Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Information Technology and Electrical Engineering
Department of Electric Power Engineering

Andreas Aadnøy

A Case Study on the Grid Integration of Electric Vehicles in Norway

In combination with Solar Power, Fast Charging Stations and an Electric Ferry

Master's thesis in Energy and Environmental Engineering
Supervisor: Magnus Korpås (NTNU)
Co-supervisor: Bendik Nybakk Torsæter and Kyrre Kirkbakk Fjær (SINTEF Energi AS)

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Abstract

Norway is one of the leaders in the electric vehicle (EV) transition, with 82.9% of new registered vehicles so far in 2022 being EVs. This high addition of EVs create challenges for the grid operators, as today's power grid are not made to withstand this large electrification. The average load from an EV charging at home is low, and the power grid in Norway will withstand a relatively large transition to electric cars. However, a high number of EV charging simultaneously in one area, can create major challenges for transformers and cables in the distribution network. By using the flexibility of EV charging and other measures it is possible spread the load throughout the day, instead of high loads within short time periods.

In this master's thesis, impact of EV charging in a modern power grid is analyzed. Three different EV charging cases are made, to analyze how different forms of charging can affect the power system. There were made one worst case scenario where all charging happens straight after work hours, 16:00-19:00, when the grid often are congested. The two other charging cases made, were more flexible, with one having charging start at randomized time steps throughout the day, except during working hours. The last case had a slow charging approach, where all cars charges constantly at a low power rate throughout the day, except during working hours. The grid and charging cases were analyzed by performing power flow calculations of the grid, with load inputs from the different cases, over a time series. By these calculations it is possible to analyze the power flow performance of the grid, for example by load demand, reactive load demand and voltage magnitudes of the buses. Analyzing power flow performance of a power grid is an important tool to determine the power and voltage quality of the grid. A high power and voltage quality are crucial for a stable and reliable power grid.

The power grid in this thesis is a test grid made from preliminary work done in CINELDI. To make the grid a modern grid are solar power production, two fast charging stations (FCS) and one electric ferry added to the system. To analyze how the EV charging impacts the power grid in different load scenarios, are two load demand scenarios defined, representing a high load demand and a low load demand.

From the EV case studies, it is evident that utilizing the flexibility of EV charging rather than charging all EVs simultaneously over a small time period, results in a minimal grid impact. In a high load demand scenario the load peaks of the system is decreased with 6 MW from the worst case scenario to the flexible charging cases. Resulting in an increase of minimum voltage magnitudes at the weakest bus, which has been raised with 0.048 p.u. and 0.049 p.u. in the two flexible charging cases. To further decrease grid impacts of the high load demanding EV charging, are three additional measures added to the charging cases: A PV park with a 4.67 MW rated power, reactive power support from EVs and fast charging stations & an electric ferry, and lastly, a battery energy storage system (BESS) added to the HDEV FCS. The measures are added to all of the three charging cases, and then analyzed, in the same way as above with main focus on the load demand and voltage performances. Each individual measure did make an positive impact on the voltage quality. However, a combination of the measures made it possible to raise the voltage quality in the system sufficiently. The overall best performing case for the power grid were a flat charging case with a combination of the additional measures: PV park, reactive power support and a large BESS.

Sammendrag

Norge er ledende i overgangen til elektriske kjøretøy, med 82,9% av alle nyregistrerte kjøretøy så langt i 2022 er elbiler. Dette høye tilskuddet av elbiler skaper utfordringer for nettoperatørene, ettersom dagens strømnett ikke er dimensjonert for å tåle denne store elektrifiseringen. Gjennomsnittlig belastning fra en elbil som lader hjemme er lav, og strømnettet i Norge vil tåle en relativt stor overgang til elbil. Et høyt antall el-lading samtidig i ett område kan imidlertid skape utfordringer for transformatorer og kabler i distribusjonsnettet. Ved å bruke fleksibiliteten til EV-lading er det mulig å spre last belastningen utover dagen, i stedet for høy belastning i løpet av korte tidsperioder.

I denne masteroppgaven er virkningen av elbil-lading i et moderne strømnett analysert. Det er laget tre forskjellige elbil-lade caser, for å analysere hvordan ulike former for lading kan påvirke strømnettet. Det ble laget et worst case-scenario der all lading skjer rett etter arbeidstid, 16:00-19:00, når nettet ofte er overbelastet. De to andre lade casene som ble laget, var mer fleksible, hvor den ene hadde ladestart på tilfeldige tidstrinn gjennom hele dagen, unntatt i arbeidstiden (08.00-16.00). Det siste tilfellet hadde en langsom ladetilnærming, der alle biler lader konstant med lav effekt gjennom hele dagen, bortsett fra arbeidstiden. Strømnettet og lade casene ble analysert ved å utføre kraftstrøms-beregninger av nettet, med ulik last behov fra de forskjellige casene, over en tidsserie. Ved hjelp av disse beregningene er det mulig å analysere kraftstrømytelsen til nettet, for eksempel lastbehov, reaktiv lastbehov og spenningsstørrelser til bussene i strømnettet. Å analysere kraftstrømytelsen til et strømnett er et viktig verktøy for å bestemme strøm- og spenningskvaliteten til nettet. En høy effekt- og spenningskvalitet er avgjørende for et stabilt og pålitelig strømnett.

Fra elbil-case studiene er det tydelig at utnyttelse av fleksibiliteten til EV-lading i stedet for å lade alle EV-er samtidig over en liten tidsperiode resulterer i en minimal nettpåvirkning. I et scenario med høyt belastningsbehov reduseres belastningstoppene til systemet med 6 MW fra det verste scenarioet til de fleksible ladetilfellene. Videre resulterer last reduksjonen i en økning av minimumsverdien på spenning i den svakeste bussen i strømnettet, som er hevet med 0,048 p.u. og 0,049 p.u. i de to fleksible lade casene.

For ytterligere å redusere netteffekten av den høye lastkrevende elbilladingen, er tre tilleggstiltak lagt til lade casene: En solcellepark som produserer 4.67 MW på det meste, reaktiv kraft støtte fra elbiler og to hurtig lade stasjoner & en elektrisk ferge, og et batteri lagt til HDEV FCS. Tiltakene legges til alle de tre ladetilfellene, som deretter analyseres, på samme måte som ovenfor med mest fokus på spenningsytelsene. Hvert enkelt tiltak hadde en positiv innvirkning på spenningskvaliteten. En kombinasjon av tiltakene gjorde det imidlertid mulig å heve spenningskvaliteten i systemet tilstrekkelig. Den casen som hadde best ytelse, alstå minst påvirkning på strømnettet, var en flat lade case med en kombinasjon av tilleggstiltakene: PV-park, støtte for reaktiv kraft og et stort batteri.

Preface

This master thesis is submitted as my final work of a Master's degree in Science of Energy and Environmental Engineering at the Department of Electric Power Engineering at Norwegian University of Science and Technology (NTNU). This thesis was completed in the spring of 2022 and builds on work done in the specialization projected delivered in December 2021.

This master thesis is written in collaboration with and is a part of the FuChar project. FuChar is a KPN project funded by The Research Council of Norway and industry partners. The FuChar project aims to minimise investment and operating costs related to the grid integration of electric transport.

I would like to thank my supervisor, Professor Magnus Korpås, for your guidance and support throughout the process of writing this thesis. I'm grateful for all your good advice and your availability for discussions, as well as always starting meetings with a big smile. I would also like to thank Bendik Nybakk Torsæter at SINTEF Energy Research for contributing to the thesis with valuable inputs, guidance and data, and for letting me be a part of the FuChar project. Also, I want to give a big thanks to Kyrre Kirkbakk Fjær at SINTEF Energy Research for sharing your knowledge and model from previous work, in addition to helping me understand the simulation model. Finally, I want to thank my friends and family for their continuous support during my education.

Trondheim, June 2022

Andreas Aadnøy

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Abbreviations

UN	United Nations
EU	Europoean Union
EV	Electric Vehicle
BEV	Battery Electric Vehicle
PHEV	Plug-in Hybrid Electric Vehicle
HDEV	Heavy Duty Electric Vehicles
FCS	Fast Charging Station
NVE	Norwegian Water Resources and Energy Directorate
PV	Photovolatics
TSO	Transmission system operator
DSO	Distribution system operators
NVE	Norwegian Water Resources and Energy Directorate
DSM	Demand side management
V2G	Vehicle to grid
SOC	State of charge
BESS	Battery energy storage system
EVCS	Electric vehicle charging system
AC	Alternate current
DC	Direct current
Dumb1	Dumb Charging 1 case
Dumb2	Dumb Charging 2 case
Flat	Fast Charging case
LOW	Low Demand scenario
HI	High Demand scenario
LEC	Local Energy Communities
OPF	Optimal Power Flow

1 Introduction

In this report, a modified reference power grid is analyzed in terms of voltage magnitude and stability, for different power injection and load consumption cases. The different cases is analyzed and compared by analyzing their load curves, and following voltage magnitudes and power quality performance in the network over the given time frame. This master thesis builds on former work done in a specializations project last semester, and therefore a several of the background and theory written in this thesis is gathered from that work.

1.1 Motivation

The climate changes is going in the wrong direction. The latest report shows that we have a long way to go in order to stop the temperature increase. United Nations (UN) and European Union (EU) have already and are coming with more decisive and precise climate goals that need to be met. These goals push governments all over the world to make changes. This impacts the car industry heavily, pushing them to make significant changes in their car portfolio and plans [1] [2]. Today almost all the major car manufacturers in the world offer electric alternatives, and most of these manufacturers are aiming to only have electric alternatives in a few years [3].

The transport sector alone stands for over 16% of all the greenhouse gasses emitted globally. Most of these emissions have been traced back to road transport such as vehicles, mopeds, trucks, and so on [3]. The transition to emission-free transportation alternatives is going to slow. In 2020 were 99.8% of all the global transport is still powered by combustion engines, and the outlooks for 2040 shows only a decrease down to 85-90%, which is still too high numbers of combustion driven vehicles if we want to stop the climate changes [4].

The integration of Electric vehicles (EV), in addition to overall electrification, impacts the power grids, especially congested distribution grids. It may therefore be beneficial to emphasize the impact of EV integration in a modern power grid, as well as analyzing possible measures for a smoother EV integration.

1.2 Objective

In this thesis is a full power flow model of a test grid based on preliminary work in CINELDI made. The objective of the thesis is to answer the following:

How does EV charging impact a modern power grid, and what are possible measures to reduce grid impact from EV charging?

In search for the answer will the following sub-objectives be investigated:

- Establishing a test grid
- Establishing charging profiles for EVs
- Establishing local solar power production
- Establish load profiles from EV smart charging based on earlier thesis
- Establishing timeseries for EVs and measures, for consumption and production to the system
- Voltage and grid impact of EVs and analyzing measure for improved power & voltage quality

1.3 Outline

The outline structure of this master thesis is divided into the following sections:

- **Section 1 - Introduction:** Gives an introduction to the thesis, with motivation, objective and outline of the thesis.
- **Section 2 - Background:** Presents background information of the topic to give the reader an overview of the topic, in forms of information, development, trends and more.
- **Section 3 - Theory & literature review:** Presents the theoretical literature and foundation for the thesis. As well as an literature review of some of the theory. This section provide context for the modeling and discussion of the results.
- **Section 4 - System description:** Presents and describes the investigated system.
- **Section 5 - Methodology:** Describes the steps used in this thesis to
- **Section 6 - Results:** The results part is divided into two sections, where the section 6 presents individually the different load and power profiles added to the system.
- **Section 7 - Results:** Here are the load cases presented and analyzed, as well as the results from additional measures added to the EV charging cases.
- **Section 8 - Discussion:** Discusses the main results from the results part, and discusses this with theory and literature.
- **Section 9 - Conclusion:** Summarise, and concludes the main findings discussed in the discussion section.
- **Section 10 - Further work:** Presents possible topics for further work based on the work and findings from this thesis.

This master thesis builds on work presented in the specialization projected, which were done in the fall 2021 [5]. This master thesis however is made such that it is possible to read the thesis without reading the specialization project. Therefore have parts of section 2, 3 and 5 been reused. The section 2 and section 3 covers the background and theory for the work, and as this master thesis is a continuation of the work presented in the specialization project, some parts are reused. However, most of the parts have been modified with updated numbers and info, also are several additional parts added. In section 5, the EV charging load and PV production models developed in the specialization project is modified and inserted to the investigated power system.

2 Background

The transport sector is a big contributor to global warming, as this sector alone stands for over 16% of all the greenhouse gasses emitted globally. Most of these emissions have been traced back to road transport such as vehicles, mopeds, trucks, and so on [3]. The transition to emission-free transportation alternatives are happening, but it's is going to slow. In 2020, 99.8% of all the global transport were still powered by combustion engines, and the outlooks for 2040 shows a decrease down to 85-90%, which is still too high numbers of combustion driven vehicles if we want to stop the climate changes [4].

2.1 EV growth

The COVID-19 pandemic have impacted almost all industries, including the car industry, where sales of new cars in Europe have decreased by over 20 % compared to 2019. However, the electric vehicle (EV) market in Europe has experienced a significant increase in 2020, with 143% increase in sales of new EVs compared to 2019 [6]. Several countries have seen a significant increase in EV sales over the latest years, where countries such as Netherlands, Sweden and Norway are currently in the front seat of the transition [3].

2.2 EVs in Norway

Especially in Norway have the transition from ICE vehicles to EV's come very far. According to the Road Traffic Information Council in Norway, the EV share of new registered vehicles has increased in the latest years, as can be seen in Figure 1. This is also the case in 2022, where the EV share of new registered vehicles in Norway so far in 2022 (as of 31.03.22) were 82.9%. This number is an increase of 20 % from the year before, and expected to increase towards the end of the year, as well as the coming years [7].

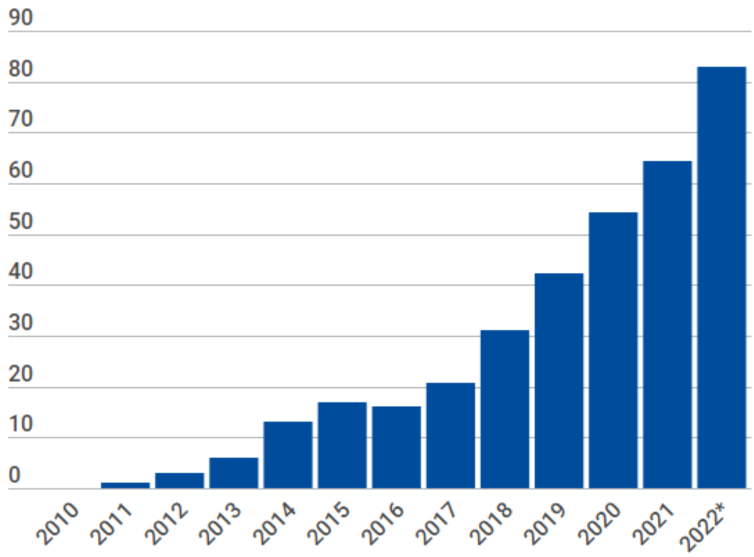


Figure 1: Bar chart of EV share of new registered vehicles over the last 11 years in Norway [7]

2.3 Development of EV models

Electric vehicles have been on an immense increase journey the last couple of years. From early 2000 were only a few EV models available, to today there are several hundred different models available globally, and the number is only increasing. From Figure 2 we can see the number of EV models available as of 2021 The blue graphs show the number of Battery electric vehicles (BEV), while the green graphs show the BEV + Plug in hybrid electic vehicles (PHEV). The navy-colored circles show the average driving range of the models each year. As can be seen in this figure there has been a large consistent increase over the last five years. From 2015 there were 88 EV models available worldwide, where 55 of them were BEVs while 33 of the models were PHEVs. Forwarding to 2020, there were a total of 370 different EV models available, which were an increase of 40% from the year before, and an increase of a whole 420% from 2015. From the 370 different models in 2020, 235 were BEVs while the rest 133 models were PHEVs. The number of available EV models is expected to continue to grow in the coming years [8].

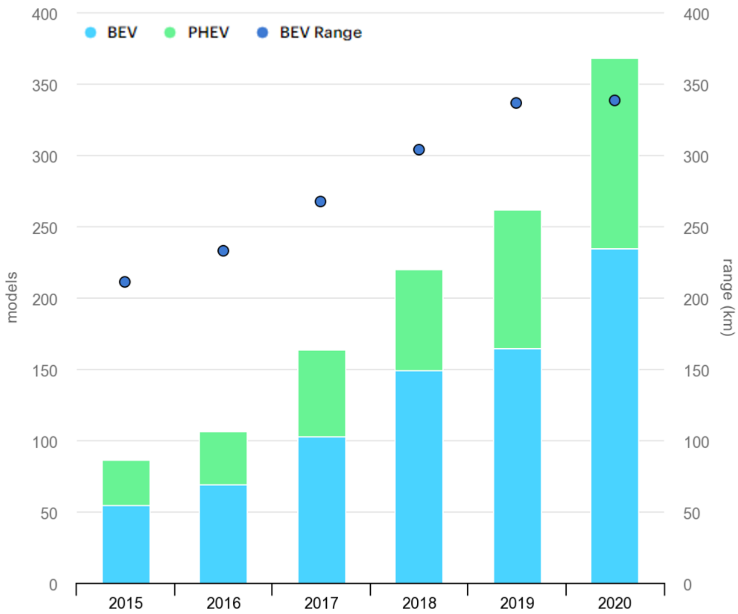


Figure 2: Number of available EV models over the last 5 years. Where light-blue bar shows number of BEV's, green bar shows number of PHEV's and the navy coloured dots shows average driving range for the BEV's each year [8].

What also can be seen from Figure 2 is that even though there are tens or hundreds of new BEV models each year, the average driving range for BEVs has been steadily increasing every year. In 2020 the average driving range of a BEV was about 350 km, which is an increase of almost 150 km from 2015 when the average driving range was a bit over 200 km [8].

The car industry is increasingly phasing out combustion engine vehicles and shifting towards greener alternatives. Several car manufacturers have already announced that they will change their car model portfolio to only electric alternatives in a few years. From Figure 3 one can see that 18 of the 20 largest original equipment manufacturers have committed to increasing the offer and sales of EVs in the coming years [8]. For example, one can see from the figure that Volvo will only sell EVs from 2030, and Ford has also announced a greener plan with them only selling EVs in Europe from 2020. Also, Volkswagen, which is the second-largest car manufacturer in the world, has announced that they aim for 70% of all car sales in Europe in 2030 being EVs [9] [10] [11]. This is only a few of the manufacturers who have announced their restructuring towards emissions-free alternatives [8].

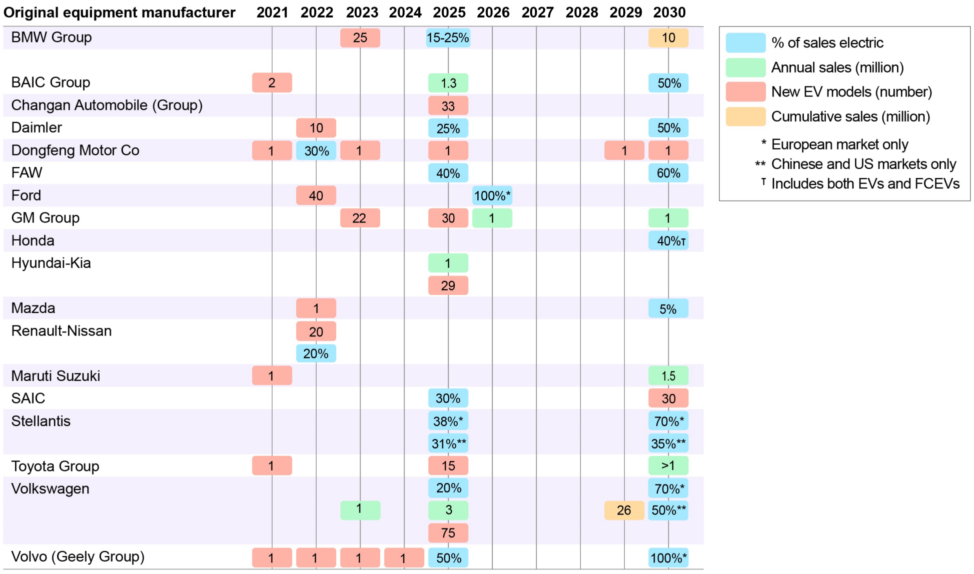


Figure 3: Overview of car manufacturers announced plans for future car fleet [8].

It is not only passenger cars that are being electrified, but now also electrifying light-commercial vehicles have taken off. As well as buses and Heavy duty electric vehicles (HDEV) which are becoming more and more frequent on the market, and expected to grow immenscly with better and cheaper battery technology in the future [12][13][14].

In addition to road transport also other transportation types such as aviation and sea transportation are also looking to greener and more environmentally friendly options. Norway are also one of the front-runners in the marine sectors transition. Where in 2015 the ferry MF Ampere were put into operation across the Sognefjorden, located west in Norway, as the first whole all-electric ferry in the world. Since then has the integration of hybrid and all-electric alternatives exploded in Norway. By the start of 2021 there were 31 ferrys in electric operation in Norway, while just one year later, in 2022 were a total of 52 ferrys were in electric operation. And a whamping 21 more ferrys are expected later this year. It is worth noting that not all of these 52 ferrys, and of the 21 to come, are not all-electric, but they are all run on some electric engines, either alone or in combination with other engines [15] [16].

2.4 Charging infrastructure

To accommodate this electric transition the grid needs to be upgraded and reinforced. The quick turnaround from fossil driven combustion engines to electric engines have left the charging infrastructure in Norway lagging behind, as it have not been able to keep up with the change.

The charging infrastructure is not build to withstand a high penetration of EV charging, and in [17] have Agder Energi Nett, a DSO in Norway, shared challenges with a high EV penetration in today's Norwegian distribution grids. For example if everyone in a residential area buys an electric car and charges with 32 amps, this will be twice the electricity they normally use. Most charging infrastructures is not dimensioned for these sizes, which may result in digging up and replacing cables and transformers with newer ones with higher capacity. The challenge is greatest for those who live far away from the nearest network station. It doesn't need to be more than 200 to 300 meters distance before the network begins to become weak. Power cable size and dimensions of the houses also play a decisive role in whether it is possible to set up a powerful electric car charger [17].

At the beginning of 2022, there will be around 4000 Fast charging stations (FCS) for EVs in Norway. By 2025 there is an expected need for around 9000 FCS, and 10-14000 FCS in 2030. There might also be a need for 1500-2000 FCS for HDEVs by 2030. However, this is only for fast charging, a well-developed network for normal charging is needed in addition to the FCS [18].

By 2030, many of today's transformers and power lines in the distribution network must be replaced due to age. The grid companies should consider reinvesting in components with a higher capacity than today, so that the grid is even better equipped to cope with full electrification of the transport sector. It may also be relevant to force reinvestments to cope with the increased electric car charging [19].

However, some grid reinforcements have already begun. Major investments are being made in the power grid at all grid levels in several places in the country. According to the Norwegian Water Resources and Energy Directorate (NVE), grid investments are expected for a total of NOK 135 billion in the ten-year period 2018-2027. It is therefore important to ensure that the costs are not greater than necessary and that the right investments are made. In addition, the costs must be distributed among the online customers in a reasonable manner [18].

2.5 Solar power

To reach the climate goals and produce enough power to meet the future energy demands, new additions of renewable energy production are needed. Solar energy is and will be a vital energy for all foreseeable future, with photovolatics (PV) panels being a key technology to harvest and produce renewable energy from sunbeams. An attribute that makes solar PV panels so crucial and valuable is that they can be deployed and utilized almost anywhere on the planet, as the sun reaches worldwide. They are abundant and cannot be monopolized by a country. Solar PV panels are and will be an essential resource to stabilize the increasing power demand, and prices [20] [21].

From Figure 4 one can see the enormous growth solar power production have had in the latest years. With an increase from around 50 GW new installations in 2015 to at least 175 GW of new installations in 2021, an increase of over 100%. The figure also shows that since 2019 have the number of new installations increased with around 30 GW each year [22]. The number of PV installations per year is expected to grow even further in the coming years, and global capacity could be over 8000 GW by 2050 [23].

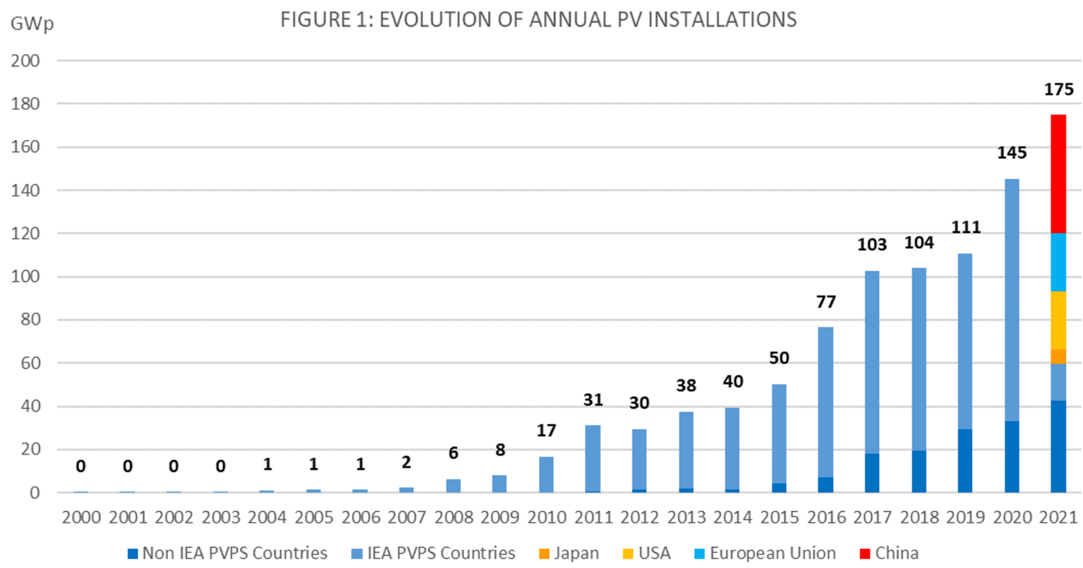


Figure 4: Historical growth of solar PV panels installations by country/region [22]

3 Theory & literature

This section will give describe the theory used in this thesis. It will include theory about the electricity grid, EV charging, power flow calculations, solar power, reactive power support, and battery energy storage systems. There is also a literature review in each of the theory subsections.

3.1 Impact of EVs on the Norwegian grid

The Norwegian grid is divided into three levels: Transmission, Regional, and Distribution grid. The transmission grid is the main road for the power system in Norway. It consists of power lines at the highest voltage levels, with normal voltage levels of 420 kV or 300 kV. The regional grid is the grid level below the transmission grid and links the transmission and levels underneath. Normal voltage levels here are 132 kV or 66 kV. The last level is the distribution type, which supplies most end-users - households, schools, services, and industry. Here the voltage levels differ from 22 kV and down to 230 V [24].

Statnett is the transmission system operator (TSO) in Norway, while there are several different distribution system operators (DSO) around the country. All of the DSOs are natural monopolists and are therefore regulated by NVE. Part of the regulations for the DSOs is to keep the voltage on their grids within certain levels to sustain stability in the grid. For example, for slow voltage variations, the voltage value shall be within the interval of ±10% of the nominal voltage, which means that the voltage magnitude should be within 0.9 and 1.1 p.u. with nominal voltage being 1.0 p.u [25].

NVE has assessed possible consequences for the power grid in [19], where grid loading at several grid companies have been analyzed. The average load from electric car charging is low, and the results show that the power grid in Norway will withstand a relatively large transition to electric cars. However, it will be the case that if many people charge the electric car simultaneously in one area, this can create challenges for transformers and cables in the distribution network. Especially in areas with weak networks, the voltage quality can be poorer with a lot of electric car charging.

In [26] are EVs impact on grid integration, as well as EV standards and charging infrastructure, investigated. The report underlines that an excessive integration of EVs represents a significant challenge for electric utilities. Possible impacts are high load peaks, voltage and frequency imbalances, power losses, and instability challenges.

In [27] are the grid impact of electric vehicle fast-charging stations investigated. Here, the grid impact of fast charging is considerably higher than slow charging, with fast charging creating severe damage to the power quality. Because the charging power is much higher, load demand is centralized at the FCS. Charging is mainly during the daytime, while slow charging is often done overnight when generally load demand is low. Furthermore, the load with fast charging is more pulsating due to shorter charging time and higher power demand.

3.2 Voltage stability - Reactive power

Power system stability issues can be categorized into three types: Rotor-angle stability, frequency stability, and Voltage stability. This thesis mainly investigates the power system stability by analyzing the voltage stability. The term voltage stability refers to the ability of the power grid to restore all buses to their nominal voltage levels after any disturbance or transient condition [28].

Voltage stability theory says that if a power system is stable, the reactive power of a source should meet system reactive power demand, such as load reactive power and load reactive power losses. If this is the case then the source reactive power curve, $Q_s(v)$ and the load reactive power curve, $Q_l(v)$ will intersect as shown in Figure 5a. Here there are two interceptions, giving out V_u and V_s. However, only V_s is a feasible solution under the circumstances. On the other hand, if the source reactive power demand does not match the reactive load power demand, the curves will not intersect, and voltage will collapse, as shown in Figure 5b [29].

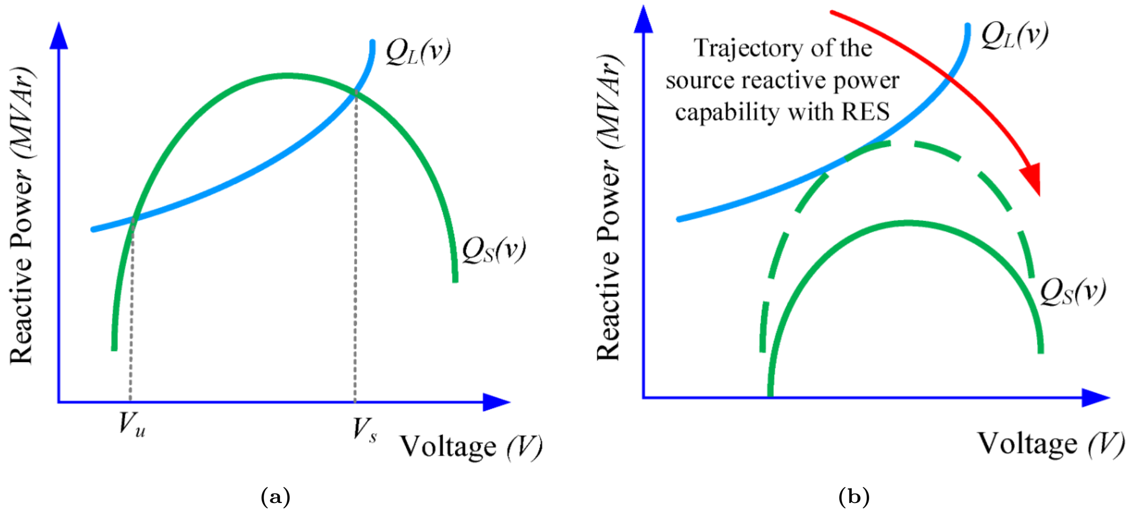


Figure 5: Representation of voltage stability as an equilibrium between source and load reactive power; (a) Stable case, (b) System moving towards voltage instability [29]

There are several ways to calculate reactive power, one of the methods are shown in the equations below, gathered from [30].

From Figure 6 with the relationship between reactive power (Q) and active power (P), Q can be found:

$$\frac{Q}{P} = \tan(\theta) \rightarrow Q = P * \tan(\theta) \tag{1}$$

where Q is the reactive power, P is the active power, while θ is the angle between P and apparent power (S) as shown in Figure 6.

When the angle θ is not defined but the power factor (PF) is, then the equation becomes:

$$Q = P * \tan(\arccos(PF)) \tag{2}$$

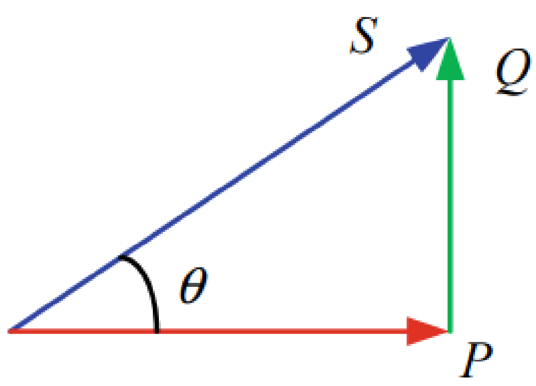


Figure 6: Power triangle. P is the active power [W], Q is the reactive power [VAr] and S is the Apparent power [VA]. θ is the angle between S and P [31].

3.3 Grid Ancillary Services

The modern grid with increased electrification and high EV penetration may face several difficulties, as described in subsection 3.1, due to generally higher load, but primarily due to sudden non-predictable high load peaks. For the grid to withstand the future load scenarios, several measures should be considered, either alone or in combination with others.

To maintain grid stability and reliability in response to variances in power supply and demand are Ancillary services identified by system operators [32]. A way of providing ancillary services to the grid are by demand side management (DSM). DSM consist of managing flexible load, with planning, implementing and monitoring load movement. DSM can help the grid with certain methods such as peak clipping, load shifting, valley filling, flexible load shape and more. An overview of a few DSM methods are presented in Figure 7. DSM is very useful for the grid as it can reduce the grid impact from distributed energy resources, as well as the larger and more frequent load demand peaks due to electrification. One of the most used DSM methods is Load shifting, which is an effective load management technique that combines peak clipping and valley filling to shift the load from peak hours to off-peak hours [33].

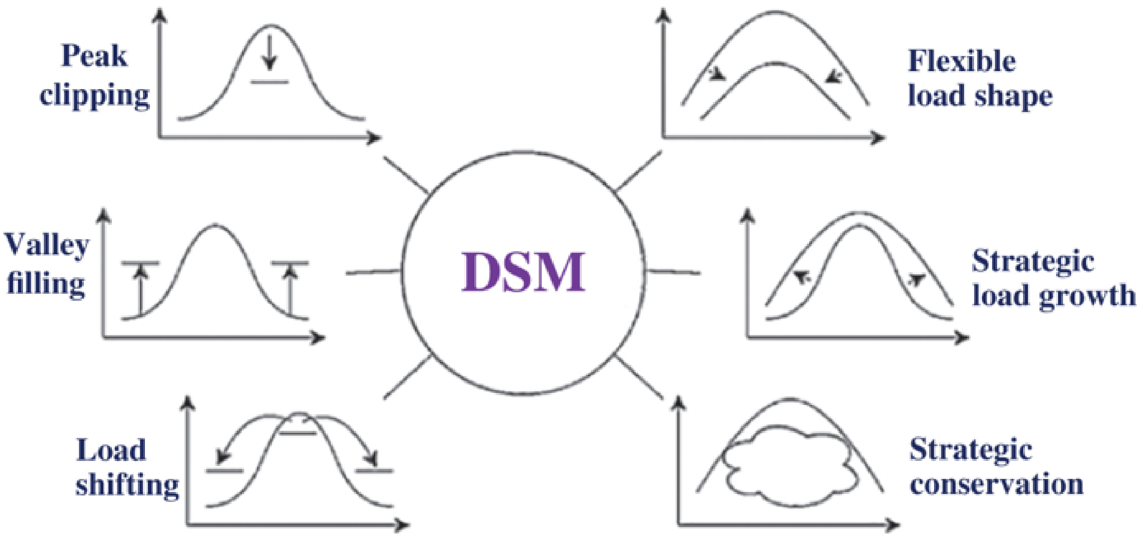


Figure 7: Overview of different types of demand side management: Peak clipping, valley filling, Load shifting, flexible load shape, strategic load growt and strategic conservation [33].

3.3.1 Flexible charging of EVs

Charging an electric car is mostly a very flexible load, making it possible for the users to move the charging from critical load demand hours to low demand hours. With power tariffs being introduced in Norway, as well as higher power prices, it is believed that this will be a great measure to get people to move their EV charging to the night to reduce the expenses [34]. Which makes flexible charging of EVs through moving the charging load to time steps that are better for the grid a load shifting service.

3.3.2 Reactive power support

An average car stands still about 98 percent of the time, and charging an electric car is, in many cases, a very flexible load. Charging an electric car is so flexible that it is possible to use the EV battery to send power back to the grid when needed. This service is called vehicle to grid (V2G) [34]. In addition to V2G using the EV battery to support the grid with active power, EVs could provide an efficient way to support power grids through reactive power injection, providing ancillary services for the voltage support. Reactive power support can be done at any time while the EV is connected to a charger, as EVs can at any state of charge (SOC) level consume or generate reactive power without it impacting the battery life [35].

As described in the subsections above, reactive power plays a vital role in voltage regulation and system stability in a power grid. Reactive power consumption results (by an inductive component) in a lower bus voltage, while reactive power injection (by a capacitive component) results in a higher bus voltage [30].

In [35] the benefits of reactive power injection from EVs are demonstrated. It is shown that the injection could help Undervoltage issues caused by active power consumption from EV charging. It is also shown that an injection of reactive power from the EV would benefit the EVs by reducing charging costs. Coordinating reactive power injection from the EVs with load shifting and load curtailment of load demand in a constrained grid is also shown to be helpful for the grid to accommodate the increasing share of EVs.

3.3.3 Battery energy storage system

A battery energy storage system (BESS) is a form of saving energy from one time to be used at another time. A BESS could be beneficial for grid operators as it is possible to charge the BESS from the grid or directly from a power plant and then discharge that energy at a later time when it is needed [36].

In a modern power grid with a lot of high load demand over short periods, as well as variable renewable energy production, will BESS and other energy storage systems be crucial to sustaining grid stability and reliability [37]. BESS can provide several services such as load shifting trough load peak clipping and then load filling.

There are several different battery chemistries for grid-scale applications, with each one having its unique advantages and disadvantages. However, today, lithium-ion is the dominating battery type used in BESS for electricity grid operations. Due to the battery technology innovations and a more significant amount of manufacturing, lithium-ion batteries have experienced a large price decline of above 70% from 2010 to 2016, and prices for batteries are expected to decline further in the coming years.

Increasing needs for system flexibility, combined with rapid decreases in battery technology costs, have enabled BESS to play an increasing role in the power system in recent years. As prices for BESS continue to decline and the need for system flexibility increases with wind and solar deployment, more policymakers, regulators, and utilities are seeking to develop policies to jump-start BESS deployment.

Battery storage is one of several technology options that can enhance power system flexibility and enable high levels of renewable energy integration. Studies and real-world experience have demonstrated that interconnected power systems can safely and reliably integrate high levels of renewable energy from variable renewable energy sources without new energy storage resources [36].

Considering the inherent characteristics and cost economics of BESSs, defining the role of BESSs and their sizing is essential [37].From work done by the US National Renewable Energy Laboratory [38], are cost projections for lithium-ion battery systems from 2020 to 2050 done, presented in Figure 8. The figure shows that all the three projections are cost decreasing to almost half of their values towards 2050.

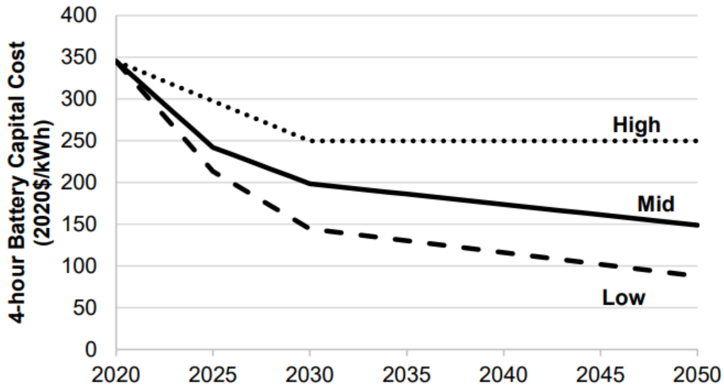


Figure 8: Cost projections for Battery 4-hour lithium-ion systems. Showcasing that for both high, mid and low costs are the costs expected to be halved by 2050 [38]

3.4 Solar power production

The modern power system consists more and more of variable renewable energy production, such as wind and solar power production. Solar power in the form of PV panels has had an immense journey in the latest years, as described in section 2.

Solar energy with electricity as output is called PV energy. Solar PV panels have a wide range of applications. They are usually placed on top of buildings to produce power for the building, possibly selling excess power to the grid. Alternatively, in larger PV power plants, where hundreds or thousands of PV panels are aligned together to provide bulk electricity [30].

Adding solar power to a power system could be beneficial, especially in congested grids. Using solar power to dampen, for example, the power peaks created from EV charging is possible. However, most of the power produced from solar panels is during the daytime, with the sun peak and production peak being in the middle of the day. So a possibility is to charge the EVs when the production is at its most.

Adding solar power production to a power grid would be very beneficial for grid operators. The power production could be used for peak clipping, local power supply in congested grids, and in combination with load shifting measures, such as moving EV charging or battery energy storage systems.

However, too much PV production in the grid can result in grid problems. If there is high power generation from PV panels and at the same time low load periods this could lead to a reverse power flow in the LV feeder, which could lead to an increase of the voltage level, possibly creating overvoltages. This has been a problem especially in Germany, where they have set a limit for maximum voltage increase on low voltage level to 0.02 p.u. [39] [40].

3.5 EV charging

An EV is run on electric power through an onboard battery which holds the energy until needed. In order to charge this battery, an EV Charging System (EVCS) is needed. An EVCS is an equipment required to condition and transfer energy from the supply grid, usually the external grid, to the DC battery in the EV to charge the EV's battery. These consist in general three different methods of charging: **conductive charging**, **inductive charging**, and **swapping the battery**. For the conductive method, there is a direct contact between the battery and a charge inlet connected by a cable. While, for the Inductive method, there is no contact between the charging infrastructure and the EV. The charging in this method happens through electromagnetic fields, which create an induced current that charges the battery. The last method is a more complicated matter, as the one here changes the whole discharged battery of the EV with a new, fully charged one. This is especially complicated because most of the different EV manufacturers, EV types, and models have their specific batteries. The conductive method is the most common as this is a much cheaper and more efficient option. However, the other two methods are becoming more and more frequent [41].

Conductive charging can be divided into alternating-current (AC) charging and direct-current (DC) charging. AC charging is the type most used for home charging, at work, and similar. Normally through simple charging systems, but also more advanced "smarter" charging systems such as the systems from *Easee* or *Zaptec*, or even small FCSs. The charging power can, for this method, be as low as a few kW or up to a maximum of 22kW. I.e. AC charging is so-called *slow charge* or *Semi-fast charge*. In this method, power from the grid, usually run on AC, is converted through an in-car inverter to DC level [42]. The other method is DC charging, also known as direct current fast charging. This method is mainly used at FCSs or other high power charging systems, as it uses a charging power from 25 to 350kW. Here is either a Combined Charging System (CCS) or CHAdeMO system used.

Conductive charging can be divided into three levels, as presented in Table 1. Levels 1 and 2 are charging on AC level, while level 3 is on DC level. In the table are the charging powers of the different levels presented, with an example of the typical placement of the EVCS. Figure 9 shows an example of what the three levels look like. An extra level 4 is also added to the table to highlight the newest charging type called "Ultra-fast charging," which charges at a level of 350 kW on a DC outlet. This is not a charging level in itself, as it is considered a part of charging level 3. Level 1 and 2 charging systems typically happen at home, in communities, at work, and more. While level 3 happens on busy roads, such as highways [43] [44].

Table 1: EVs charging levels. Level 1 - 3 are the main levels, as level 4 is a part of charging level 3 and only presented alone to highlight the newest charging type: Ultra-fast charging [43] [44]

Charging levels	**Type**	**Power [kW]**	**Charger type**	**Typical location**
Level 1	Slow charge	$\leq$ 3.7 kW	AC	Households
Level 2	Semi-fast charge	3.7 - 22 kW	AC	Workplace, Shops
Level 3	Fast charge	$\geq$ 50 kW	DC (CCS or CHAdeMO)	Highway
Level 4	Ultra-fast charge	350 kW	DC (CCS)	Highway

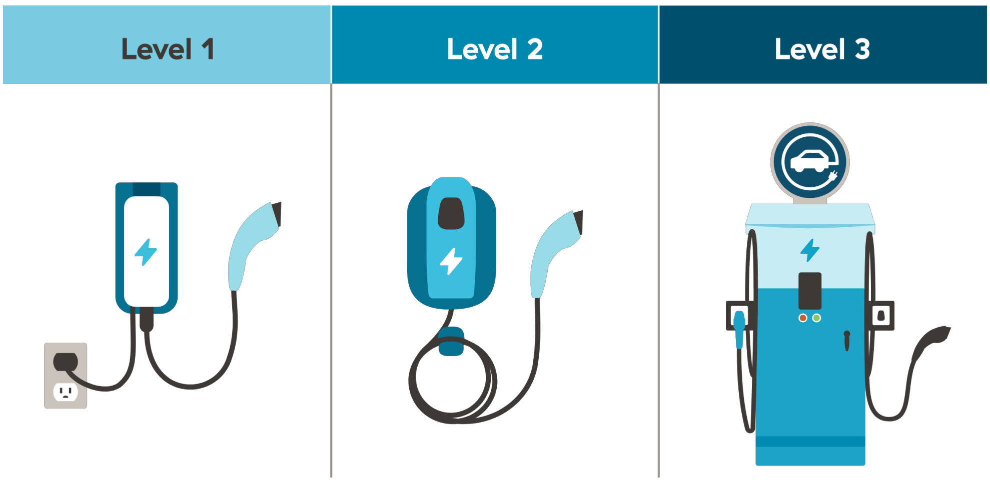


Figure 9: Charging levels and their configurations. Level 4 will look similar to the Level 3 figure only with a higher power [45].

3.6 Power flow

Power flow analysis is the most essential electrical network computation, as it allows insight into the steady-state behavior of the power system. Power flow analysis makes it possible to look at the distribution of current, voltage, and power flows at every bus in the system. To conduct a power flow analysis, input values about the network parameters and bus information are needed. There are three types of network buses, where each bus type only has two of four parameters known, as shown in Table 2.

Table 2: Overview of the different network bus types

bus type	Specified	Unknown
Slack	V, δ	P, Q
Generator bus (PV)	P, V	Q, δ
Load bus (PQ)	P, Q	V, δ

where V is the voltage magnitude, δ is the voltage angle, P is the active power, and Q is the reactive power. The slack bus is a necessary bus in a power system, which there is only one of. It serves as a reference for the other buses and is therefore often also called the reference bus. It is the only bus with voltage magnitude and angle specified, typically $1pu$ and $0°$.

The power flow computation is, in fact, the calculation of the voltage magnitude and angle at each bus of the power system under specified conditions of system operation. Other system quantities such as the current values, power values, and power losses can be calculated when the voltages are known. The power flow problem is nothing more than a system consisting of as many nonlinear equations as there are variables to be determined.

The following equations, obtained from [46] and [47], show the steps of how to obtain an equation to calculate power flow:

Net complex power injected to a bus i is defined as:

$$\overline{S_i} = \overline{V_i} * \overline{I_i} \tag{3}$$

where S_i represents complex power at bus i and I_i* represents the conjugate of the current at bus i. From Kirchoff's Current Law, KCL, it is stated that that current injected to a bus equals the sum of the currents flowing out from the bus. This means that I_i can be defined as:

$$\overline{I_i} = \sum_{j}^{n} \overline{V_i} * \overline{Y_{ij}} \tag{4}$$

where V_j is voltage at bus j and Y_{ij} represents tha admittance on the line ij. By putting (x) into (x) one gets:

$$\overline{S_i} = \overline{V_i} * (\sum_{j}^{n} \overline{V_j} * \overline{Y_{ij}}) = \sum_{j}^{n} |V_i||V_j||Y_{ij}|\angle(\delta_j - \delta_i - \theta_{ij}) \tag{5}$$

where δ_i represents the angle at bus i, δ_j represents the angle at bus j and θ_{ij} represents the angle of Y_{ij}. Furthermore one can now define active power, P, and reactive power, Q:

$$P_i = |S_i| * \cos(Im(S_i)) \ \ and \ \ Q_i = |S_i| * \sin(Im(S_i)) \tag{6}$$

where P_i and Q_i are the active power and reactive power at bus i, respectively. Put into (6) this gives the power flow equations at bus i, which are the fundamental equations when trying to solve the power flow problem [48].

$$P_i = \sum_{j}^{n} |V_i||V_j||Y_{ij}| \cos(\delta_j - \delta_i - \theta_{ij}) \tag{7}$$

$$Q_i = \sum_{j}^{n} |V_i||V_j||Y_{ij}| \sin(\delta_j - \delta_i - \theta_{ij}) \quad (8)$$

Newton-Rapshon Method

There are several ways of solving the power flow problem. One could solve the problem analytically. However, this tends to be rather time-consuming in situations with more than two buses, as one could get quite many equations. Another way of solving the problem is the Newton Raphson method. This is an iterative method whose goal is to find unknown angles and voltage magnitudes such that the power flow equations are similar to rated values. In the given power system, only two of four quantities are known for every bus. To find the remaining quantities in this thesis, are the Newton-Rapshon method used through the python package 'Pandapower,' with Equation 7 and Equation 8 [48].

3.7 Generating a normal load demand

In order to make a power system from scratch, are grid parameters, as well as loads and power input needed to give a realistic representation as possible. When normal loads are not given, they could be made or assumed. SINTEF Energy, have made a model which creates generic load demand over a time period [49]. Through their model, generic load profiles could be made for as much as 11 different end-user groups, such as Households, Agriculture, Schools, Retail shops, and more. The generic power demand curves are made from the following Equation 9:

$$P_{d,h} = A_{d,h}T_d + B_{d,h} \quad (9)$$

where the power demand $P_{d,h}$ for a day d at hour h is based on coefficients $A_{d,h}$ and $B_{d,h}$ and the inputted temperature T_d. The coefficients $A_{d,h}$ and $B_{d,h}$ differ throughout the hours h in a day d, with the day d being categorized as a weekday or weekend, with either high or low demand. The coefficients are made through this FASIT project.

In a bus, there may be several numbers of units in the different end-user categories. By multiplying the number of units of each category in each bus, one can create an aggregated load. To get as realistic aggregated load profile as possible, the load is scaled, as shown in Equation 10.

$$P_{d,h}^{end-user} = P_{d,h} \frac{W_{end-user}}{W_{general-profile}} \quad (10)$$

where $W_{end-user}$ is total actual energy demand for a year for all end-user groups. While $W_{general-profile}$ is the sum of the hourly load $P_{d,h}$ for a whole year.

The model for making generic load demand profiles is used in several other research studies. In [50] the generic load demand model was used to make a representable base load for a power system in Alvdal, Norway, in order to analyze the grid impact of implementing EV and HDEV FCSs. The model was also used in [44] to make a base load for the power system, in order to investigate the power quality of the system with different load cases.

4 System description

This chapter describes the system used for the simulations and research done in this thesis.

4.1 Power grid topology

In this thesis is a power flow model of a test grid based on preliminary work from CINELDI done. CINELDI is a research center for environmentally friendly energy, which works to develop the future electricity grid. The test grid is a basic power grid inspired by real-life Norwegian grids, made to work as a reference grid. It is a digital power grid that is representative of the real grid and made less robust such that changes in load demand and power generation do affect the grid [51].

An overview of the power grid topology is presented in Figure 10. There are a total of 124 buses in this grid, where the external grid or main feeder, *MF* marker in the figure, is connected to bus 1. Some buses have branches with more buses connected, while others do not. All of the buses contain aggregated loads, with some buses containing more loads than others.

All of the 124 buses contain houses connected to them, and there are a total of 2223 houses in the whole power system. In addition to houses, some buses also contain other forms for loads, as can be seen in the Figure 10 with the different color marks:

- There are a total of 11 offices located in the buses marked in red (bus 73, 49, 55, 6, 105, 103, 46, 111, 120, 32). These buses contain 1 office - except for bus 73 which contains 2 offices.
- There are also included two electric charging stations in this power grid, located in the buses marked green (bus 48, 78). In bus 48, there is a charging station for HDEVs, while in bus 78, there is a charging station for regular EVs.
- An electric ferry, which is charged with direct shore power, is also included in the grid, located in the bus marked in yellow (bus 111). Worth noting is that bus 111 contains both a ferry, an office, and houses.

The preliminary work received from CINELDI was a basic dataset containing a snapshot of grid specifications and power flow, not over a time series. Therefore in this thesis are, a power flow time series model made for this power system, with additional assumptions and limitations, to analyze the power flow of the power system over time.

In addition to the specified loads and inputs to the power system were several other additions made to the system:

- **EV charging** - Each house were assigned one EV. Specifications for the EVs differ as there are ten different EV models in the power system. A more detailed explanation is given in the next subsection. Three different EV charging cases are initially made, which differ in charging period and charging power.
- **Solar PV panels** - Each house and office are assigned a specific number of PV panels. There is also added a solar PV park to bus 65 at a later case.
- **Reactive power support** - FCSs, ferry, and EV charging are all set to produce reactive power to the grid during their load periods.
- **Battery energy storage system (BESS)** - A BESS is added to the HDEV FCS in bus 48, as an extra case.

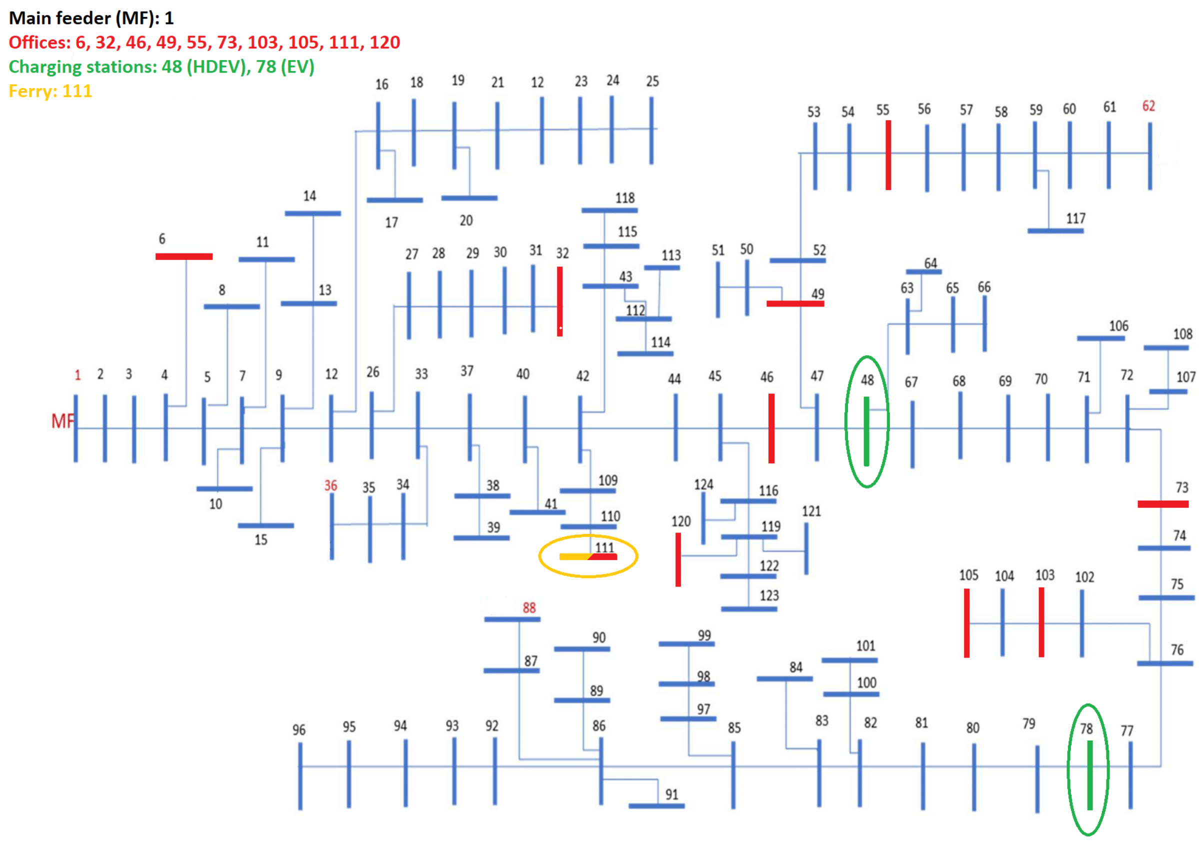


Figure 10: Topology of the power grid

4.2 EV models - Home charging

In order to showcase the most realistic charging behavior for an EV as possible, actual data from some of the top 10 most common EVs in Norway in 2019 is used, inspired by work done in [52]. The EV models used in this thesis, with their different specifications, are presented in Table 3. Each EV has a given battery size, maximum charging power, consumption, and percentage, which shows the adjusted market share of the top 10 EVs in 2019. Tesla is also a popular EV in Norway, but it was dropped from the top 10 list and dropped from this thesis due to its charging network. The number of each EV models in each bus is decided by the number of houses in that bus. For example, if there are 100 houses in a bus, there are 34 Nissan Leafs as the model stands for 34% of the market share.

Table 3: Overview of the different EV models used in this project, with specifications of the different models. These were the top 10 most common EVs in Norway, and the percentage-column describes how many percents of the top ten list were the given models.

Model type	**Battery size [kWh]**	**Max charging power [kW]**	**Consumption [kWh/km]**	**Percentage [%]**
Nissan Leaf	40	50	0.164	34
Volkswagen e-Golf	35.8	40	0.168	23
BMW i3	33	50	0.16	14
Kia Soul	42	50	0.171	10
Volkswagen Up!	18.7	40	0.168	5
Hyundai Ioniq	30.5	69	0.144	5
Nissan E-nv200	40	46	0.2	3
Mitsubishi I-miev	16	40	0.161	2
Jaguar I-pace	90	100	0.229	2
Audi E-tron	95	150	0.232	2

5 Methodology

In the following section, a detailed description of the methodology in the thesis is presented. First, the modelling of the grid and making time-series calculations are described before an overview of the load cases and load combinations are given. Then all of the different types of loads and power production will be described. Lastly, the making of the three additional measures and a combination of these are described.

5.1 Modeling the grid

The power system used in this thesis is described in section 4. The power system is based on a reference power grid made by CINELDI. To conduct power flow analysis in Python, a package called 'Pandapower' were used. Pandapower is a simple power system calculation-based python-package for power system analysis [53]. To conduct power flow analysis of a power system, the power grid with its specifications need to be created. In this thesis, the power grid representation was created in pandapower. This was done by inputting specifications for the power grid, such as specifying data for the buses, lines, and more. For this thesis, the power grid specifications received from CINELDI were given in a data set in a 'matpower' format, which is a power flow calculations package in Matlab. In order to meet pandapower requirements, some of the data sets had to be modified to have the correct designations. For further explanation about modelling a grid in pandapower, the reader is referred to its documentation [53].

5.2 Timeseries

A time series loop is needed to analyze the power flow over a certain amount of time. In pandapower there is a module called timeseries, which does Newton-Rapshon power flow calculations for each time step. This gives an overview of how the power system performs over the given time series. The time series module takes in the modeled grid and the chosen load combination. A flowchart of the time series module is presented in Figure 11.

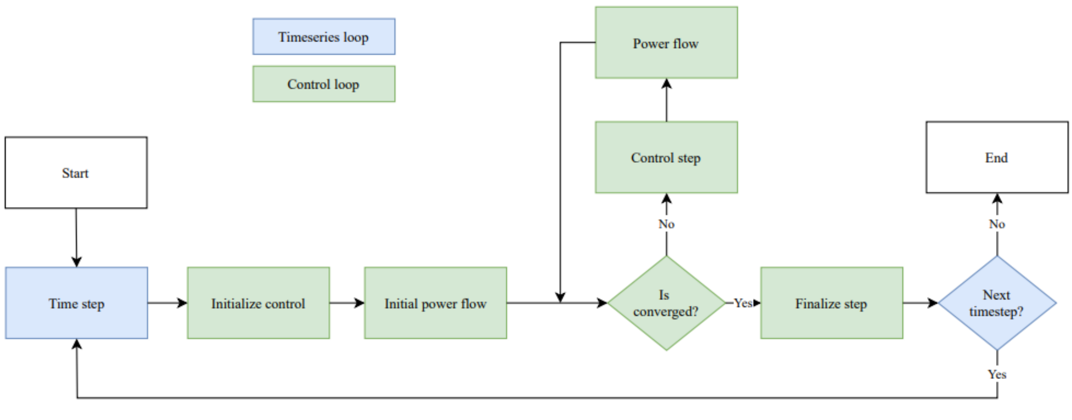


Figure 11: Flowchart of the time series module in pandapower [44] [54]

The output of the timeseries module is then power flow analysis of the system for each time step, which for this thesis is for 15 min intervals for one day(24 hours), meaning there are 96-time steps in total. The resulting output of the power flow analysis is load demand per bus, total load demand in the system, power production in the buses, reactive load consumption and production in each bus, voltage magnitudes at the buses, and more.

5.3 Overview of the modeled loads & cases

The purpose of this thesis is to analyze the impact of EV charging in a modern power grid and analyze some measures to support the power system with the EV charging impact. Therefore, several different load profiles are made to analyze the impact of different load demands at different time steps.

This thesis is based on a Norwegian representative power grid. Norway has significant variations in load demand throughout the year due to a considerable variation in climatic conditions. There is usually a higher load demand during the winter, while there is a lower load demand during the summer. In order to get a comprehensive analysis of how the power system performs throughout the year, are two different load demand scenarios made: a high demand scenario (HI) and a low demand scenario (LOW).

Each case in this thesis will be investigated for both load demand scenarios. Furthermore, each case will have its unique combination of loads and power. In Figure 12 is a simple overview of the combination steps shown.

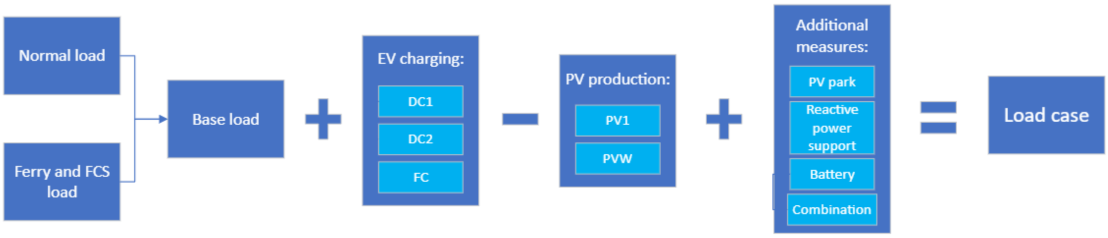


Figure 12: An overview of the making of each load case

A base case is first made to serve as a reference case to understand the impact of the EV loads and the additional measures. This base case is the base loads for the power system before any EV load, or other additions are made. As can be seen in the grid topology in Figure 10, the grid consists of 2223 houses, 10 offices, 1 electric ferry, 1 EV FCS, and 1 HDEV FCS. The base case consists of load profiles for the normal load from the houses and the offices, a load profile for the two FCSs, and the load profile for the ferry. In short terms, the base load is equal to the normal load plus FCSs & ferry loads.

Each load case is made to have its load profile or load curve, consisting of a load profile sum of the chosen load combination. The load profiles are made by making a summed load profile for each bus in the given case. Starting with the base load of the bus, which is standard for all cases and only differs between the two demand scenarios. Then the chosen EV load in the bus is added before PV production in the bus is subtracted from the summed bus load profile. These steps are repeated for each bus in the system. The steps are shown in the following Equation 11:

$$\text{SumLoad}_{\text{bus}}^{\text{case}} = \text{BaseLoad}_{\text{bus}}^{\text{Scenario}} + \text{EVcharging}_{\text{bus}}^{\text{EVcase}} - \text{PVproduction}_{\text{bus}}^{\text{Scenario}} \tag{11}$$

where $BaseLoad_{Scenario}$ is the normal load in the given bus for the chosen demand scenario, plus for bus 48, 78, and 11 are load from FCSs and ferry added. $Evcharging_{EVcase}$ is the load from the chosen EV charging case in the given bus, and $PVproduction_{PVcase}$ is the PV production in the given bus, only making an impact during the LOW scenario as it is set as 0 MW during the HI scenario.

These calculations are done on each of the buses in the system. When the summed load in all buses are calculated, are the load in all buses are summed together to give an total load curve for each case, as shown in Equation 12. Meaning that one now have one total load curve in the system for the chosen load case.

$$\text{TotalLoad}^{\text{case}} = \sum \text{SumLoad}_{\text{bus}}^{\text{case}} \tag{12}$$

where $SumLoad_{bus}^{case}$ are calculated through Equation 11 for all buses.

For the cases with additional measures, are the steps above repeated, only with implementing the measures to the loads and cases. A further and more detailed overview of each load case, with what load combinations are added together in the different cases, are shown in Table 4.

Table 4: Overview of the cases with their different load inputs and combinations. The additional lines all have a * at the mark under EV charging, this is to highlight that for all these measures all three of the EV charging cases (Dumb1, Dumb2, Flat) are analyzed one at a time.

Case	Load demand scenario	Normal load	FCS & Ferry	EV charging	PV	Reactive injection	Battery (HIEV FCS)
Base case	LOW	X	X				
	HI	X	X				
Dumb1	LOW	X	X	X	X		
	HI	X	X	X			
Dumb2	LOW	X	X	X	X		
	HI	X	X	X			
Flat	LOW	X	X	X	X		
	HI	X	X	X			
PV park	LOW	X	X	X*	X (PV2)		
	HI	X	X	X*			
Reactive power support	LOW	X	X	X*	X	X	
	HI	X	X	X*		X	
Battery	LOW	X	X	X*	X		X
	HI	X	X	X*			X
Combination of measures	LOW	X	X	X*	X (PV2)	X	X
	HI	X	X	X*		X	X

5.4 Modeling normal load

In addition to specifying grid parameters, loads in the system are also an input needed to be specified to make the power flow analysis. This thesis is about how different loads affect a power system, meaning that load profiles will differ from case to case. However, there is an aggregated load in each of the buses in all cases, called normal load. This load is the same for all cases and only differs in scenario type, i.e., there is one normal load for the LOW scenario and one for the HI.

The given data set with the power system information was insufficient for this thesis because the data set lacked some load inputs. Some of the buses contained load values, but not everyone, as some of the buses were set to have a load demand of 0 MW. There was neither any information about the load nor what was creating the loads, houses, offices, etc. Therefore, it was made an assumption to calculate a normal load for each of the buses and then divide them into two different load categories, and a number of that load category in the different buses. Therefore, loads for the buses that initially had 0 MW load were made by finding the median value of the given load values. Meaning that for all buses where the load initially was 0 MW, there was now a load demand equal to the median value of the loads which were given, which was 0.077638 MW.

The load demand of each bus was assumed to be the average load demand over one day (24h) for the worst scenario, i.e. HI scenario. Now each of the buses had an aggregated average load, the next step was to divide them into load categories, which for this thesis were done by categorizing all of the buses into either Offices or Households. All the buses with values over 0.21 MW were set as having offices, while the rest were set only to have households. The number 0.21 were chosen as this would give an almost equal split in total load demand between the households and the offices.

The next step was to calculate the number of houses and offices in each of the buses and then make a load demand for each of the buses over a given time. This was done by generating generic demand profiles developed by SINTEF Energy Research, described in section 3.

To find out how many houses are in each bus, a generic load demand profile for one house is made, then another load demand for another house is added to the load demand for the first house. This repeats itself until the average load of the load demand of the bus equals, or as close as possible, to the average load given from the CINELDI input data. The same procedure is repeated for the offices, but here one office has a much higher load profile than one household. Therefore, all the office buses only have one office except for bus 73, which has two. In order to come as close to the given average load for the buses given in the CINELDI input data, are houses added in addition to the office. This results in a power system where all buses have households connected to them, and a few of the buses also have offices.

As described earlier, two different load scenarios are made, one HI and one LOW scenario. Therefore, the procedure above is only the case for the normal load for the worst load demand scenario, the HI scenario. With information about the number of houses and offices in each bus, it is possible to generate a load profile for the buses with the LOW scenario. This is done by following the steps of the original generic load demand model made by SINTEF, as described in subsection 5.4: Multiplying the number of units of each category in each bus with the load demand profile made for one. To get an as realistic aggregated load as possible, the load is scaled, as shown in Equation 10.

There is now a load demand profile over a whole day (24h) for each of the buses, which can also be summed together to look at the whole load demand as one curve. This is done for both load demand scenarios.

5.4.1 Making reactive load

A representative reactive load is made in relation to the active load. This is done by first finding the PF of the buses, which is given in the data set as 0.95 leading. With now knowing the PF for each bus, it is now possible to calculate the reactive load in each bus by using Equation 2, with the base load for each bus being the inputted P to the equation.

5.5 Modelling the FCSs and ferry loads

The expressed plan for the reference system grid, as can be read more about in [51], is to have two charging stations connected to the system, as well as an electric ferry. However, the received data set were missing load data for these load inputs. Therefore, load profiles for the two charging stations and the ferry were created and added to the system in the assigned buses.

5.5.1 Fast charging stations

Load profiles from charging stations are made from a simulation model made by K.K. Fjær for his master thesis [50]. From his model was a load profile for one HDEV FCS and one from normal EV FCS gathered. A more detailed description of his work is given in section 3. For a more detailed explanation, the reader is referred to [50] and [55]. The load profile for the HDEV FCS was added to bus 48, while the load profile for the EV FCS was added to bus 78, as seen in section 4

5.5.2 Electric ferry

Taken inspiration from a report by the Norwegian Public Roads Administration about energy-efficient and climate-friendly ferry operations [56], are a load profile for an electric ferry made. The ferry in question is a fully electric battery ferry charged with shore power. It is a battery-driven aluminum-made ferry with the capability of 70 passenger cars. In Table 5 is the specifications for the ferry presented, taking inspiration from the report.

The ferry's battery is modified from having a capacity of 1000 kWh in the report to 500 KWh in this thesis. This is done for the sake of simplicity when creating the load profile, such that if the ferry is charged at a charging rate of 2000 kW for 15 minutes, the battery will be fully charged. This is shown in the following calculation:

Table 5: Specifications for the electric ferry

Ferry type	Capability	Max speed	Range at max speed	Battery capacity	Battery max charging / discharging rate
Aluminium made battery ferry	70 cars	10 knots	14 km	500 kWh	2000 kW

$$\text{Battery}_{\text{Cap}} = \text{Battery}_{\text{ChargingRate}} * \text{TimeInterval} = 2000\text{kW} * 0.25\text{h} = 500\text{kWh} \tag{13}$$

From the specifications is a fictive ferry crossing made, based on an example of an electric ferry crossing from the [56]. The fictive ferry is set to cross between two fictive places, Aadnøy and Korpås. The distance of one crossover is 6.8 km, meaning that a round trip is equal to 13.6 km, 0.4 km underneath the driving range limit of the ferry at max speed. Meaning that the ferry needs to be charged after each round trip. One crossover takes around 22 minutes, but combined with on and offloading is one crossover assumed to take 30 minutes. The charging is set to happen at Aadnøy after each roundtrip. Here the battery is put to be fully charged in a maximum of 15 minutes. The ferry is set to have a total of 32 crossovers a day, with the ferry driving non-stop, except for when it is charging, during a lunch break, and a longer break during the night. A complete timetable of the fictive ferry, with charging time, is presented in Table 6. As seen in the figure, the battery is slowly charged during the lunch break and night break, which means the battery is charging at a lower power rate than normal during the whole break period. When the break is over, the battery shall be fully loaded.

Table 6: Timetable for the fictive electric ferry, which crosses between the fictive places Aadnøy and Korpås. Charging, marked in orange, happens at Aadnøy right after arrival from Korpås, so that the ferry is fully charged when departing Aadnøy

Time	Departing from	11:45	Korpås	18:45	Korpås
05:00	Aadnøy	12:15	BREAK - Slow charging	19:15	Charging
05:30	Korpås	12:45	BREAK - Slow charging	19:30	Aadnøy
06:00	Charging	13:15	Aadnøy	20:00	Korpås
06:15	Aadnøy	13:45	Korpås	20:30	Charging
06:45	Korpås	07:15	Charging	20:45	Aadnøy
07:15	Charging	14:30	Aadnøy	21:15	Korpås
07:30	Aadnøy	15:00	Korpås	21:45	Charging
08:00	Korpås	15:00	Korpås	22:00	Aadnøy
08:30	Charging	15:30	Charging	22:30	Korpås
08:45	Aadnøy	15:45	Aadnøy	23:00	Charging
09:15	Korpås	16:15	Korpås	23:15	Aadnøy
09:45	Charging	16:45	Charging	23:45	Korpås
10:00	Aadnøy	17:00	Aadnøy	00:15	Charging
10:30	Korpås	17:30	Korpås	00:30	Aadnøy
11:00	Charging	18:00	Charging	01:00	Korpås
11:15	Aadnøy	18.15	Aadnøy	01:30-05	BREAK - Slow charging

Based on this timetable was a load profile for the electric ferry made, which charges at the times marked charging in the Table 6 at a rate of 2000 kW for 15 minutes. The charging power during the breaks was calculated by taking the needed capacity of 2000 kW and dividing it by number of 15 minutes intervals in the given break.

5.6 Modelling PV production

To reduce load demand in the power system and help the buses' voltage stability are, local power production from solar PV panels introduced. As described in section 4, there are a total of 2223 houses and 11 offices spread between the buses. In this thesis are all of these houses and offices assigned PV production. This production is modelled by each end-user category (house or office) being assigned a specific number of PV panels. Through the website *www.renewables.ninja* are assumed power production from solar PV panels gathered for a chosen location. "Renewables Ninja" is a tool that estimates the amount of energy over time generated by wind or solar plants at an inputted location worldwide. The location chosen in this thesis is a place called Hommersåk, in southwest Norway. This place is chosen because its surroundings match the power grid topology, with the possibility of being a ferry and FCSs around this area. As well as, solar PV production is more favorable in the south of Norway due to better climatic conditions for PV production there than further north in the country.

Each solar PV panel installed is the same standard model, with one panel having a capacity factor (kwp) of 0.25. To separate the two end-user categories from each other is the chosen approach is that they all are assigned to have a different number of PV panels installed. Each of the houses in the system are assigned 6 PV panels, while each of the offices are assigned 100 PV panels. Due to difficulties finding good and relevant sources, the number of PV panels in each category is assumed. A reason for these difficulties is that for each of these categories, building type and size will always differ from another one, as well as the cost and utility of PV panels influencing installation size. Therefore, as these numbers are assumptions, it is crucial to be a bit critical of these assumptions.

Each PV panel will have the same power profile, and because all houses have six panels, all houses will have that same power profile. The same goes for offices, with each office having 100 panels. However, each bus has a different number of houses or offices and will differ from each other. Due to the power profile for one bus being the sum of the power profiles for all houses and offices in the bus, as shown in the following Equation 14:

$$\mathrm{P_{Bus}} = (\mathrm{P_{House}} * \mathrm{Nr.Houses_{Bus}}) + (\mathrm{P_{Office}} * \mathrm{Nr.Offices_{Bus}}) \tag{14}$$

where P_{Bus} is the power profile of the bus, $Nr.Houses_{Bus}$ and $Nr.Offices_{Bus}$ is the number of houses and offices in the given bus, and P_{House} and P_{Office} is the power profile for one house and one office calculated by the following Equation 15 and Equation 16:

$$\mathrm{P_{House}} = (\mathrm{P_{Panel}}) * 6 \tag{15}$$

$$\mathrm{P_{Office}} = (P_{Panel}) * 100 \tag{16}$$

where P_{Panel} is the power profile of one PV panel. 6 and 100 are the number of PV panels for one house and one office.

As described above, two different load scenarios are defined: LOW in the summer and HI in the winter. These scenarios also affect the PV production as solar PV panels' power output in southwest Norway is very low during the winter. Hence, for simplicity, the production during the winter is set as 0 during the whole day. Therefore the solar PV production cases will only impact the LOW scenario.

Further in the thesis, PV production from households and offices for the LOW scenario will be defined as PV1, while PV production during the HI scenario is defined as PVW.

5.7 EV home charging

In order to analyze the impact of EV charging in a power system are, three different charging cases through 2 different approaches conducted. The first approach is called *Dumb-charging* and the second approach is called *Flat-charging.* These approaches fall in reality under the category of dumb-charging, with both charging throughout the day except during work hours 08:00 - 16:00. Neither of the methods considers pricing or impact on the grid in choosing when to charge. Which, in reality, could be unfavorable for both the end-user and the grid operator, hence the name dumb-charging.

In the following Table 7 are the different EV cases shortly described to give an overview of the different cases before they are further described in the coming subsections.

Table 7: Overview of the different cases

EV - charging case	**Home charging**	**Charging speed**	**Note**
Dumb charging 1 - Dumb1	100 %	3.1 kW	All EVs starts to charge at 16:00, and charges until fully charged.
Dumb charging 2 - Dumb2	100%	3.1 kW	Randomized charging outside the working hours
Flat charging - Flat	100 %	Calcutlated	Low-power charging over longer time, hence the name Flat-charging

For all the EV home charging cases created, some assumptions were made: Taking inspiration from the work done in [57] , all EV models are set to have driven $35.6\frac{km}{day}$ when they start to charge. For simplicities sake, the time-consuming differences between charging an EV battery up to 80% and the final 80-100 % were not considered in this thesis. Another assumption inspired from [57] is the charging speed, i.e., magnitude of the charging power, which is put as a standard charging speed for all EV models. It is set to be $3.1kW$ as it is in [57], where it's claimed to be the average speed in Norway in 2015.

Having a standard daily driving distance for all the models makes it possible to calculate how much power is used to drive the driving distance. This tells us how much power the different models need to be charged to reach a fully charged battery again. This was done with Equation 17.

$$\text{Charging}_{\text{model}}[\text{kWh}] = \text{Consumption}_{\text{model}}[\frac{\text{kWh}}{\text{km}}] * 35.6[\text{km}] \tag{17}$$

where $Consumption_{model}$, the consumption for the different model-type, is gathered from Table 3, and $35.6km$ is the daily driven distance as described above.

Now the power needed to charge the EVs to full capacity again is calculated, then the next step is to find out how long time each of the EV models needs to charge to cover the required power, which is done with Equation 18

$$\text{ChargingTime}_{\text{model}}[\text{h}] = \frac{\text{Charging}_{\text{model}}[\text{kWh}]}{3.1[\text{kW}]} \tag{18}$$

where $Charging_{model}$ is calculated in Equation 17, and the $3.1[kW]$ is set as a standard charging speed as described above. The charging time is rounded to the closest whole hour for simplicity's sake.

5.7.1 Dumb Charging

The first charging approach is called dumb charging, where the charging takes place **outside** of the working hours 08-16. For the dumb charge approach, there are made two different cases:

1. **Dumb charge 1 (Dumb1)**

   In Dumb1, the EVs are set to start charging once they get home from work, i.e., all cars begin to charge at 16:00 at a given power rate and charge until they are fully charged. The needed charging power and time to charge the needed power were calculated through respectively Equation 17 and Equation 18. This would give out a significant load demand in the few hours the EVs charge but zero in the remaining hours.

2. **Dumb charge 2 (Dumb2)**

   In Dumb2, the EVs are randomly placed to charge during the possible charging hours. Each EV in each bus is randomly set to start charging throughout the possible charging hours between 16:00 to 08:00. However, the charging needs to be done by 08:00. If this is not the case, then the charging start for the given EV is randomized again until it gets an approved charging start and time. Also, here the needed charging power and charging time of the different EV models were calculated through Equation 17 and Equation 18. It is essential to add that the randomization in Dumb2 only happens once, which means that the charge-time values are the same for every case of Dumb2.

5.7.2 Flat charging (Flat)

The second approach is named flat charging, shortened to Flat. The Flat approach could, in theory, also be categorized as a dumb charging method. However, the difference from the other dumb-charging approach is that all the EVs will constantly charge throughout the day, except for the working hours 08-16. This means that the EVs will have a continuous flat charging line at a constant low power during the charging hours, hence the name flat-charging. In this approach, the needed power is also calculated through Equation 17, but here the charging time is known, as all cars will charge from 16:00 - 08:00, i.e., 16 hours. The missing parameter here is the power of the charging speed, which was $3.1kW$ in the other approach. To find what power magnitude the different EV models need to charge at to charge constantly for 16 hours, the Equation 18 is changed. This is done to get the output of charging speed and not charging time. The new equation used for Flat is shown in Equation 19.

$$\text{ChargingPower}_{\text{model}}[\text{kW}] = \frac{\text{Charging}_{\text{model}}[\text{kWh}}{\text{ChargingHours}[\text{h}]} \tag{19}$$

where $Charging_{model}$ is calculated in Equation 17 and the $ChargingHours$ is the number of hours the EV will be charging.

5.8 Making additional measures

After the EV cases are made and analyzed, additional measures are added to the cases to analyze the system's performance with this combination. The following subsections will give a detailed description of how each measure is made.

5.8.1 PV park

The first measure is adding a PV park to the power system. This is done in addition to solar PV production from rooftops of households and offices in the system (PV1). In this measure are a solar PV park added to bus 65. The reason for the chosen location for the PV park is because of the expressed desire to add local energy communities (LEC) to some of the buses in the system, including bus 65. This can be read further about in a SINTEF blog [51]. Bus 65 was randomly chosen ahead of the other planned LEC buses.

The objective of this measure was to add a local power production that would make a significant impact on the load demand in the system and, indirectly, the voltage stability. Therefore were, a PV park with a rated power production of close to 5 MW chosen. This measure is built in the same way as the PV1 production described in subsection 5.6. Because of how the PV production model is built, a choice to insert a high number of PV panels and then get a power output magnitude was taken instead of inserting a certain rated power level. Resulting in defining the PV park to consist of 15000 PV panels, which gave a rated power of around 4.67 MW, just below 5 MW, enough to make a significant impact.

From before are PV1, and PVW defined, see subsection 5.6, now PV2 production will be defined. PV2 is equal to the PV1 production plus the production from the PV park. These abbreviations are made to make it easier to distinguish between them.

5.8.2 Reactive power support

The second additional measure added to the EV charging cases is reactive power support. In the other cases, reactive power in the system is calculated as a reactive load from the normal load due to the normal load having a 0.95 leading PF. This measure, reactive power support, means that reactive power is produced and injected into the system as a direct measure to support the voltage stability. The reactive power is set to be produced from the FCSs & ferry, in correlation to their load curves, and has the same value for all cases. In addition, are all (home charging) EVs set to deliver reactive power to the grid during their charging period. Here the reactive power support will vary between the different charging cases, as they have different charging power and charging hours. There are a total of 6 cases with this measure, as it is done for all three EV cases for both load demand scenarios.

The reactive power support is calculated by the Equation 2, with setting the PF of the FCSs & ferry and the EV case as 0.95 lagging, as this would result in support of reactive power to the grid. The reactive power is calculated individually first for the FCSs & ferry, calculating the reactive power injection for each bus. The power input to each calculation is the FCSs & ferry load demand for each bus. The same is done for the EV cases. Total reactive power support is the sum of reactive power from the FCSs & ferry and the chosen EV case.

5.8.3 Battery Energy Storage System

The third measure is to insert a battery energy storage system (BESS) at the HDEV FCS. The HDEV FCS was chosen as the place to locate the BESS, as this had the highest load peaks between the two FCSs and the ferry. Inserting a BESS to this FCS would help dampen the load demand in critical hours for the grid by load shifting, i.e. moving the load to other time steps. Inserting a BESS at the HDEV FCS will impact the load profile for the HDEV FCS in the way that the load peaks will be dampened, and the removed load demand will then be inserted at another time step. Shortly explained: the load profile of the HDEV FCS will be changed with the BESS implementation.

For this measure, two different BESS are added, one small BESS and one large BESS, with only one of the batteries being implemented at a time. This is first to analyze how a small BESS affects the power quality and then compare it with the power quality analysis of a large BESS. The small BESS is set only to step in and deliver power to the HDEV FCS at load levels larger than 2.4 MW, while the large BESS steps in at load levels higher than 1.2 MW. The batteries are made so that they step in for levels higher than their limit, such that the load demand for the HDEV FCS will at that interception time step be equal to this limit. In other words, the limit of the chosen BESS is the maximum load peak of the HDEV FCS. Another reason for analyzing the impact of two batteries that differ in size is to analyze the cost versus utility between the BESS. Small batteries are often cheaper than large batteries, but larger batteries can make a more significant impact. An overview of the specifications of the batteries is given in Table 8. Worth noting is that these are made in a simple way, in a real world scenario would specifications such as SOC limits and charging/discharging efficiency need to be defined, this is excluded in this thesis as the batteries are only made as an addition to the main objective.

Table 8: Specifications for the two different batteries in the BESS at the HDEV FCS.

BESS size	Capacity	Max charge/discharge rate	Limit
Small	0.3 MWh	1.2 MW	2.4 MW
Large	6.0 MWh	2.4 MW	1.2 MW

The BESS is set to start the day, at 00:00, with an empty capacity, i.e., it needs to be charged. With the BESS being a very flexible load, the charging of the BESS is set to happen when there is no-load demand from the HDEV FCS. In addition, is it not possible to charge the BESS between 15-18:30 due to these being critical hours for the grid.

5.8.4 Combination of measures

Up until now have, three additional measures been made to investigate how this would help the grid integration of EVs. In order to analyze how a combination of the measures would affect the power system is, a combination of measure cases made. This is done by inserting all the measures into the three EV charging cases. The BESS size chosen here is the large BESS, as the objective of the combined measure is to better the power quality, especially the voltage stability, as much as possible with the presented measures. Therefore are a combination of the following measures made:

- **PV park** with 15000 PV panels installed at bus 65
- **Reactive power support** from FCSs & ferry and EVs
- **Large BESS** at the HDEV FCS

Worth noting is that when the BESS is inserted at the HDEV FCS, this will impact the load profile of the HDEV FCS, which further then impacts the reactive power support from this FCS.

6 Results: Loads and Generation

In this section are all of the loads individually presented and described. This is done to get an overview of the loads and their individual load profiles before they are combined and analyzed as cases in the next section.

6.1 Normal load

The normal load profile represents the summed normal loads from all the different buses, which all differ in magnitude due to the type of load, household or office, and the number of that type of load in the bus. The normal load for each bus was created stepwise as described in subsection 5.4, with a model made by SINTEF as described in subsection 3.7.

The Figure 13 showcases the normal loads for the HI scenario in blue color and for the LOW scenario in orange color. Worth noting is that the HI scenario has a load demand curve almost twice the size of the LOW scenario. Both curves have a lower load demand at night, from around 23:00 to 6:00. While the rest of the day, the curves behave almost like a continuous line, with relatively minor deviations.

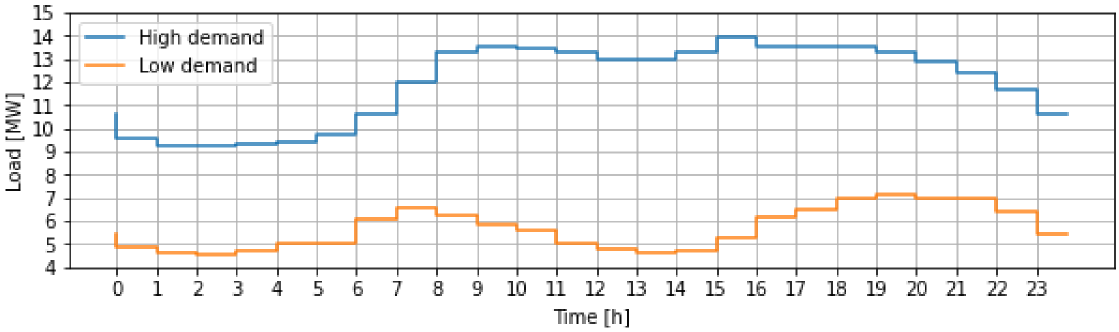


Figure 13: Normal load curve for the high load demand (HI) scenario, in blue color and low load demand (LOW) scenario, in orange color

6.2 Fast charging stations & electric ferry

In addition to normal load, there are also added loads from charging stations and an electric ferry, which are connected to the power system as described in section 5.

The load curves for the FCSs and ferry loads are shown in the top figure in Figure 14 where the blue curve represents the load curve for the HDEV FCS, the orange one for EV FCS, and the green curve for the electric ferry charging.

The lower figure in Figure 14 presents a combined load curve for the FCSs % ferry load. The curve clearly shows that there may be large load demand deviations from one time step to the next. During some time steps, the load curve is zero, while during some time steps, the load is rather high, such as at 16:30 and 17:45, where the combined load demand exceeds 5 MW.

The base load in this thesis is a load profile consisting of the normal loads in combination with the load curves for the FCSs and ferry. This is presented in the next section section 7.

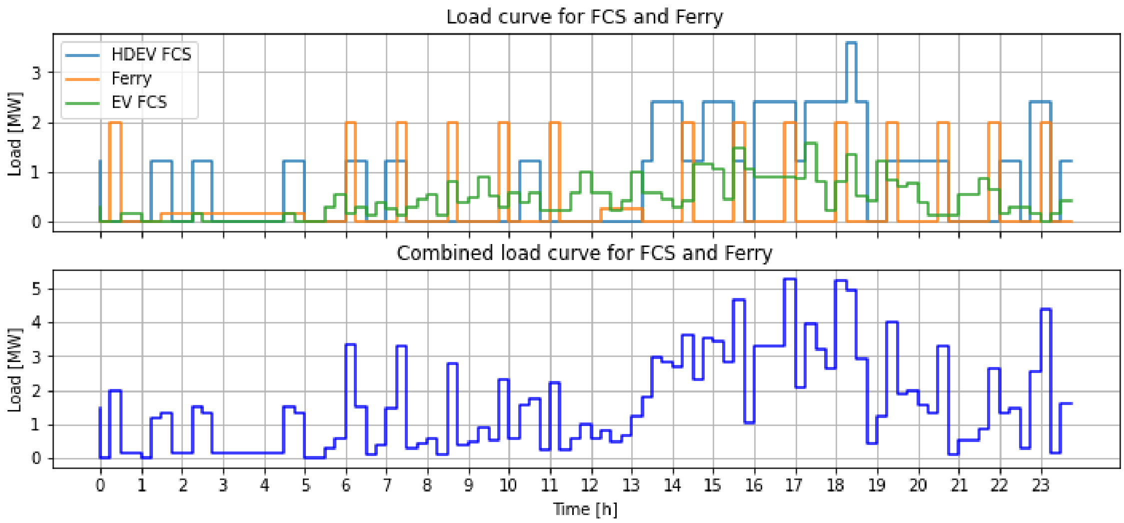


Figure 14: Load curves the two different charging stations for HDEVs and EVs, and for the ferry charging. As well as a combined load curves for the two charging stations and the ferry charging

6.3 PV power production

The power curves from the different solar power production cases are shown in Figure 15, where the red curve represents PV1, the blue PV2, the green PVW, and the light-blue represents the load profile of the PV park. The power curves show how much power is produced during different time steps throughout the day. The power curve of PV1 shows the total production from when all the houses in the system have solar PV panels on their roof producing power. While the PV2 is a combination of PV1 and a PV park, consisting of 15000 PV panels giving a total of almost 5 MW rated power at the most. From the figure, it is clear that the power production corresponds to the sun's behavior during the day. Production slowly increases from sunrise until the middle of the day (12:00-13:00), when the sun is at its highest, and thereby the production hits its peak. The power peak of PV1 is a bit below 1.75 MW, while the PV2 has a power peak of almost 4 MW higher than PV1, at around 6.3 MW. From the sun peak and power peak in the middle of the day, the production slowly decreases until sunrise. During the night, when there is no sun, the production equals 0 MW. For the PVW case, power production is 0 MW during the whole day, as described in section 5.

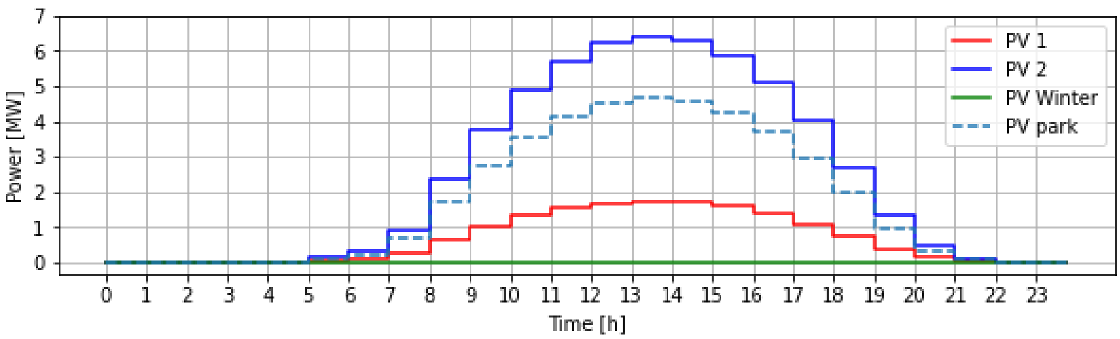


Figure 15: Power curves for the different solar power production cases

6.4 EV home charging

The load curves for the different EV home charging cases are shown in Figure 16. The blue curve shows the load demand for the Flat case, the orange shows the Dumb1, while the green shows the Dumb2. The differences between the cases can be seen in the figure, with the Dumb1 case having 0 load demand during the whole day except from 16-18/19, where the peak is above 6 MW, a lot higher than the load demand peak any of the other cases. The flat charge case (Flat) has, as the name implies, a flat charging curve throughout the day at 0.823 MW, except for during working hours. The randomized case Dumb2can be seen to be almost equal to the slow charging Flat case, with slight deviations throughout the charging hours.

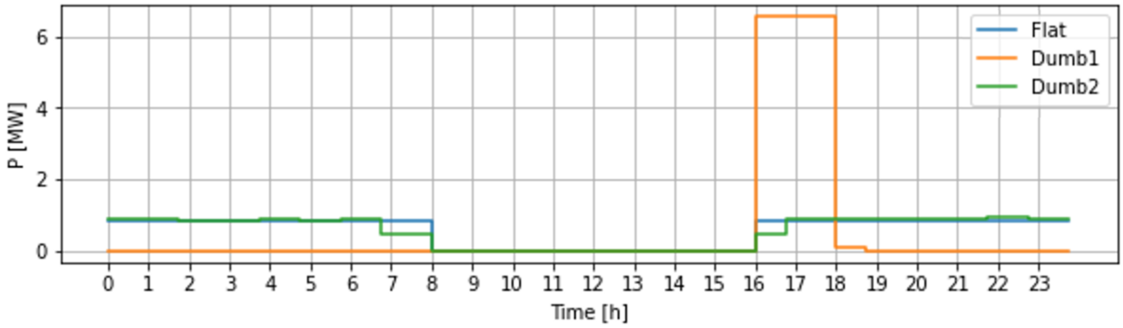


Figure 16: EV home charging: Flat in blue colour, Dumb1 in orange and Dumb2in green.See subsection 5.7 for labelling.

A close-up of the two flexible charging cases, Flat and Dumb2, are presented in Figure 17. Here the differences between these two cases are shown with the Flat being a constant flat charging curve throughout the charging period, while the Dumb2being a randomized curve, made from randomizing charging in each of the buses and then summed together.

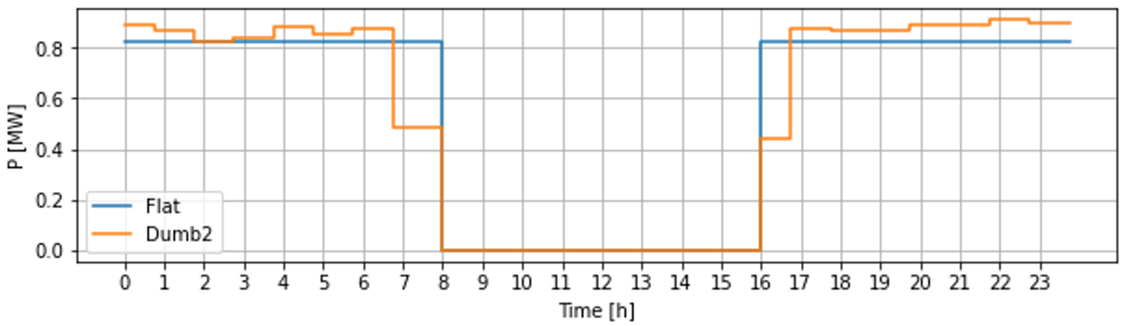


Figure 17: Close up on the load curves for the EV home charging Dumb2 and Flat. See subsection 5.7 for labelling.

Flat - EV models

For the flat-charging (Flat) case, the charging curves of the different EV models were first calculated, as shown in Figure 18. Then these load curves were split accordingly into the different buses to the number of EVs in the system. The total Flat charging load curve for all EV models summed is shown in Figure 16.

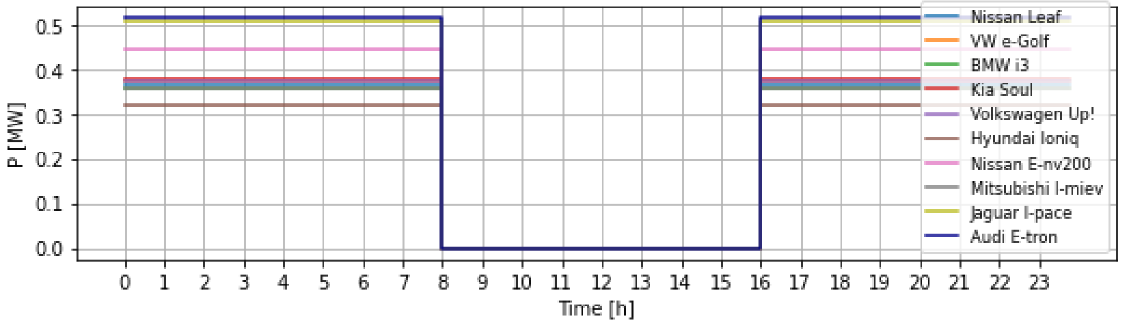
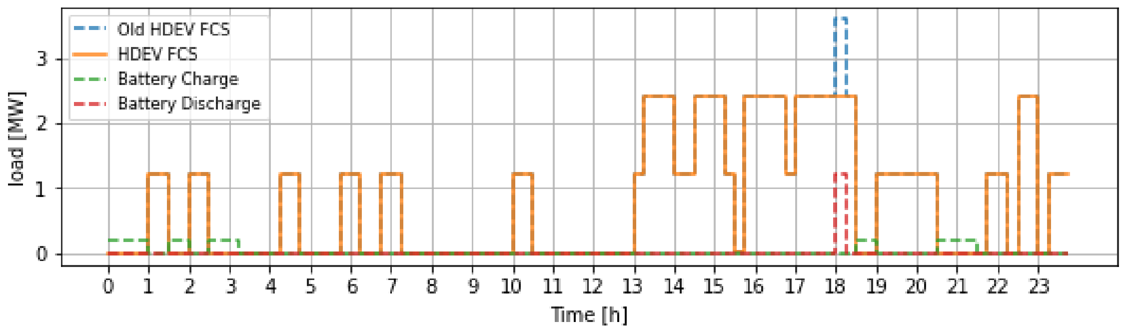


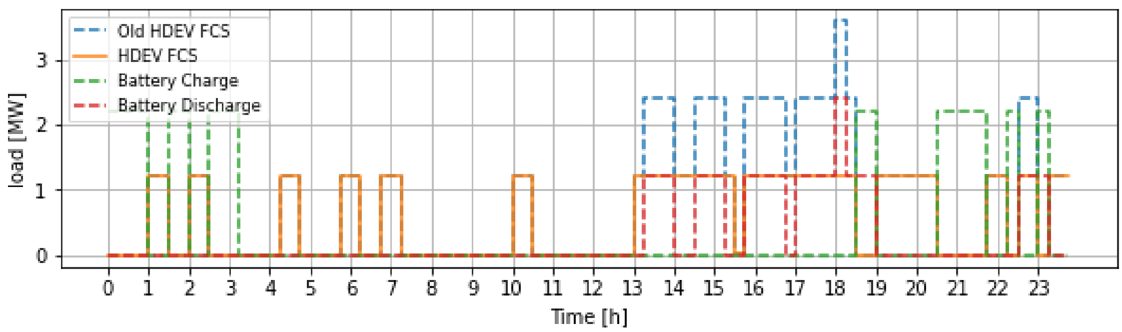
Figure 18: EV flat-charging for the different models. For one EV per EV model.

6.5 Battery energy storage system

The BESS starts the day at 0:00 with being empty, i.e., 0 MW charged up. It is then charged in every possible time frame, which happens when there is no other load demand coming from the bus, i.e., that there are no HDEVs charging in this FCS. The BESS is charged until it is fully charged. To dampen the load demand from the grid, is it not possible to charge the BESS between 15:00-20 as there is a high load demand during this time window. When there is a load demand over the specified limit, such as at 18:00, the BESS steps in, and power is discharged from the BESS to the HDEV FCS. However, the power discharged from the BESS is only the needed power above the limit and not the whole load demand. For example, at 18:00, when there is a 3.6 MW load demand, only 1.2 MW is discharged from the BESS and to the HDEV, as 1.2 MW is the difference between the 3.6 MW demand and the 2.4 MW limit. The resulting 2.4 MW is delivered from the grid.



(a) Small BESS - limit 2.4 MW



(b) Large BESS - limit 1.2MW

Figure 19: Load curves for the HDEV FCS with the two BESS installed. The blue curve shows the old load profile for the HDEV FCS without the BESS. The orange curve shows the new load profile for the HDEV FCS with the BESS. The green curve shows the charging load profile from the BESS, while the red shows the discharging power profile from the BESS.

7 Results: Power Flow

There are made several different load cases in this thesis, with each case having its unique combination of loads and powers. From the last section are all the individual loads presented.

In this section, the results from all the cases are presented. First, the base case will be presented, and then the EV charging cases for both load scenarios will be presented. Further, the EV charging cases are presented with additional measures before a summary of all cases is shown at the end. Due to a large number of different cases and many figures, are only some of the figures presented and highlighted. However, the figures which are not presented in this section are attached in the subsection A. A further description is given in the relevant case sections.

7.1 Base case

The base case is a load situation consisting of the normal load for the power system and charging loads from FCSs and a electric ferry, as described in the subsections above. The base case is made to be a reference case when comparing and analyzing the coming EV charging cases.

There are made one base case for the HI scenario and one for the LOW scenario, which is presented in Figure 20. The base case for the HI scenario is in blue, while the LOW scenario is in orange. To highlight how the implementation of the FCSs & ferry loads affects the load demand, are the load curves for the normal load included as dashed lines in the figure. With normal load during the HI scenario in green color, and during LOW scenario in red color.

One can see that the FCSs & ferry load does affect the load curve because it has large deviations in small time frames instead of a roughly even line as the normal load curve has.

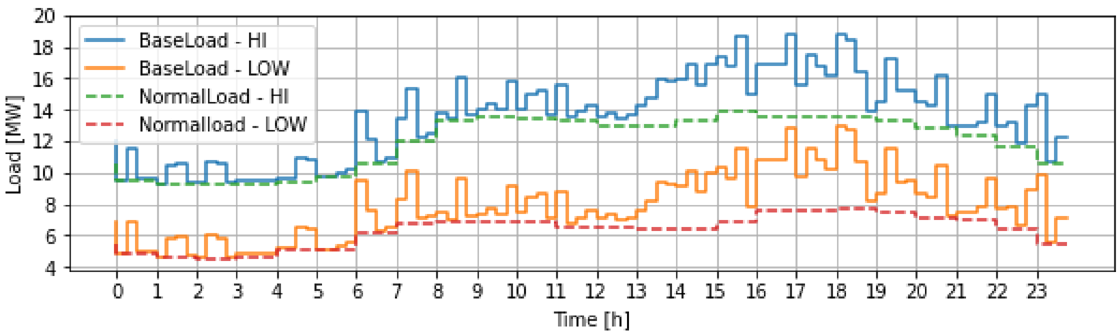


Figure 20: Base load curve for the HI scenario, in blue color and LOW scenario, in orange color. Normal loads is in a dotted line as comparison, with normal load for the HI scenario in green color and for the LOW scenario in red.

7.1.1 Base case - Performance

In this thesis, a power system will be analyzed to look at how different EV charging loads and other loads and measures to better the power quality affect the power system.

In order to analyze and discuss how the different load implementations and measures affect the system, a reference case, a base case, is needed. The load profile for the base case for both load demand scenarios is presented in the following figures in the subsection above. Further performance from the base case for the two scenarios be presented and used as reference. In Figure 21 and Figure 22 are the performance for the base case for respectively the LOW scenario and HI scenario presented. The total reactive load for the system in each of the scenarios is presented with blue coloring in the top figure, while the voltage magnitude for the different buses is presented in the lower figure.

For the LOW scenario, the voltage magnitude starts at a level over 0.95 from 0:00 until around 6:00, when the magnitude at the worst-performing buses decreases to around 0.94. The curves bounce a bit over and underneath this level until about 13:30, when the magnitude decreases further. It decreases until it reaches its lowest point at 18:30, at 0.897 p.u. The magnitude of the buses then increases towards midnight.

The reactive load has a low demand of around 1.6 MVAr from 0:00 to around 6:00. Then the total reactive load increases to around 2.2 MVAr, a level it stays around until 16:00 when the load increases a bit to over 2.4 MVAr as can be seen in the figure.

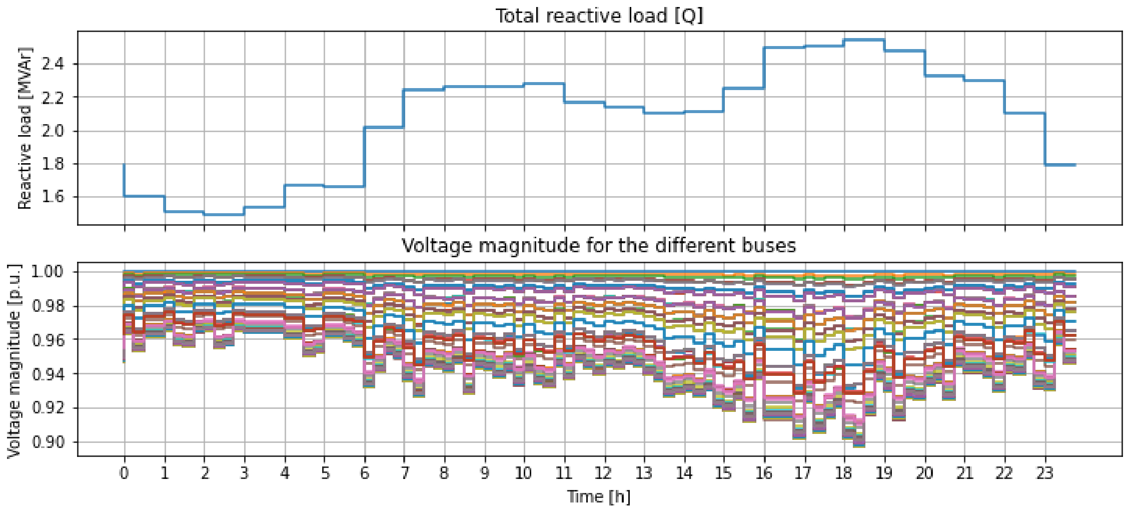


Figure 21: Voltage magnitude for base case for the LOW scenario

The behavior of the base case for the HI scenario is quite similar to the LOW scenario, only in this scenario, the load demand is higher, resulting in higher loads and lower voltage magnitudes. It has a total reactive load of a bit over 3.0 MVAr from midnight till the morning, where the load increases slowly to around 4.5 MVAr, a level the load stays around from 08:00 to 19:00. The voltage magnitudes behave the same as the LOW scenario, with a better performance of around 0.93 p.u. from midnight until morning hours. Then the voltage magnitude slowly decreases in correlation with load, and reactive load increase. During the afternoon hours, 15:00-19:00 where the voltage magnitudes are performing the worst for this scenario, with a voltage magnitude around 0.85 p.u., a decrease of almost 0.08 p.u. from early hours of the day.

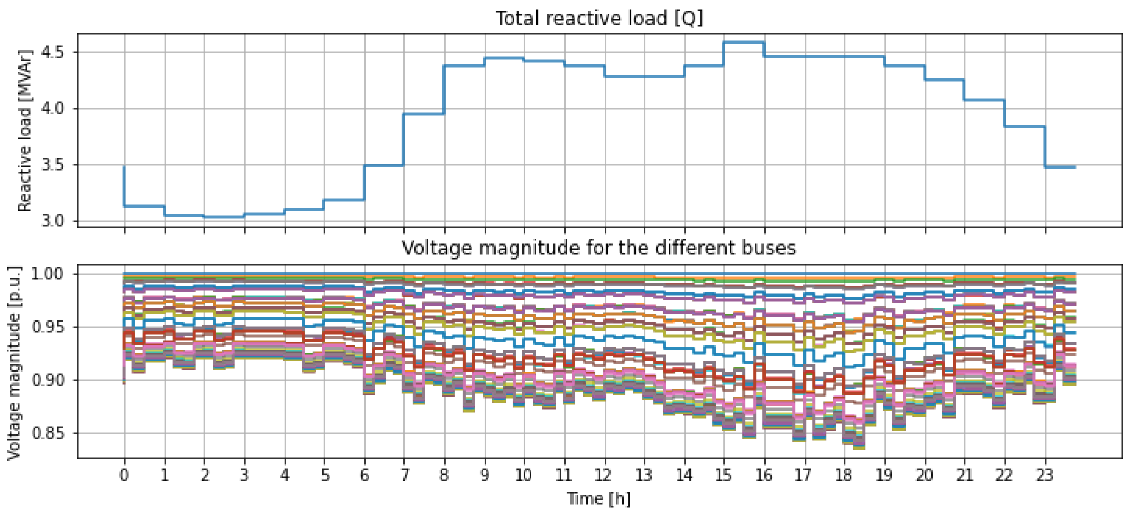


Figure 22: Voltage magnitude for base case for the HI scenario

7.2 EV charging cases

With the different charging profiles and the base case presented, the total load curves can now be presented. The different curves represent the cases, consisting of a sum of the base load, solar PV power production, and their charging load. The total load curves for the different cases for both scenarios are presented, with the Base case also added to the figures in a dotted line to be a reference.

7.2.1 Low demand scenario

Total load curves for the different cases for the LOW scenario are presented in Figure 23. The cases with long charging periods, Dumb2 and Flat, are primarily throughout the time frame having a more significant load demand than the base load and Dumb1. Except for during working hours, 08-16, there is no EV home charging. The load curves for the cases should be equal to the base case for this time period. However, due to the power production from PV1, the load demand for the EV cases is lower than the base case. The difference is 1.75 MW at the most, in the middle of the day. This drop-in load demand also gives a corresponding result in the voltage magnitude of the power system.

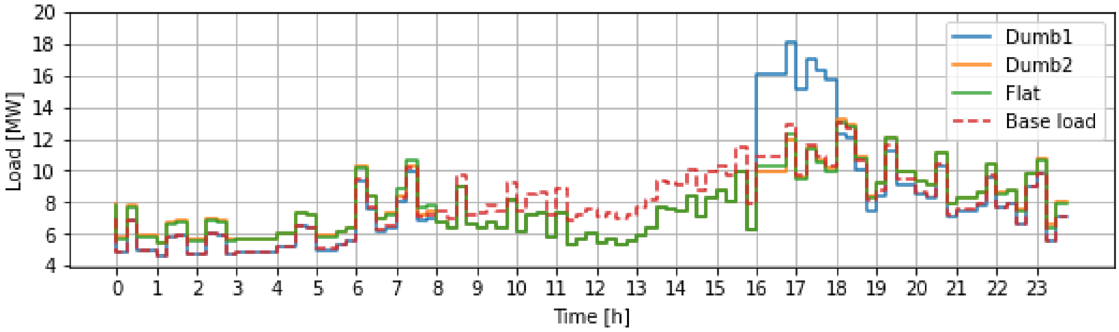


Figure 23: Load curves for the different cases for the LOW scenario. The three charging cases have PV1 production, while base case is without PV production. See subsection 5.7 for labelling.

7.2.2 High demand scenario

The total load curves for the HI scenario are given in Figure 24. Comparing this figure with the load curves for the LOW scenario,Figure 23, highlights the significant differences between the scenarios. The HI scenario has a total average from all the cases (excluding the base case) of 14 MW, while 7.8 MW for the LOW scenario.

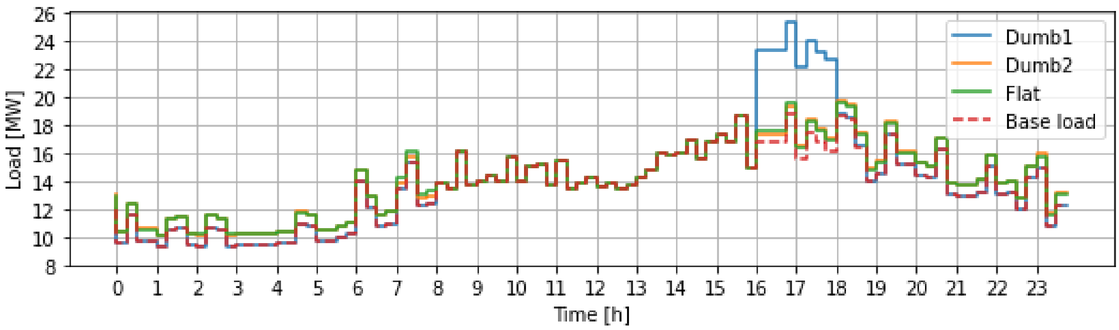


Figure 24: Load curves for the different cases for the HI scenario. See subsection 5.7 for labelling.

7.3 Analysis of the charging cases

In this subsection, the performance of the charging cases will be presented in order. It is mainly the performance voltage magnitudes of the 124 buses throughout the day that is presented, with the load profiles for the cases already presented in the subsection above.

7.3.1 Dumb charging 1 (Dumb1)

The total load curve for the Dumb1 case is shown above in Figure 23, where Dumb1 is the blue curve. The Dumb1 case has a zero load profile throughout the day except for 16:00-18/19, where it charges at the maximum power rate possible. This is why this load profile is quite different from the others, which is seen in the figure with it having a much higher load peak than the other cases. The Dumb1 case has a total maximum load peak at 18.7 MW at 17:45, which is almost 6 MW more than the Dumb2 and Flat cases, which have 13.1 and 13 MW at the same time step.

The resulting voltage magnitudes at the different buses for the Dumb1 case with different PV production are shown here in the coming figures. Figure 25 shows the results for the LOW scenario, with solar power production from all households and offices. In Figure 26 are the results for the Dumb1 case with the HI scenario shown, with 0 MW solar power production as this is set as no production for the HI scenario as described in section 5.

For this case, the EV charging load makes a clear remark in the figure, with the significant load demand in the small time frame (16 - 18/19) creating significant problems for the grid. The lowest voltage magnitudes stay around 0.96-0.93 p.u. before the charging period, when the time hits 16 and charging starts, the voltage magnitude for some buses drops from 0.06-7 p.u. to around 0.86 pu. That is a substantial decrease in such a short time frame, and 0.86 p.u. is a very low voltage magnitude, which means the bus and power system are very unstable.

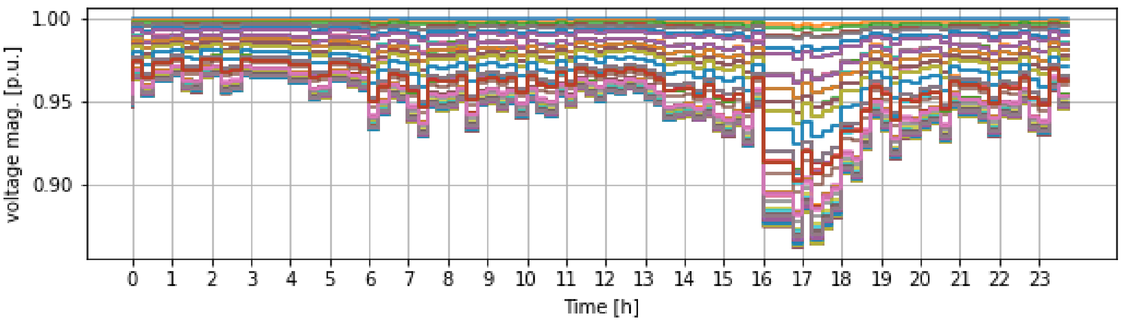


Figure 25: Voltage magnitudes for the different buses for case Dumb1 with PV1 production

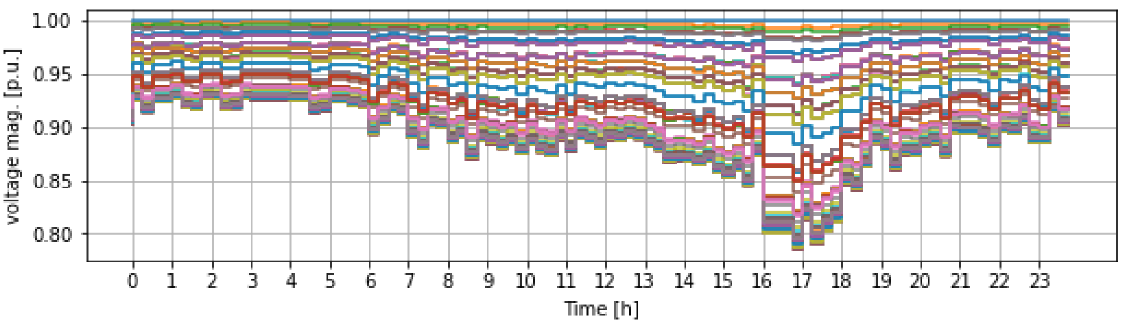


Figure 26: Voltage magnitudes for the different buses for case Dumb1 for the HI scenario

The addition of the PV1 solar power does affect the Dumb1 charging, with 1.38 MW still being produced at 16:00, which is when the EV charging load starts for this case. The impact of solar power for the Dumb1 case decreases as the power production decreases towards the afternoon.

However, it still makes an impact, and at 19:00, when the charging for Dumb1 is finished, there is still 0.36 MW produced from the solar panels. This drop-in load demand also gives a corresponding result in the voltage magnitude of the power system, and without this power production, the voltage magnitudes would be even worse. Something that is seen in voltage magnitude for the HI scenario, in Figure 26, where no solar power production in combination with a higher normal load creates a much more unstable power grid than for the LOW scenario.

7.3.2 Dumb charging 2 (Dumb2)

The analyzing results of the Dumb2 case are presented in Figure 27 and Figure 28 for respectively LOW and HI scenario. The voltage performance is better for this charging case than for the Dumb1 charging case for both scenarios. This is because, as seen in Figure 23 and Figure 24, the charging loads are much more spread out throughout the day, rather than all charging in a small interval as for the Dumb1 case.

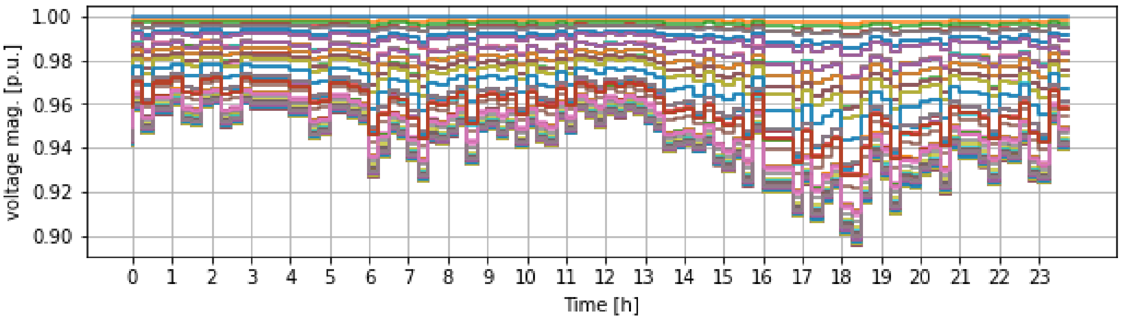


Figure 27: Voltage magnitudes for the different buses for case Dumb2 with PV1 production

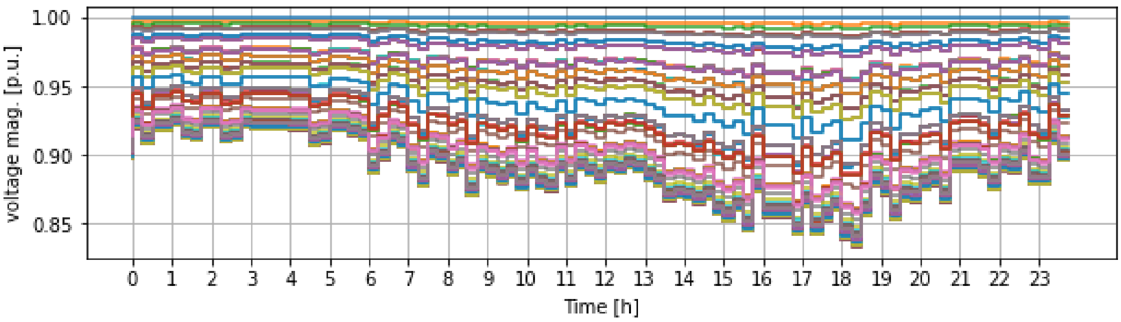


Figure 28: Voltage magnitudes for the different buses for case Dumb2 for the winter scenario

7.3.3 Flat charging (Flat)

The flat charge case is a slow charging case where all the EVs in the system are charged for the whole day, except during working hours. This results in a flat charging curve as presented in Figure 16, and the difference in load demand between the different EV models can be seen in Figure 18. The Flat case combined with the base load are presented in Figure 23 and Figure 24 for, respectively, LOW and HI scenario. For both the scenarios, the Flat load profile is constantly a bit higher than the base case, except during working hours when it is equal to the base case. The power systems stability is presented through the performance of voltage magnitude in the different buses in the power system, which are presented in Figure 29 for the LOW scenario and Figure 30 for the HI scenario. The lowest points are at 18:00 for both scenarios, where the voltage magnitude is below 0.90 p.u. for the LOW scenario and a further 0.06 p.u. down for the HI scenario, which has a performance of around 0.83 p.u.

In the HI scenario, most buses have a voltage magnitude below 0.90 p.u. during most of the day. Also, several buses have a magnitude as low as or even below 0.85 p.u. during multiple time steps during the afternoon. On the other hand, the LOW scenario has much better performance, with almost all the buses above 0.94 p.u. from noon to midday / early afternoon. The performance drops gradually down to the lowest point at 18:00. The large deviations in performance between the HI and LOW scenarios are primarily due to the difference in the base load demand. However, solar power production is also a factor in the difference as this does make a notable impact on the load profile. This can be clearly seen during the daytime for the LOW scenario, where the voltage magnitude recovers from a drop down to 0.94 p.u. at 06/07:00 to almost 0.96 p.u. at noon.

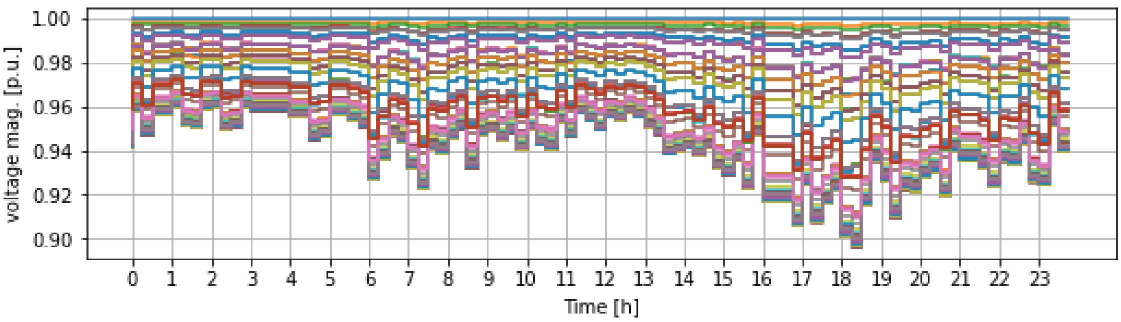


Figure 29: Voltage magnitudes for the different buses for Flat charging with PV1 production (LOW scenario)

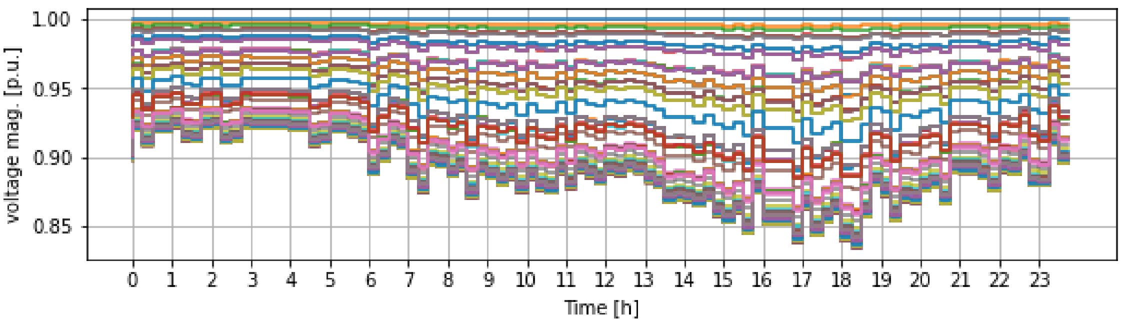


Figure 30: Voltage magnitudes for the different buses for Flat charging case in the HI scenario

7.4 Additional measures

Up until now have the base case and the three EV charging cases been presented. The addition of EV charging impacts the power system in all three charging cases. Therefore, additional measures are implemented to improve the power and voltage quality of the grid. In this section, the EV cases with four additional measures will be presented individually before all additional measures are combined, looking at how a combination of the measures may impact the grid with EV charging.

7.4.1 PV park

The first additional measure is adding a PV park to the power system. This is done by adding a PV park consisting of 15000 solar PV panels to bus 65 as described in section 5. This is an indirect measure of the voltage stability, as it injects local power production into the system, which further will increase the voltage stability due to this power addition. This measure is only analyzed for the LOW scenario, as there is no power production from any PV panels during the HI scenario in this thesis.

Adding a local power production of almost 5 MW affects the load curves heavily, as presented in Figure 31. Here, the load curves for the different load cases with PV2 production are presented. The base load, without any PV power or EV load, is added to the figure in a dashed line with the objective of being a reference curve. The high power production in the middle of the day pushes the load curves towards a negative load demand. A negative load demand would mean more power produced than consumed at that time step.

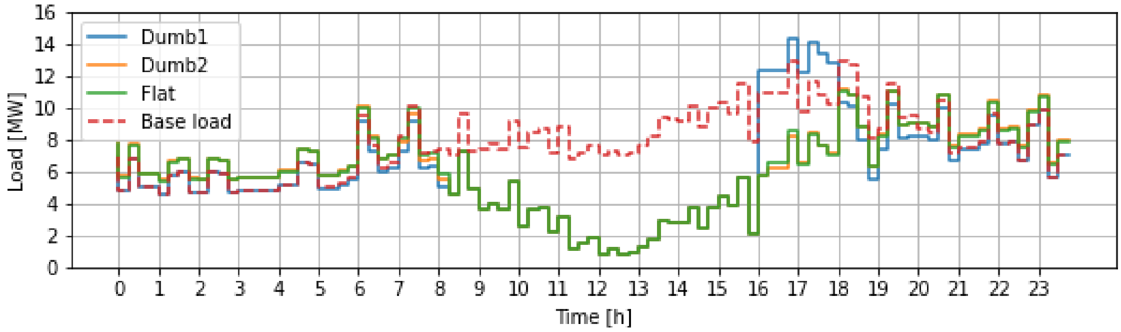


Figure 31: Load curves for the different cases with PV2 production (LOW scenario). The base load is added to the figure as a reference case. See subsection 5.7 for labelling.

The voltage magnitude for the EV cases Dumb1 and Dumb2 with the PV2 solar production case are presented in respectively Figure 32, Figure 34. The results for the Flat case with PV2 production are added in subsection A. Adding more local power production affects the voltage quality of the buses in all the cases, which can be seen in the figures below. All of the buses for the three charging cases perform a high voltage magnitude during the mid-day due to the implementation of this PV park. The benefits of this measure can be even clearer when comparing the voltage stability from this measure to the voltage stability from the EV cases with PV1 production.

Dumb1 charging

The impact of adding a PV park into the Dumb1 case can be clearly seen in Figure 32, where the voltage magnitudes at the buses in the system are presented. During the middle of the day, when PV production is at its highest, the voltage magnitudes have their best performance. All buses increase towards the nominal voltage, 1.0 p.u, during this time. Two buses, Bus 65 and Bus 66, even have a voltage magnitude just above 1.0 p.u. at a few steps due to the solar PV park being located at bus 65. The magnitudes then drop due to the high EV charging load demand at 16:00.

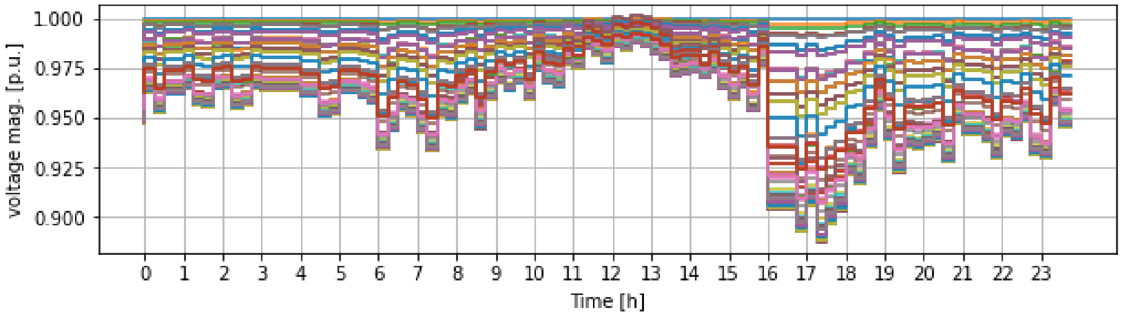


Figure 32: Voltage magnitude for the Dumb1 case with PV2 production

With the PV park measure, the load profiles for the buses are the same as before, except for bus 65, which now til have a negative load profile, meaning that there is more power produced than there are load consumed. This is shown in purple colouring in Figure 33. The figure shows the load profile for all the 124 buses in the system.

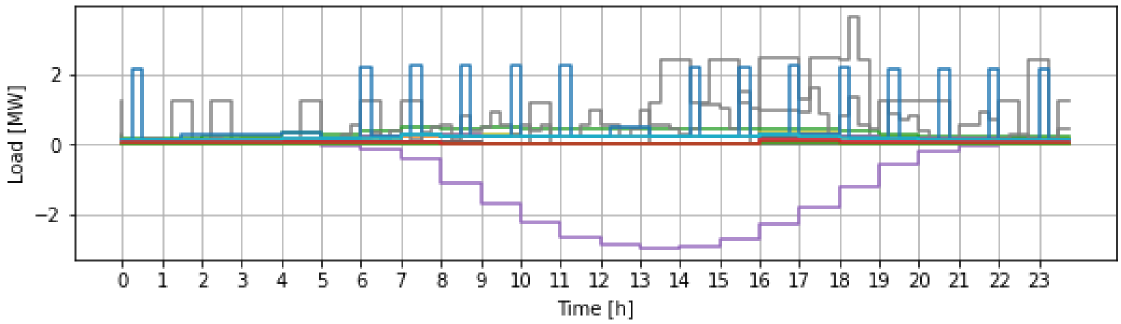


Figure 33: Load and power profile for all the 124 buses in the power grid for Dumb1 charging case with a solar PV park added to bus 65.

Dumb2 charging

By making a randomized charging case, the load demand from EV charging is spread out during the day, unlike the Dumb1 case, where all charging happens simultaneously during a small time window. Meaning that the Dumb2 case has a lot lower load demand peak and a higher bottom point of voltage magnitudes than the Dumb1 case. Adding a PV park with a rated power of almost 5 MW will work as an indirect measure to better the voltage magnitudes of the buses. The measure pushes all the voltage magnitudes higher up towards the nominal voltage. However, there are some minor bottom points outside of the power production peak, which are barely improved. The bottom points of the voltage magnitudes for the buses are around 0.915 p.u.. An increase of almost 0.015 p.u. from the Dumb2 case with PV1 production and without any measures as seen in Figure 27.

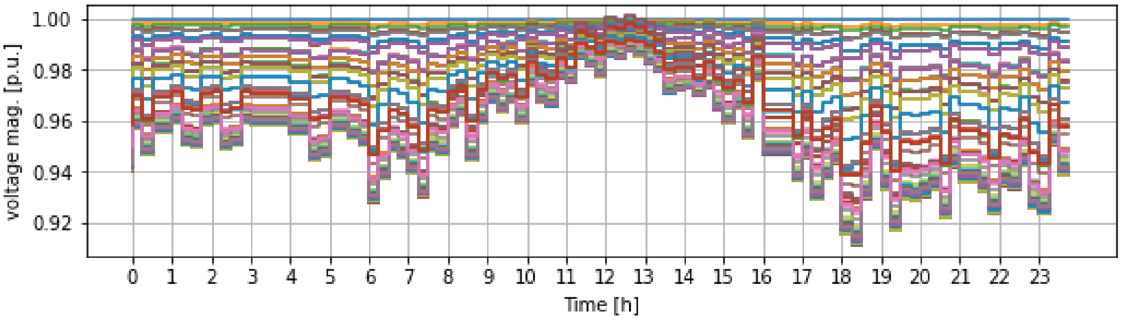


Figure 34: Voltage magnitude for the Dumb2 case with PV2 production

7.4.2 Reactive power support

As described in the section 3, the implementation of EVs may create problems due to high load peaks. However, EVs may also be beneficial to the grid, with the possibility of delivering services to the grid. Such as active power supply, but maybe even more crucial for the voltage quality, reactive power supply. Reactive power support is a direct measure of the voltage stability, as the reactive power production added to the system directly betters the voltage stability in the buses.

For this additional measure is all EVs, as well as ferry and FCS, set to supply reactive power to the grid, with a 0.95 leading power factor during the whole day, as described in section 5. Meaning that the reactive power support from FCSs & ferry will be the same for all the cases in this measure. Only the reactive injection from the EV charging cases differs between the cases. The following figures present the total reactive power and voltage magnitudes for both Dumb1 and Flat charging cases with reactive power support for both demand scenarios. Active load curves as presented in Figure 23 and Figure 24 are still the same for the three EV cases. However, the measure affects reactive power curves and the voltage magnitude profiles. Each figure presented consists of two sub-figures: The top sub-figure shows the total reactive power in the system for the given case. Then the voltage quality of the buses is shown in the lower sub-figure.

Dumb1 charging

The voltage performance for all buses in the power grid with Dumb1 EV charging and reactive power injection is presented for both load demand scenarios in the following figures.

Figure 35 shows the results for the LOW scenario. Here, the reactive power injection in from the EV charging, from 16:00-19:00 for this case, makes a notable impact. The total reactive load has a negative value during these hours, meaning more reactive power is delivered to the grid than consumed. In addition to the reactive supply from the EVs, the FCSs and the ferry also supply the grid with reactive power for several time steps throughout the day. This is seen with the voltage magnitudes, which behave accordingly with the reactive power load.

Reactive power support to the grid with the Dumb1 EV charging case for the HI scenario is presented in Figure 36. The reactive power support is the same as the LOW scenario because EV charging and FCSs & ferry are the same for both scenarios. However, for this HI scenario, the total reactive load is much higher than for the LOW scenario. The same is true for the voltage quality, with the voltage magnitudes being lower for the HI scenario than the LOW scenario. This is due to the differences in normal load, with the reactive load being calculated with the normal load for the two scenarios as input.

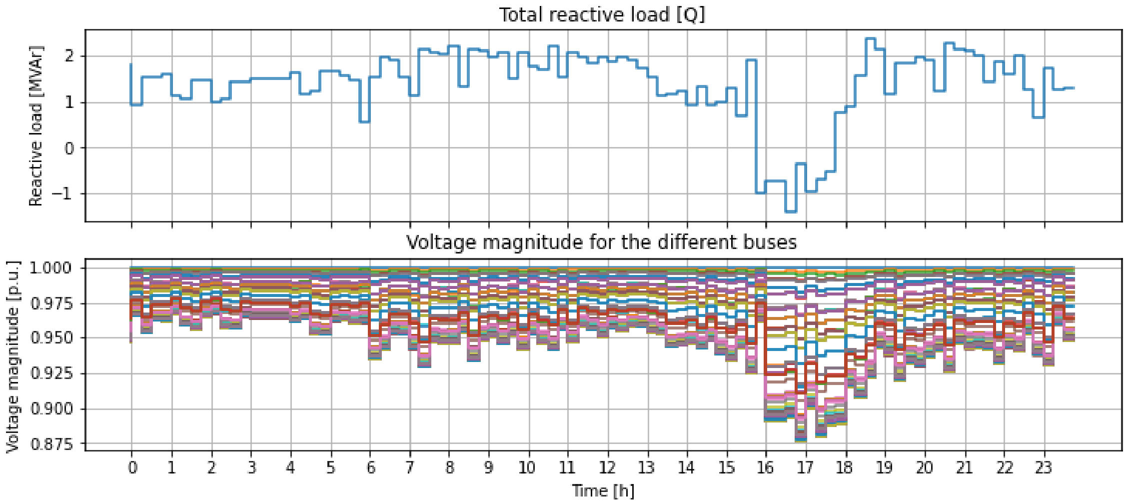


Figure 35: Reactive power support for Dumb1 case for the LOW scenario with PV1 production

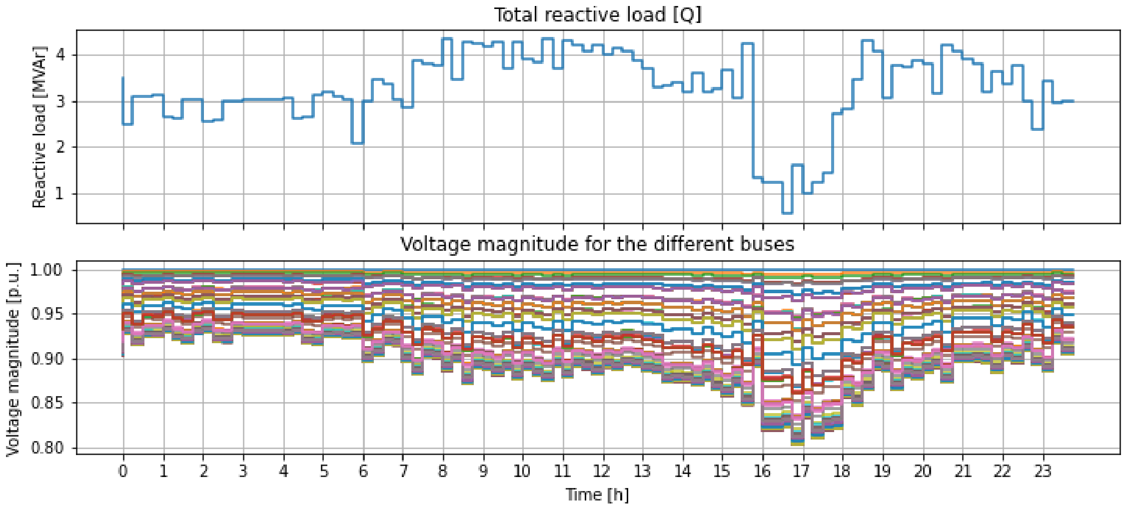


Figure 36: Reactive power support for Dumb1 case for the HI scenario

Flat charging

For the Flat charging case with reactive power, support is the reactive power injection spread more out during the day, depending on the charging load. The Flat charging is constantly slow charging during the charging hours 16-08, as seen in Figure 17. Therefore, the EV reactive power support is also constant from 16-08. This directly affects the voltage magnitudes in the system as presented in Figure 37.

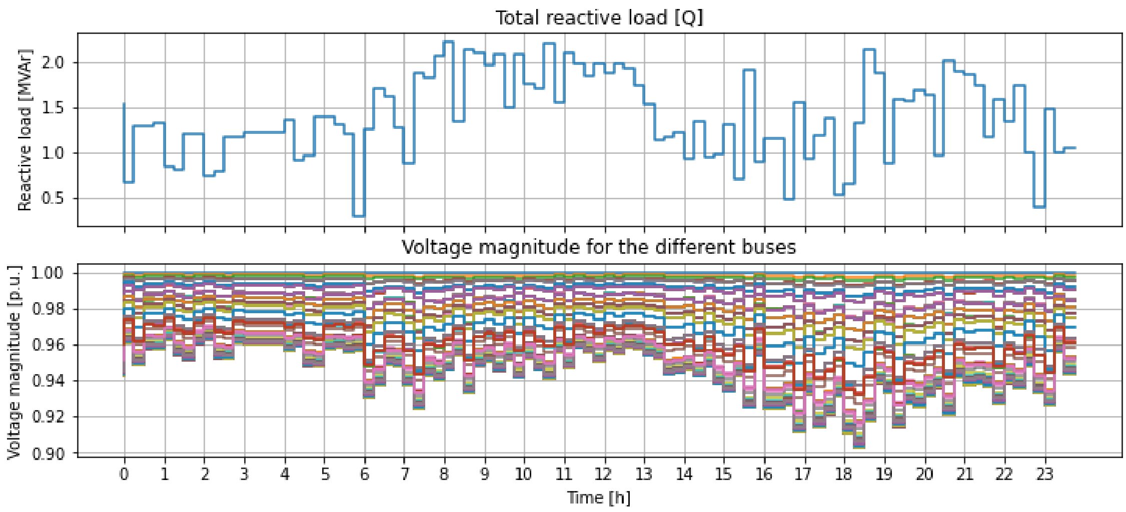


Figure 37: Reactive power support for Flat case for the LOW scenario with PV1 production

For the HI scenario is, the reactive power support the same due to EV charging and FCSs & ferry load being the same for both scenarios. The only difference is that the normal load is much higher for this scenario, meaning that the total reactive load is then increased. As presented in Figure 30 this reactive load increase leads to a higher total reactive load and then worse resulting voltage magnitudes in the buses for this HI scenario than for the LOW scenario. However, by comparing the voltage magnitudes results from this measure to the ones from the non-additional Flat case, as seen in Figure 30, it is shown that the reactive power support results in an improvement of the voltage quality.

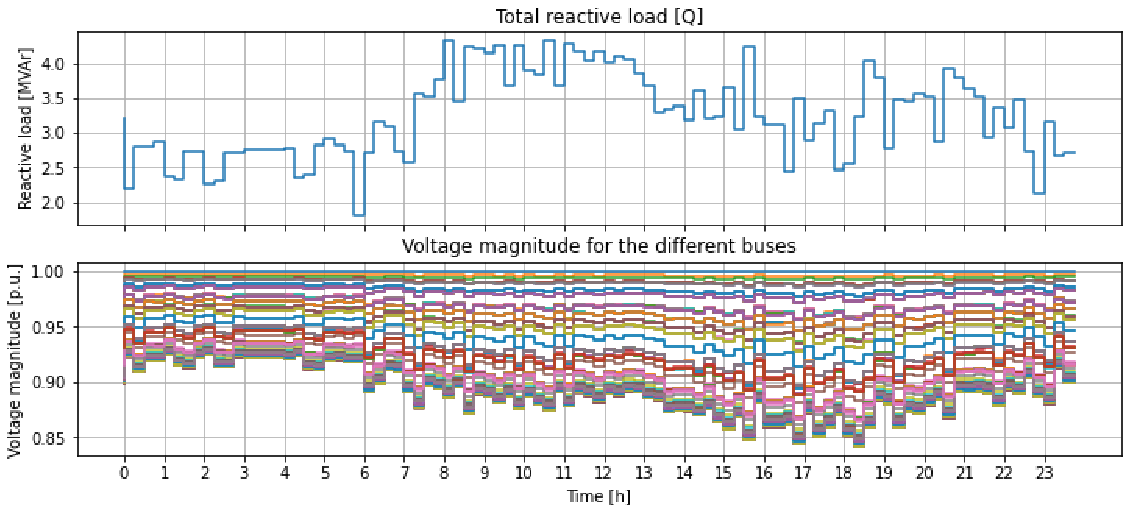


Figure 38: Reactive power support for Flat case for the HI scenario

7.4.3 Battery energy storage system

The second additional measure added to the EV cases is a BESS installation. This is an indirect measure, as it does not affect the voltage stability directly. However, in the same way as the PV power park, this measure affects the voltage indirectly by affecting the load profile. The BESS do not impact or lift the power and voltage quality throughout the day. Instead, it lifts the quality in the most critical load demand hours. In theoretical terms, this is categorized as load shifting.

The measure is made with two different BESS into the bus 65 to dampen the load demand from the HDEV FCS, as described in section 5. The small BESS only strikes in for load values over the 2.4 MW and the second for values over 1.2 MW. The load profile of the BESS, with an overview of the behavior of the BESS' is shown above in Figure 19a and Figure 19b. The performance of the buses in the grid with the implementation of the two BESS' for EV case Dumb1 and Flat for the HI scenario are presented in the figures below. Figures showing the performance of Dumb2 and all cases during the LOW scenario with the BESS implemented are added to subsection A.

Dumb1 - HI scenario

The voltage magnitudes of the buses in the system for the Dumb1 case with the small BESS installed are presented in Figure 39. This is for the HI scenario when the load demand is highest. As shown in Figure 19a the small BESS only strikes for one time step at 18:00. The bottom point of the voltage magnitudes is just below 0.80 p.u. with the small BESS.

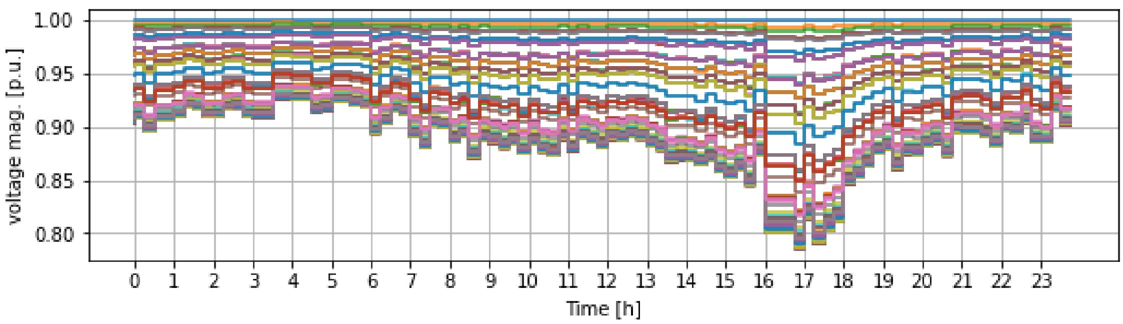


Figure 39: Voltage magnitude at the buses for the Dumb1 charging case with the small BESS for the HI scenario. The small BESS only steps in to dampen the top peak of levels over 2.4 MW at the HDEV FCS

For the large BESS, the voltage magnitudes of the buses for the Dumb1 case are presented in Figure 40. The behavior is similar to the figure presented above, but the voltage magnitudes are higher here, with the lowest point being a bit over 0.80 p.u.. This is because of the large BESS' more significant impact over a more extended time period in the HDEV FCS.

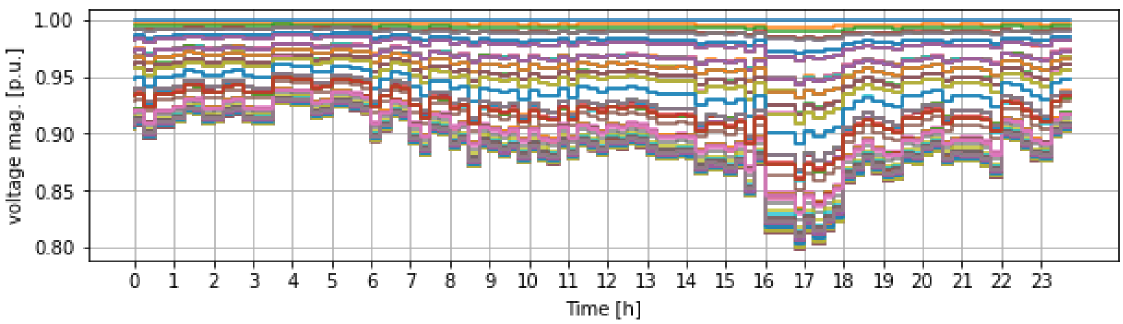


Figure 40: Voltage magnitude at the buses for the Dumb1 case with the large BESS for the HI scenario. The large BESS steps in to dampen the load peaks over 1.2 MW at the HDEV FCS

Flat - HI scenario

In Figure 41 and Figure 42 are results of voltage magnitudes in the buses for both BESS sizes with the Flat charging case presented. By comparing the Figure 41 with the original voltage results for the Flat charging (HI scenario), in Figure 30, the impact of the small BESS is notable. The bottom point of the voltage magnitudes in the original Flat charging case is 0.835 p.u. at 18:15. By implementing the small BESS, the voltage magnitude is pushed towards 0.85 p.u.

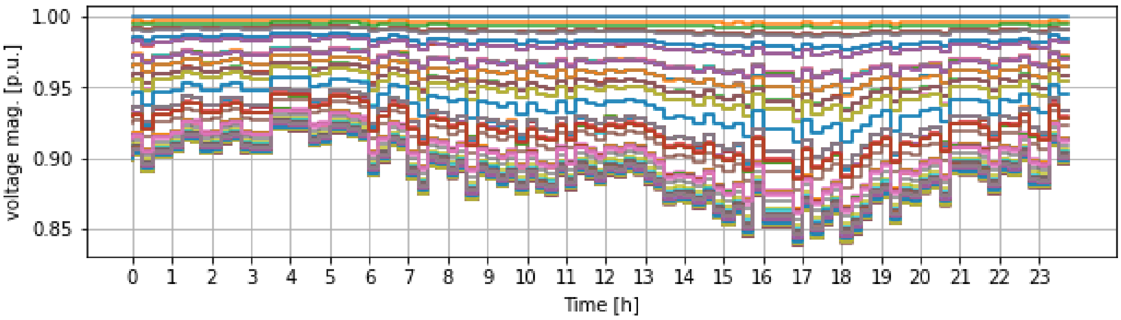


Figure 41: Voltage magnitude at the buses for the Flat charging case with the small BESS for the HI scenario. The small BESS only steps in to dampen the top peak of levels over 2.4 MW at the HDEV FCS

Figure 42 presents the voltage quality with the large BESS for the Flat charging case during the HI scenario. By comparing the large BESS with the small one, the impact of the large BESS is clearly shown. The more significant load reduction leads to a more considerable increase in the voltage magnitude for most buses in several time steps during the afternoon.

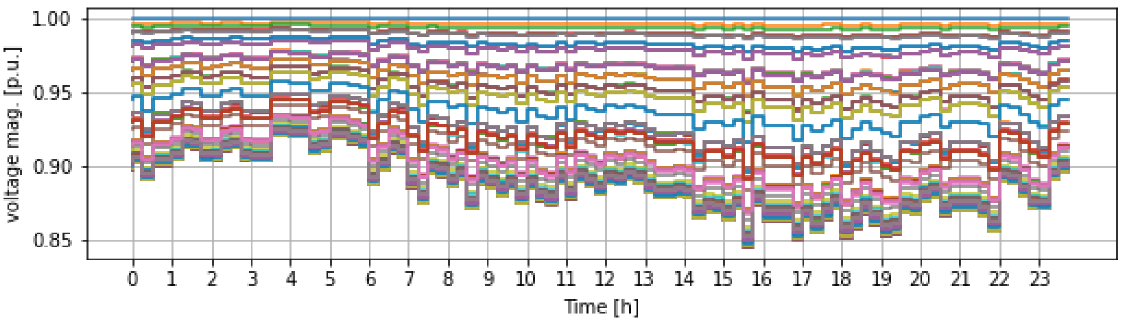


Figure 42: Voltage magnitude at the buses for the Flat case with the large BESS for the HI scenario. The large BESS steps in to dampen the load peaks over 1.2 MW at the HDEV FCS

7.4.4 Combination of measures

Until now, all the additional measures have been analyzed individually, one at a time. A combination case is made to highlight how a combination of these measures would affect the charging cases. In both scenarios, will the cases analyze a solar PV park, the reactive power support from EV charging and FCSs & ferry loading, and a large BESS at the HDEV FCS. However, due to no solar power production during the winter, PV production is still set at 0 MW during the whole day, also for the PV park. The BESS size in this combination measure will be the largest one, stepping in if load values exceed 1.2 MW. This is chosen to get the most significant impact possible to better the system's power quality.

The following figures will present the results for the case with a combination of measures for both Dumb1 and Flat charging. For the Dumb1 charging, will the performance for both load demands be presented, while for Flat charging, only the LOW scenario will be presented. The HI scenario for Flat charging with a combination of measures is added in subsection A. Here are also the results for the Dumb2 charging with this load case combination presented.

The figures are divided into three sub-figures. The top sub-figure (blue coloring) shows the total active load profile for the system, and the middle sub-figure (orange coloring) shows the total reactive load profile in the system. The bottom sub-figure shows the voltage magnitudes for the buses.

Dumb1 Charging

Combining the measures for the Dumb1 case with the LOW scenario is presented in Figure 43. The large charging pattern of the Dumb1 charging is easy to recognize also in this figure. However, by comparing this figure with the original load profile for the Dumb1 case in Figure 25, it is clear to see that a combination of measures does make an impact on the power system with this charging. The bottom point of the voltage magnitudes in the original Dumb1 charging case for the LOW scenario is 0.86 p.u.. For the combination case, the bottom point increased from 0.05 p.u. to 0.91 p.u..

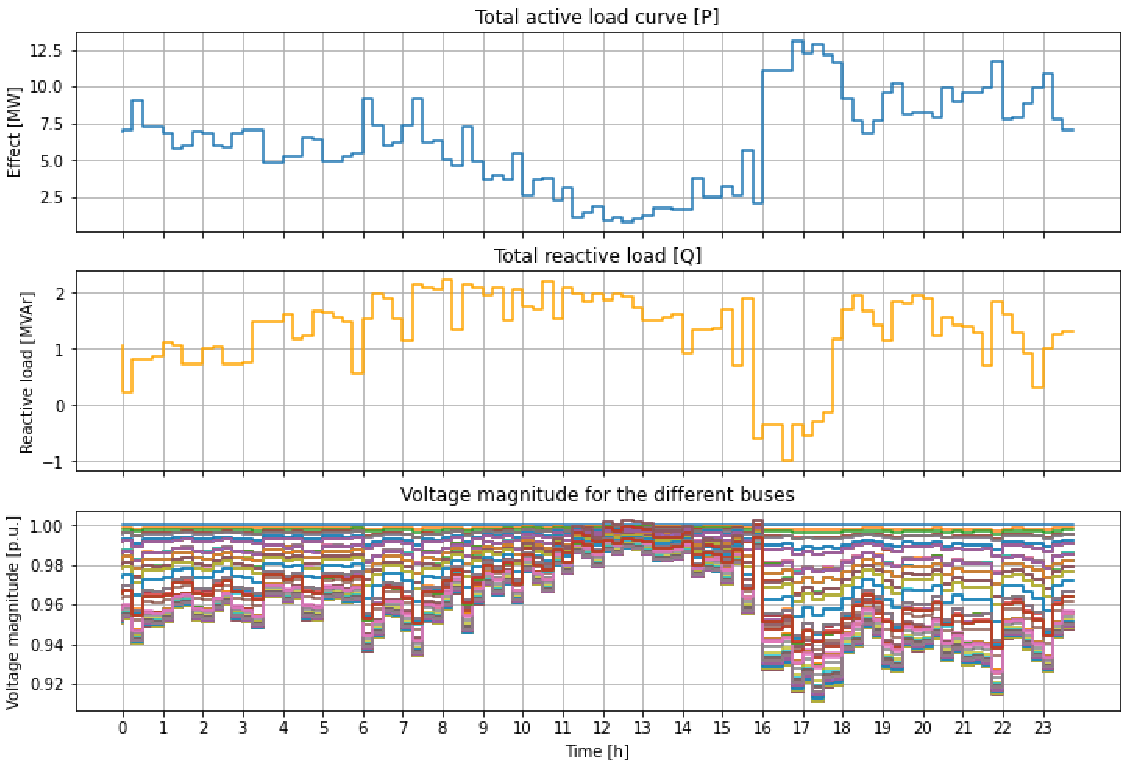


Figure 43: Performance of a Dumb1 case for the LOW scenario with a combination of all additional measures: PV2 solar power production, reactive power support and a large BESS at the HDEV FCS.

For the HI scenario, does the PV park not make an impact, as the production is put as 0 during the winter. Meaning that the power system misses out on almost 5 MW power production at the most, compared to the LOW scenario. In addition to a much higher load demand during the HI scenario. However, the combination of the measure does still make an impact. In Figure 44 are the results from the HI scenario for Dumb1 charging with a combination of measures presented. The total load peak is at 24,2 MW, while the bottom point of the voltage magnitudes is at 0.815 p.u.. This is a load decrease of 1,2 MW and a voltage magnitude increase of 0.03 p.u. from the Dumb1 case without any measures, as shown in Figure 26.

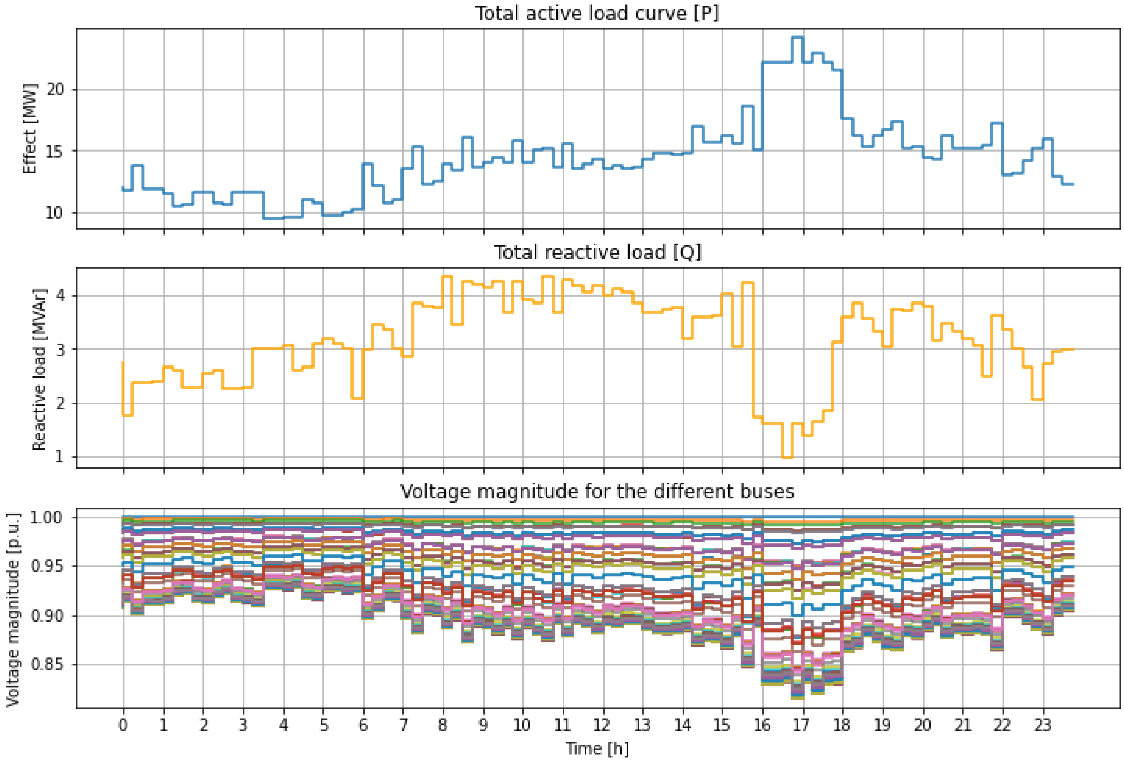


Figure 44: Performance of a Dumb1 case for the HI scenario with a combination of all possible additional measures: Reactive power support and a large BESS at the HDEV FCS.

Flat charging

A combination of measures implemented for the Fast charging case is presented in Figure 45. This figure presents the case for the LOW scenario, which can be clearly seen with the significant drop in active power in the middle of the day. The figure shows that the voltage levels at the buses are relatively high compared to all the other analyzed cases. Looking away from the bottom point of the case, which is around 0.91 p.u. for one short time step, are the voltages over 0.94 for most buses throughout the day.

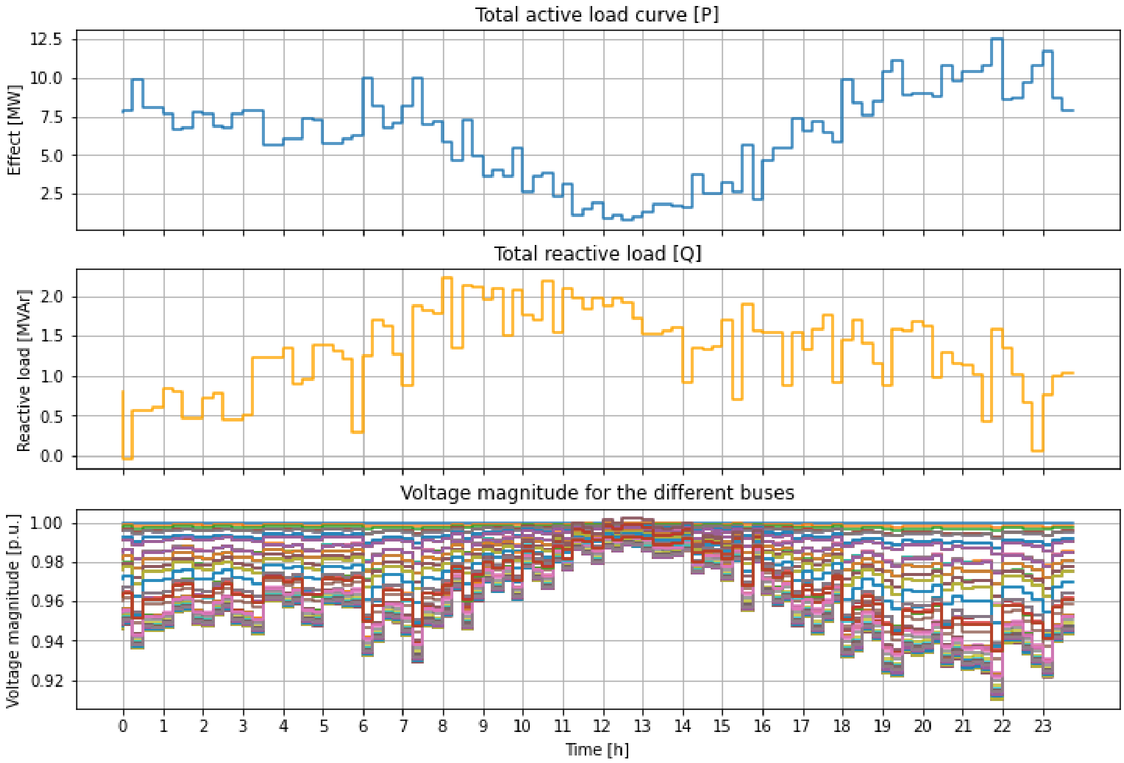


Figure 45: Performance of a Flat case for the LOW scenario with a combination of all additional measures: PV2 solar power production, reactive power support and a large BESS at the HDEV FCS.

7.5 Summary of power flow results

A summary of the results from the different cases is made to get a total overview and comparison of the cases. The results for the LOW scenario are presented in Table 9, while the results for the HI scenario are presented in Table 10. The tables consist of two main results for each case: The peak value of the summed load curves for the different cases, i.e., the highest load value (in MW) in the summed load curves for each case. Here are also the time of the load peak added. The other result highlighted in the tables is the lowest voltage magnitude of the system for each case (shown in p.u), i.e., the bottom point of the voltage magnitudes in all buses. Here is both time of the occurrence added and what bus had the lowest magnitude in the cases.

For the cases with additional measures are, the best and worst-performing values highlighted in coloring. The highest summed load peak of the different cases is highlighted in red coloring, and the lowest load peak is colored green. For voltage magnitude, the highest bottom point from the voltage magnitudes of the cases is colored green, while the lowest bottom point is colored red.

7.5.1 Low demand scenario

From Table 9, it is shown that for the LOW scenario, the Dumb2 and Flat charging cases barely perform worse amplitude values than the base case. The two charging cases have a slightly higher load peak than the base case and a lower voltage magnitude bottom point. Charging case Dumb1 is seen alone performing a lot worse than the other two charging cases and the base case. The case Dumb1 has a load peak of 5 MW higher than the other cases and a voltage magnitude bottom point of 0.862, which is almost 0.04 p.u. lower than the other.

By comparing the additional measures with the three charging cases, it is seen that each of the measures does make a positive impact. For all cases with additional measures have the lowest voltage magnitudes increased compared to the regular charging cases. For example, the regular Dumb1 charging case has the lowest voltage magnitudes of 0.862 p.u.. By implementing the reactive power support measure this is increased to 0.876, with both of these bottom points occurring at the same time step of 16:45. The case with the lowest load peak is the PV park with Flat charging case, which has a load peak of 11.088 MW. Here are the best performing voltage magnitudes, with a bottom point of 0.912 p.u. at bus 96. The reactive power support only affects the reactive load of the system and then the voltages, but not the active power. Therefore, the highest load peak of the additional measures at this measure with Dumb1 charging, which has an equal value to the regular Dumb1 charging case of 18.043 MW. However, the worst-performing voltage magnitude is at 16:45 for the Dumb1 charging case with the large BESS measure. Here the voltage magnitude is 0.873 p.u., which is 0.04 p.u. lower than the best performing magnitude.

Table 9: Summary of the results for the LOW scenario

Case			Load		Voltage magnitude		
			Peak total		Lowest		
Load case:		**PV:**	**Load [MW]**	**Time [h]**	**vm [p.u.]**	**Time [h]**	**Bus nr.**
Base case		-	12.953	18:00	0.897	18:15	96
Dumb1		PV1	18.043	16:45	0.862	16:45	96
Dumb2		PV1	13.091	18:00	0.8959	18:15	96
Flat		PV1	13.047	18:00	0.8963	18:15	96
PV park	Dumb1	PV2	14.334	16:45	0.888	17:15	96
	Dumb2	PV2	11.131	18:00	0.911	18:15	96
	Flat	PV2	11.088	18:00	0.912	18:15	96
Reactive power support	Dumb1	PV1	18.043	16:45	0.876	16.45	96
	Dumb2	PV1	13.091	18:00	0.902	18:15	96
	Flat	PV1	13.047	18:00	0.903	18:15	96
Battery system (Large)	Dumb1	PV1	16.843	16:45	0.873	16:45	96
	Dumb2	PV1	12.698	21:45	0.905	21:45	96
	Flat	PV1	12.630	21:45	0.906	21:45	96
Combination	Dumb1	PV2	13.134	16:45	0.911	17:15	96
	Dumb2	PV2	12.608	21:45	0.9095	21:45	96
	Flat	PV2	12.54	21:45	0.910	21:45	96

7.5.2 High demand scenario

For the HI scenario, do the Dumb2 and Flat charging cases perform around 0.8 MW higher load peak than the base case. As seen in Table 10, the base case has a total load peak of 18.851 MW, the Dumb2 case 19.62 MW, Flat case 19.674 MW, and the Dumb1 case has a bit higher load peak of 25.406 MW.

Of the cases with the three additional measures and a combination of the measures, the Dumb1 charging case with reactive power support has the worst load peak performance with a bottom point of 25.496 MW, the same as the regular Dumb1 case. The best power peak summed load peak results is 18.629 MW and occurs at 15:30 for the charging cases Dumb2 and Flat, with both the large BESS measure and a combination of measures. For the lowest voltage magnitudes, the Dumb1 charging case with a combination of measures performs the worst with a magnitude of 0.799 p.u. The Flat and Dumb2 charging cases with a combination of measures has the best performing voltage magnitudes of 0.848 p.u. at 15:30 for bus 96.

Table 10: Summary of the results for the HI scenario

Case			Load		Voltage magnitude		
			Peak total		Lowest		
Load case:		**PV:**	**Load [MW]**	**Time [h]**	**vm [p.u.]**	**Time [h]**	**Bus nr.**
Base case		-	18.851	16:45	0.842	18:15	96
Dumb1		-	25.406	16:45	0.786	16:45	96
Dumb2		-	19.6196	18:00	0.834	18:15	96
Flat		-	19.674	16:45	0.835	18:15	96
PV park	Dumb1	-	-	-	-	-	-
	Dumb2	-	-	-	-	-	-
	Flat	-	-	-	-	-	-
Reactive power support	Dumb1	-	25.406	16:45	0.802	16:45	96
	Dumb2	-	19.62	18:00	0.841	18:15	96
	Flat	-	19.674	16:45	0.842	18:15	96
Battery system (Large)	Dumb1	-	24.206	16:45	0.799	16:45	96
	Dumb2	-	18.629	15:30	0.845	15:30	96
	Flat	-	18.629	15:30	0.845	15:30	96
Combination	Dumb1	-	24.205	16:45	0.815	16:45	96
	Dumb2	-	18.629	15:30	0.848	15:30	96
	Flat	-	18.629	15:30	0.848	15:30	96

7.5.3 Summary of voltage quality at bus nr. 96

The two tables presented above show that bus 96 is the bus where the bottom points of the voltage magnitudes occur for all cases. The reasoning for this is due to the power grid topology, as shown in Figure 10, with bus 96 being the end bus of the grid. Meaning that the power consumed from the external grid goes through the whole system before it reaches bus 96, meaning that the voltages will be lowest at this bus. To further compare the results of the voltage quality between the different cases are the voltage magnitude performance of bus 96 from the cases plotted together, presented in Figure 46 for the LOW scenario and in Figure 47 for the HI scenario.

Adding a PV park with a rated power of almost 5 MW greatly impacts the power system. This can be seen in the LOW scenario figure, with bus 96, which is the end bus of the power system, almost having voltage levels close to the nominal voltage in the middle of the day. What also can be seen in the figure is that the more flexible charging methods, Dumb2 and Flat, have voltage levels just below the voltage levels of the base load and Dumb1 cases. Except for during charging hours of the Dumb1, where the voltage magnitudes drop considerably below the other voltage curves.

By looking at the figure for the HI scenario, it is seen that the voltage levels are generally lower than it is for the LOW scenario. As described before, this is mainly due to the higher load demand in this scenario than for the LOW scenario. This is created by the high normal load in the scenario, but also worth noting is that for the HI scenario are there no local power production from PV panels. Neither from rooftops of households and offices or the PV park. In the LOW scenario, the voltage levels of the bus 96 for the different cases stay above 0.92 p.u. trough most of the day. For the HI scenario are, the voltage levels around and below 0.90 p.u. through most of the day.

For both load demand scenarios, it is seen that the cases with Dumb1 charging perform the worst voltage quality. However, by looking at the figures, it can be seen that each of the implemented measures to the Dumb1 charging does make a positive impact. For the LOW scenario, the bottom point of the voltage levels increased from 0.862 p.u. for Dumb1 without any measures to 0.911 p.u. with a combination of measures. In the HI scenario, does not the PV park make any impact, but

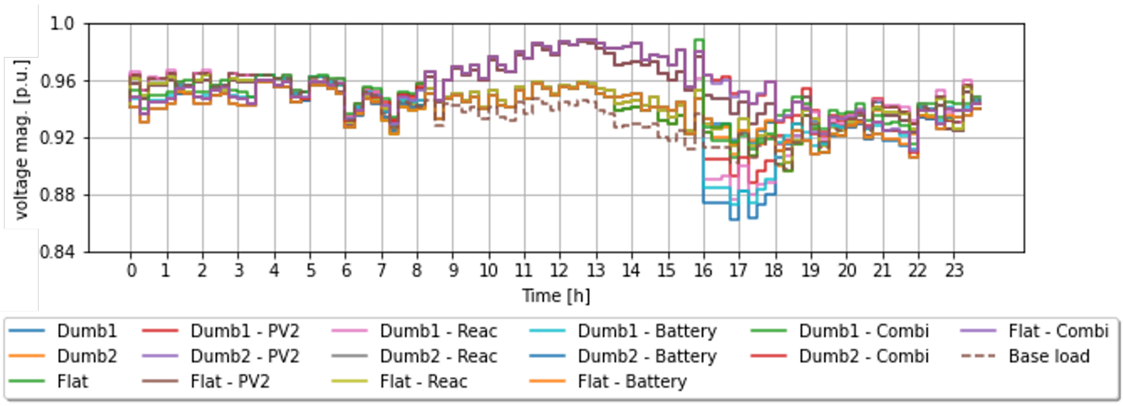


Figure 46: Voltage magnitude for bus 96 for the different cases

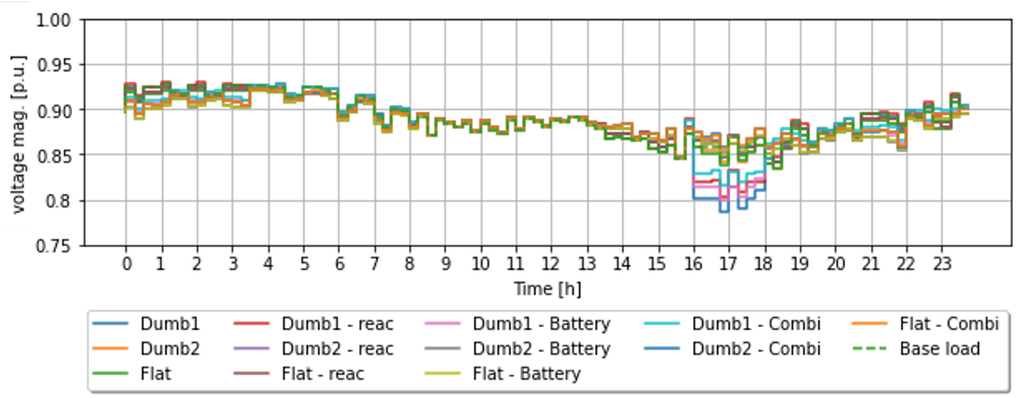


Figure 47: Voltage magnitude for bus 96 for the different cases

voltage levels are still increased from 0.786 p.u. for Dumb1 without measures to 0.815 p.u. with a combination of measures.

8 Discussion

The following section aims to summarise, discuss and compare the main findings from the result sections. The first subsection discusses the base case performance before the impact of EV charging is discussed. Further, the impact of PV production, as well as the additional measures, is discussed. Then, grid infrastructure is discussed, where a cost vs utility discussion about grid investments takes place. In the end, uncertainties, assumptions, and limitations in the thesis are discussed.

8.1 Performance of the base case

The base case was made to highlight the performance of the power system with the base load from the system, to be used as a reference case when analyzing the cases. The base load consists of the normal load from all households and offices in the system and the load profile for two FCSs and a ferry charging. Results from the base case for respectively LOW and HI scenario are presented in Equation 9 and Equation 10. For both scenarios, the reactive power correlates with the voltage magnitudes. This can be seen in the LOW scenario figure with the voltage magnitudes performing their best during the whole day, with over 0.95 p.u., when the total reactive load is at its lowest, around 1.6 MVAr. Further, the lowest-performing voltage magnitudes can be seen correlating with the total reactive load, which is at its highest of around 2.4 MVAr during afternoon hours. The behavior of the base case for the HI scenario is quite similar to the LOW scenario, only in this scenario, the load demand is higher, resulting in higher loads and reactive loads and lower (worse) voltage magnitudes.

8.2 Impact of EV charging

The aim behind adding EV charging to the power system was to highlight and analyze the impact EV charging can affect a power system. As described in section 3, EVs bring challenges to the grid, with high load demand over short and possible critical hours. However, EV charging is a flexible load, which can be spread out throughout the day and at a lower power rate. Therefore, three different EV charging cases are made in this thesis to analyze this flexibility.

The Dumb1 case was made as a worst-case to highlight a high amount of charging straight after work hours when power grids are often congested. In addition to the Dumb1 case, two more flexible cases, Dumb2 and Flat charging, were made to analyze how a more flexible and spread out charging would affect the grid. Looking at the load curves for the EV cases for both demand scenarios in Figure 23 and Figure 24, it is clear that the Dumb1 case has a much higher load peak than the other cases. The load peak of the Dumb1 makes a very notable impact on the voltage stability of the buses. This is especially true for the HI scenario, where the voltage is already not stable from the base load. Adding Dumb1 load on top of the base load makes the voltage magnitudes drop even further in the hours 16-19, as seen in Figure 25. With the lowest magnitudes staying around 0.80 p.u. during the three charging hours, a bottom point as low as 0.786 p.u..

The active load differences are displayed again for the voltage magnitudes, where Dumb2 and Flat cases have much better voltage stability results than the Dumb1, as seen in respectively Figure 27 and Figure 29. Both these charging cases have a more flexible charging than the Dumb1, with charging hours being spread throughout the day, except for during working hours, as seen in the figure Figure 16. For the Dumb2 case, all cars are charging at the same power and duration as in Dumb1. The only difference is that the charging of each car is set to start at a randomized (possible) time step. In contrast, the Flat charging is a slow charging case, where all cars charge throughout the day, except for working hours, at a lower power rate than the Dumb1 and Dumb2 charging. The load profiles for the Dumb2 and Flat charging cases are pretty similar, with only slight deviations as shown in Figure 17. This results in a similar performance in different cases, with only slight differences.

8.3 Impact of solar power to the grid

In this thesis, PV panels are added to the power system to clip load peaks by producing local solar power to the grid. The magnitude of power production differs between the two load scenarios, with power production from the PV panels set as 0 MW during the HI scenario. The reasoning behind this is that the HI scenario is defined to represent load demand in Norway during the winter. During the winter in Norway, there are usually small amounts of power to produce from PV panels due to climatic conditions. However, for the LOW scenario, which is defined as during the summer, there is a possibility of producing a higher magnitude of power from PV panels. Each household and office in the power system are assigned a specific number of PV panels, where each PV panel produces the same amount of power. The power curves of the PV panels are made solely for this thesis, based on the assumed power output gathered for a chosen location in the southwest Norway.

The addition of produced power from solar panels from all the households and offices in the power system can be seen making an impact. First in Figure 23 where the EV cases have dropped a few MW underneath the Base Load case, 1.75 MW at the most. Further, this load demand drop gives a corresponding result in the voltage magnitude of the power system as shown in Figure 25, where also Dumb1 charging load is seen making an impact.

As an additional measure, a PV park has been added to the system. A PV park consisting of 15000 PV panels, giving a rated power of almost 5 MW, is assigned to bus 65 in the power system. By adding a PV park and the already power production from households and offices, it is now a high production of solar power in this system. This highly affects the load demand, with the produced power clipping the load peaks. This further impacts the voltage magnitudes, with lower load demand and the local power production adding voltages to the system. As seen in the summary of the cases in Table 9 the voltage magnitudes are highly affected by the high addition of solar power. The Flat charging case with PV2 production (PV production from households and offices and the PV park) resulted in the highest bottom point of voltage magnitudes among all cases, with a magnitude of 0.912 p.u. By comparing the charging cases with PV park measure in Figure 46 with the base load, it is clear to see that a large number of PV panels impacts the voltage magnitudes in a very positive way. The high power production pushes the voltage magnitudes at the sun peak hours towards a nominal voltage of 1.0 p.u. Such addition of power production is missing in the HI scenario, where most of the voltage magnitude curves are constantly staying around and below 0.90 p.u. throughout the day, as seen in Figure 47.

8.4 Impact of additional measures

Adding EV charging to the power system affects the power and voltage quality. Using the flexibility of EV charging and spreading the charging throughout the day in cases Dumb2 and Flat, the resulting power and voltage quality were seen to increase compared to Dumb1 results. To further better the quality of the power system are, additional measures implemented. The first additional measure of adding a PV park has already been discussed in subsection 8.3, the further additional measures and a combination of these will be discussed in the following subsections.

8.4.1 Impact of Reactive power support

The second additional measure added to the charging cases is reactive power support from EV charging and FCSs & ferry. This is a direct measure of the voltage quality as it affects the reactive load, which directly affects the voltages in the buses as described in subsection 3.2. By inserting the measure to the three charging cases, one can see that the reactive load in the system is dampened for all cases compared to the base reactive load shown Figure 21. The reactive power support in Dumb1 charging, from 16:00-19:00, makes a notable impact as seen in Figure 35 and Figure 36 for the LOW and HI scenario. The total reactive load has a negative value during these hours, meaning more reactive power is delivered to the grid than consumed. In addition to the supply from the EVs, does also the FCSs and the ferry supply the grid with reactive power for several time steps throughout the day. This reduction of reactive load due to the reactive power support impacts the power grid in the way that the voltage stability increases. As described in section 3: "Reactive power consumption results in a lower bus voltage, while reactive power injection results in a higher bus voltage".

8.4.2 Impact of the battery energy storage systemy

A BESS was also added as an additional measure to further utilize the flexibility of the loads in the grid. A BESS makes it possible to shift load demand from load peaks to other time steps, i.e., peak clipping and load filling. The BESS was in this thesis added to the HDEV FCS in bus 48 to dampen the high peak loads here. There were made two different BESS sizes, one small BESS to dampen the highest peaks and one large BESS to dampen more load peaks. The small BESS does make a positive impact on the load demand. This can be seen by comparing the voltage results for the Dumb1 charging case with a small BESS in Figure 39 with the Dumb1 charging without any measures in Figure 26, both for the HI scenario. However, the impacts from the small BESS are of small magnitude. Therefore, are further in the thesis, the larger BESS mostly used when looking at the BESS as an additional measure.

By implementing a larger BESS, the resulting impact of a BESS becomes clear. The large BESS decreases the load demand from the HDEV FCS in the most critical load demand hours. This load reduction is beneficial for both power quality and voltage quality, as it increases most of the buses' voltage magnitudes around afternoon hours.

8.4.3 Impact of a combination of measures

A combination case of the additional measures was made to analyze how a maximum voltage quality increase would affect the power system. For the HI scenario are the three charging cases with a combination of measures performing the highest bottom point of the voltage quality in the system, as seen in Table 10. The flexible charging cases perform best with 0.848 p.u. as the bottom point voltage magnitude. This is an even better performance than the base case, which had a bottom point of 0.897 p.u. The correlation between low load demand giving a high voltage quality is also shown in the table, with the load peaks also being dampened in the flexible charging cases with the combination of measures.

For the LOW scenario, the combination case with all the additional measures resulted in the best voltage quality performance of all cases. As can be seen in Figure 46, the voltage curves from the charging cases with a combination of measures perform the best. However, looking at the bottom point performances between the cases as seen in Table 9, is it the Flat charging case with PV park measure that has the best voltage quality bottom point, of 0.912 p.u. The reason behind the PV park giving the best bottom point, and not the combination measure, or equal bottom points, is because of the BESS. The BESS performs load shifting by moving loads from critical to other time steps.

8.5 Discussing the grid

This thesis aims to analyze the impact of EV charging in a modern power grid and analyze possible measures to reduce grid impacts from EV charging. As described in subsection 2.4, are today's power grids not dimensioned to withstand the high electrification seen in the latest of years and expected to come in the following years. The grid needs to be upgraded and reinforced to accommodate this electric transition. Several grid reinforcements have already begun, and more are expected to come in the following years.

The problem, however, is that grid planning and investments may take years before they are put in motion. The high increase of new EVs, electric ferries, and other electrified services may not take that many years, resulting in a need for action. The question then is whether one should accelerate the grid reinforcements to a higher cost or implement ancillary grid services, such as DSM, in the meantime. Applying DSM to the grid could be beneficial to maintaining grid stability and reliability in response to variances in power supply and demand due to the high electrification. By implementing the additional services investigated in this thesis, such as PV production, reactive power support, and a BESS, it is possible to utilize DSM methods such as load shifting, peak clipping, and valley filling.

Pricing of electricity and costs was not part of the objectives of this thesis but will be decisive for whether one chooses to upgrade the power grid or use these flexibility options as analyzed in this thesis. It is possible to run "optimal power flow" (OPF), which minimizes the total costs of operating the grid. However, it will also require many assumptions about the pricing model for power system costs, access to power system data for BESS management, and more. Which is out of scope for the task but a possible further work.

8.6 Uncertainties, assumptions and limitations

There are several assumptions and limitations made in this research. Therefore, it is essential to emphasize that the result is not precisely realistic in the real world. However, several assumptions and limitations are inspired by literature or similar work and are made as realistic as possible. Also, by comparing the results with literature and similar work, it is possible to draw lines to reality. The discussion, comparisons, and conclusions made from the results are drawn based on theory and literature.

Especially in the making of the grid, it is important to emphasize that it is not totally equivalent to real-world grids. Firstly it is worth noting that converting the grid specifications from matpower format to pandapower format may include some errors. However, the conversion was done in the best possible way, using the theory given in their respective documentations and electric power theory and literature. Another uncertainty is that power system input values received from CINELDI are not made to match the objective of this thesis. With the received grid specifications not being near able to handle the significant load cases investigated in this thesis.

Due to little information about the grid in the forms of what was creating the loads and more, several assumptions were taken. Making aggregated loads and dividing them into building categories according to load size. The HI scenario has a very high load demand which makes the system unstable. In the real world, the monopolized DSOs are obliged to keep the power system stable at all times.

The chosen power system used in this thesis is, with the assumptions made and FCSs & ferry additions, a very congested and unrealistic power system. A possibility could have been to shift the normal loads such that the system would be more realistic. However, this was considered unnecessary, as this was not in the scope of the work. The objective of the thesis was to analyze how adding EV charging would affect a power system and then present measures to better the power quality with this addition. This is possible to do even in an already congested power system. For future work, a more realistic power system with better voltage stability from the base case could be of desire.

9 Conclusion

In this master's thesis, the impact of EV charging in a modern power grid has been analyzed. Three different EV charging cases are made to analyze how different charging strategies can affect the power system. A worst-case scenario was first made here all charging happens straight after work hours, 16:00-19:00, when the grid often is congested. The two other charging cases were made more flexible, with the first case consisting of EVs having to start charging at randomized time steps throughout the day, except during working hours (08:00-16:00). The last case had a slow charging approach, where all EVs constantly charge at a low power rate throughout the day, except for working hours. The grid and charging cases were analyzed by performing power flow calculations of the grid, with load inputs from the different cases, over a time series. These calculations make it possible to analyze the impact of EV charging on the grid, for example, by load demand, reactive load demand, and voltage magnitudes of the buses. The most essential technical variable in this analysis is the voltage magnitudes in the buses, which describes the voltage quality of the system. In a power grid, the voltage quality of the system is an important aspect, as the voltage of each bus needs to be within certain limits to secure a stable power grid.

The power grid used for this thesis is a test grid made from preliminary work in CINELDI. Several additions are made to the test grid in order to have a modern representation. Local solar power production is added to the system by assigning PV panels to all buildings in the system. In addition to PV panels are some loads from electrified transportation added: A fully electric ferry and two FCSs, one for EVs and one for HDEVs.

The EV case studies show that utilizing the flexibility of EV charging rather than charging all EVs simultaneously over a small time period results in a minimal grid impact. In a high load demand scenario, the load peaks of the system are decreased by 6 MW from the worst-case scenario to the flexible charging cases. The decrease of load demand results in an increase in voltage magnitudes at the buses, where the bottom point of the weakest bus has been raised by 0.048 p.u. and 0.049 p.u. in the two flexible charging cases.

To help better the grid integration of the load demanding EV charging, three additional measures are implemented to the charging cases. The additional measures added to the EV charging cases are a PV park with a 4.67 MW rated power, reactive power support from EVs and FCSs & ferry, and a BESS added to the HDEV FCS. The measures are added to all three charging cases, which are then analyzed in the same way as above, with most focus on the voltage performances. Each measure did make a positive impact on the voltage quality. However, a combination of the measures made it possible to raise the voltage quality in the system sufficiently. The overall best performing case for the power grid were a flat charging case with a combination of the additional measures: PV park, reactive power support and a large BESS.

The number of EVs will only increase globally and in Norway in the coming years. The grid impacts of this EV integration may be significant. Therefore, to accommodate this integration and ensure the stability and reliability of the power grid, it is crucial to upgrade the grid infrastructure and/or implement measures to welcome the large electric integration. To answer the objective of this thesis it is shown how damaging dumb charging of EVs can be to the power and voltage quality. Further, it is shown how implementing different measures, individually or in combination, may be crucial to secure grid stability with EV integration in a modern power grid. To conclude, flexible charging of EVs may benefit the power and voltage quality of the grid but will not always be enough to secure stability. Hence, implementing additional measures such as solar PV production, reactive power support, or BESS can be decisive. Especially by combining these measures in flexible charging scenarios, the voltage and power quality could be increased immensely.

10 Further work

The work done in this thesis is can be taken further in many different directions depending on what one wants to investigate. Some specific possible further work to this thesis could be:

- Making the power grid more realistic, with real load demands for all buses. More information about the buses and load, such as what is creating the load demand.
- Adding pricing and dynamic pricing into the research. For example with grid tariffs, pricing on FCSs, on home charging and a more pricing review and overview of the additional measures.
- By adding pricing into the research it is possible to do OPF analysis, which could give an even better discussion about cost vs utility of grid investments to meet future load demand.
- Adding more Local energy communities (LEC) or other local energy production to the power system to analyze how this would affect the system
- Develop vehicle to grid (V2G) to the system, such that EVs can be service the grid with active power in needed hours.
- Develop controllers to the system. For example controllers for reactive power support to increase the voltage stability, such that reactive power support is only activated when the voltages is below certain limits.
- Making the additional measures more advanced. For example the batteries in the BESS could me made more advanced and realistic.
- Further develop the system and making it more advanced, loads and generations could be made more realistic and advanced.

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Appendix

A Power flow results - Additional measures

A.1 PV park

Flat charging

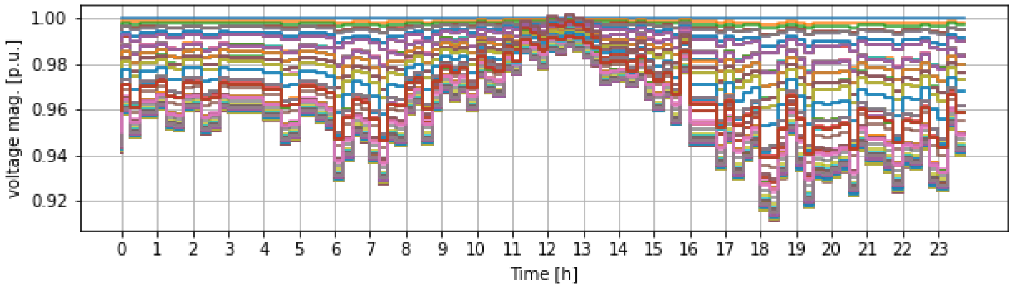

Figure 48: Voltage magnitude for the Flat case with PV2 solar power production

A.2 Reactive power support

Dumb2

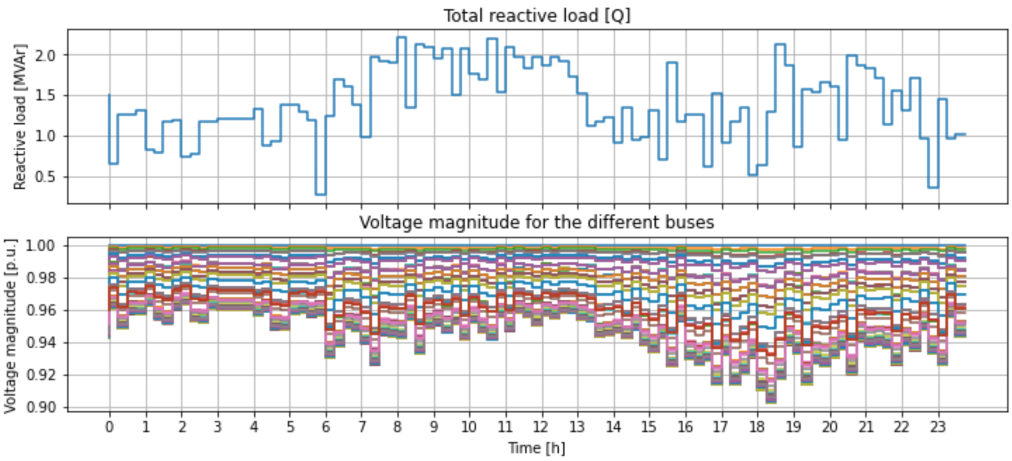

Figure 49: Voltage magnitude for the Dumb2 charging case with reactive power support for the LOW scenario

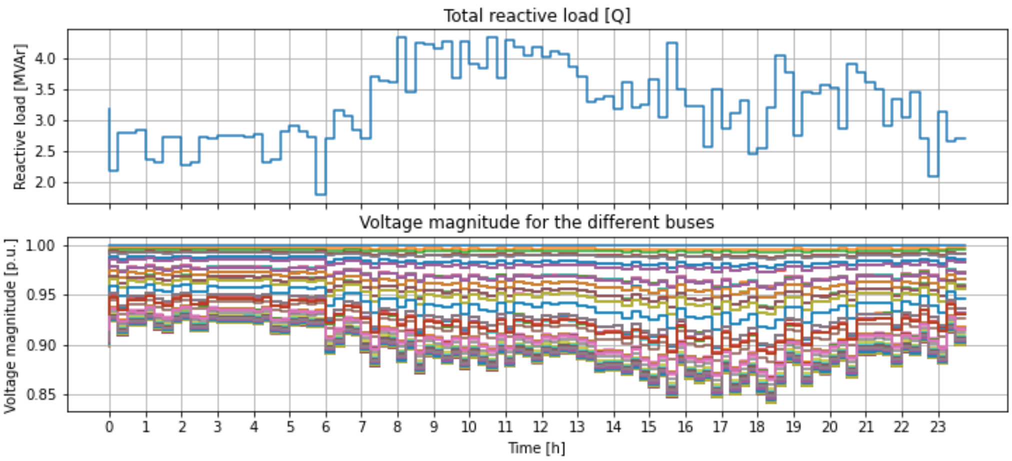

Figure 50: Voltage magnitude for the Dumb2 charging case with reactive power support for the HI scenario

A.3 Battery - Large

Dumb1

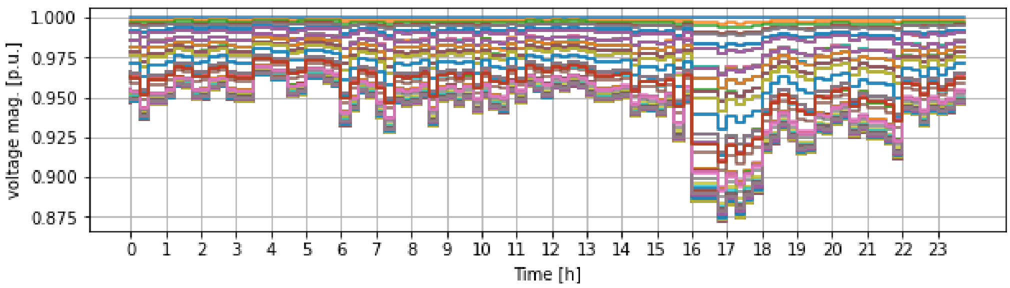

Figure 51: Voltage magnitude for the Dumb1 charging case with large battery placed with the HDEV FCS for the LOW scenario

Dumb2

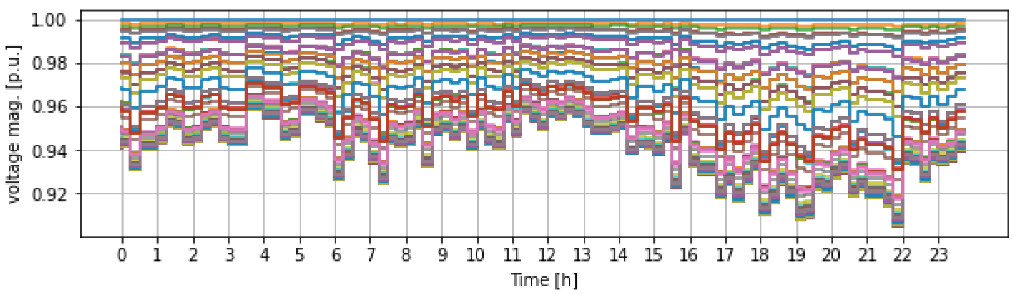

Figure 52: Voltage magnitude for the Dumb2 charging case with large battery placed with the HDEV FCS for the LOW scenario

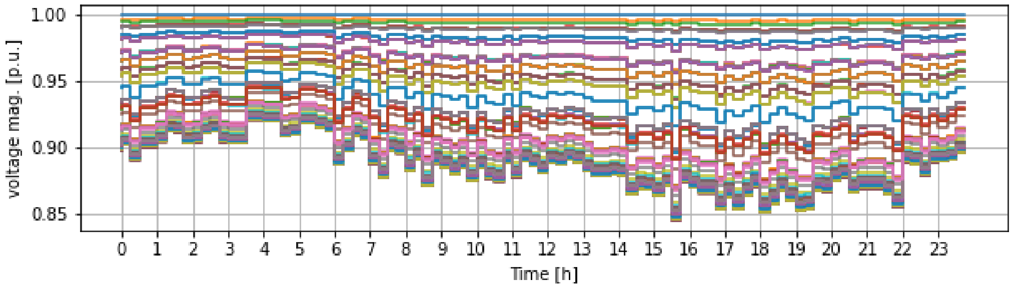

Figure 53: Voltage magnitude for the Dumb2 charging case with large battery placed with the HDEV FCS for the HI scenario

Flat

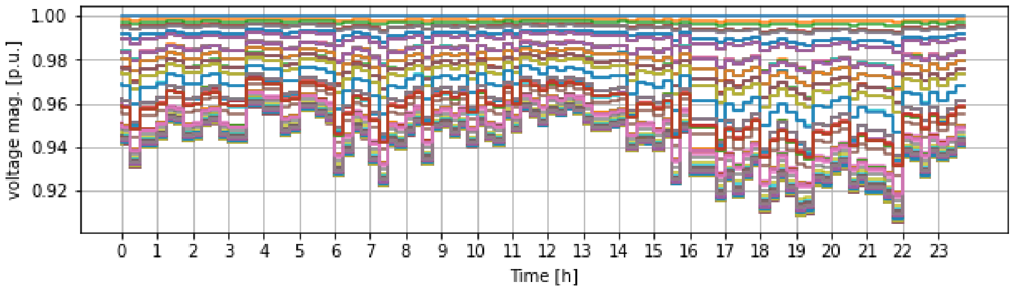

Figure 54: Voltage magnitude for the Flat charging case with large battery placed with the HDEV FCS for the LOW scenario

A.4 Combination of measures

Dumb2

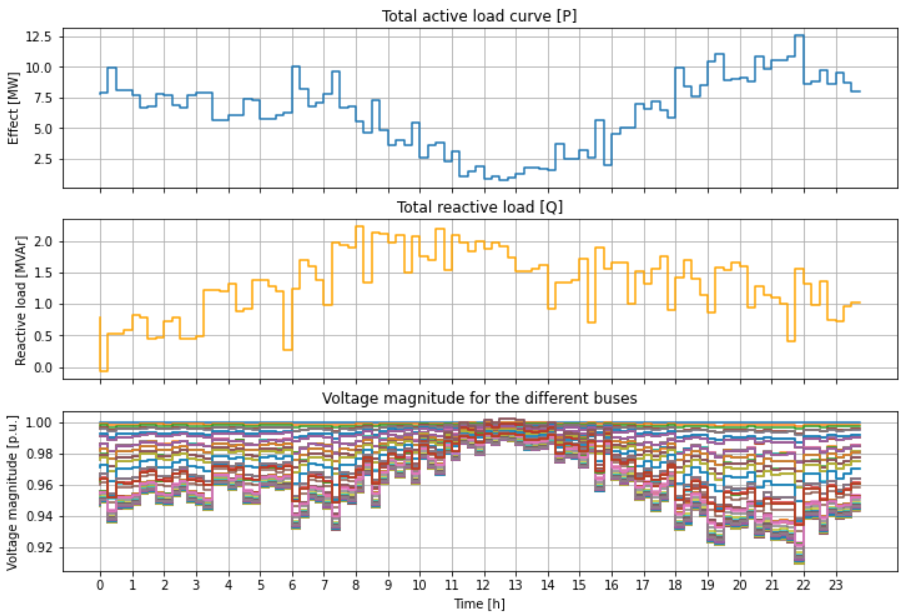

Figure 55: Voltage magnitude for the Dumb2 charging case with combination of measures for the LOW scenario

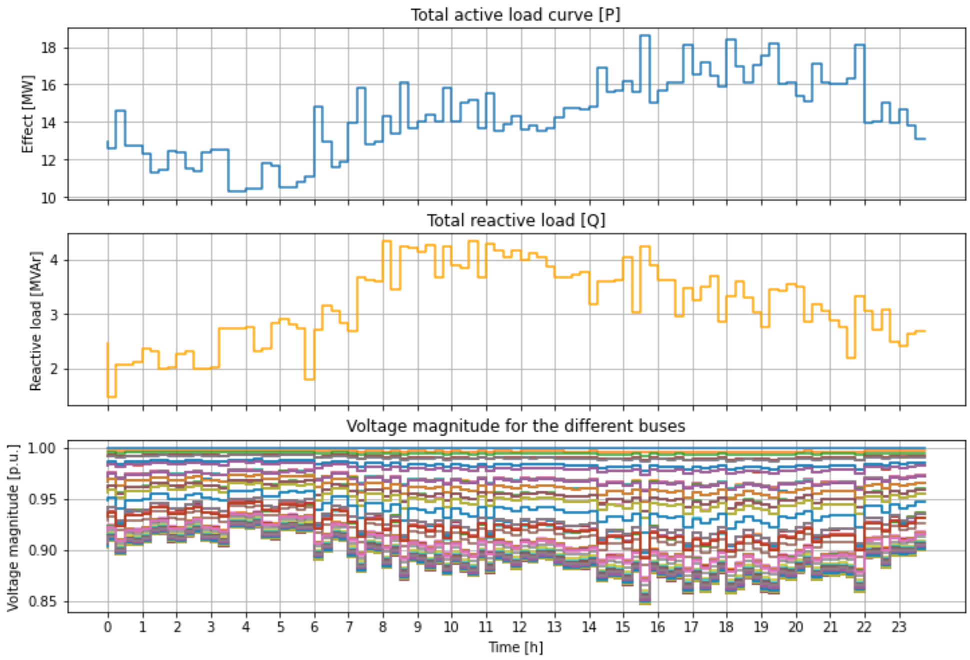

Figure 56: Voltage magnitude for the Dumb2 charging case with combination of measures for the HI scenario

Flat

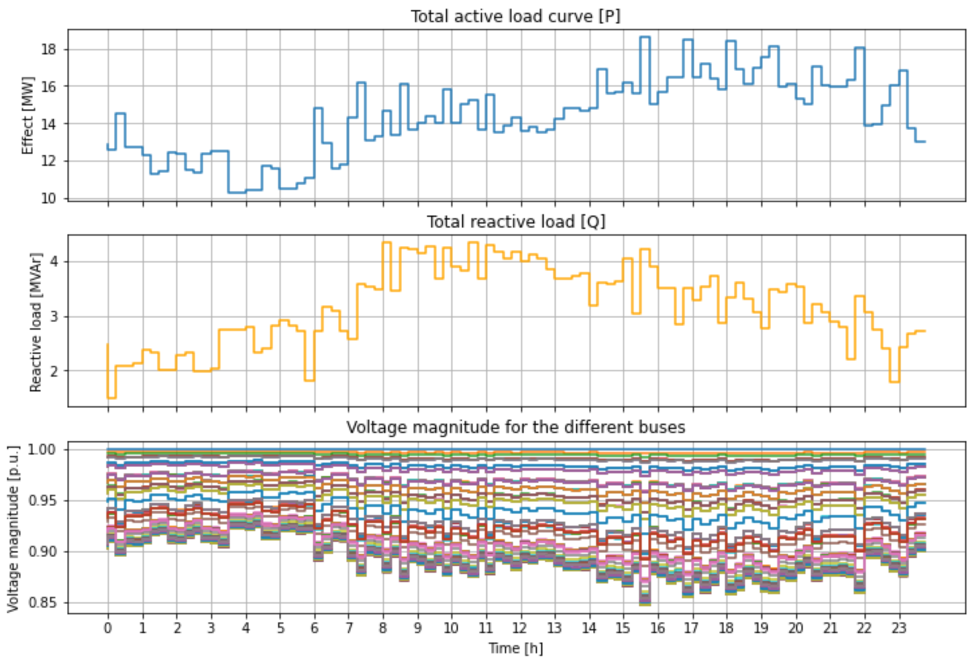

Figure 57: Voltage magnitude for the Flat charging case with combination of measures for the HI scenario

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