence 001

Figure E.1: Voltage measured for smart charging scenario 2



(a) SOC with storage sized 864 kWh, 22nd Dec 2010



(b) Power matching from grid with storage sized 864 kWh, 22nd Dec 2010

Figure E.2: Result from Energy Storage