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Flexibility Solutions in Distribution Networks

Case Study Utsira

Master's thesis in Energy and Environmental Engineering
Supervisor: Irina Oleinikova
Co-supervisor: Hanne Sæle
June 2021

Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Information Technology and Electrical Engineering
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Abstract

The modern power system is currently facing challenges regarding increasing electrification, the integration of variable renewable energy (VRE), and the growth of distributed energy resource (DER)s. Flexibility in the power grid is seen as an important part in overcoming these challenges. This work presents an analysis of the potential and need for flexibility in the distribution grid on the island of Utsira. Flexible resources such as energy storage and load shifting have been discussed and presumed to be valuable for achieving ample grid conditions in regard to future electrification. A model of the distribution network has been made, and possible scenarios constructed, to show through simulations that increased electrification of the island will cause significant voltage variations in the grid without sufficient alleviation. Scenario cases with implemented flexibility solutions, such as energy storage and shifting of loads, were then simulated, demonstrating a significant, positive impact on grid conditions.

Sammendrag

Dagens kraftsystem står ovenfor flere utfordringer knyttet til elektrifisering, integrering av variabel fornybar energi og veksten av distribuerte energiressurser. Fleksibilitet i kraftnettet blir sett på som en viktig del av å løsningen for disse utfordringene. Dette arbeidet presenterer en analyse av potensialet og behovet for fleksibilitet i distribusjonsnettet på øyen Utsira. Fleksible ressurser som energilagring og lastflytting har blitt diskutert og er antatt å være verdifulle for å oppnå gode nettforhold med hensyn til fremtidig elektrifisering. En modell av distribusjonsnettet har blitt laget og mulige scenarioer konstruert for å gjennom simuleringer kunne vise at økt elektrifisering av øyen vil føre til betydelige spenningsvariasjoner i nettet uten tilstrekkelig utbedring. Scenario caser med implementerte fleksibilitetsløsninger som energilagring og lastflytting ble deretter simulert, noe som demonstrerte en betydelig positiv innvirkning på nettforholdende.

Preface

This master thesis concludes our five year Master of Science (MSc) degrees in Energy and Environmental Engineering at the Norwegian University of Science and Technology (NTNU). The work in this thesis is done in cooperation with Haugaland Kraft Nett AS and FME CINELDI.

We would like to thank our supervisor, Professor Irina Oleinikova, for your guidance. We are grateful for your support, availability for discussions, and for motivating us during the process. Further, we would like to thank our co-supervisor Hanne Sæle for your expertise and for giving us new insight. Additionally, we would like to extend our acknowledgment to Kristian Finborud Hansen and Leif Eivind Nesse, and the rest of Haugaland Kraft for providing us with the necessary information and data for completing our thesis.

Contents

List of Figures

List of Tables

Abbreviations

AMS advanced metering system

BESS battery energy storage system

CEP the Clean Energy Package

DER distributed energy resource

DG distributed generation

DSO distribution system operator

DSR demand side response

EU European Union

EV electric vehicle

EWH electrical water heaters

IEA The International Energy Agency

NR Newton- Raphson

NVE Norges vassdrags- og energidirektorat

PF power factor

PV photovoltaic

TOU time-of-use

TSO transmission system operator

V2G vehicle to grid

VRE variable renewable energy

Introduction

Motivation

As the global energy demand is increasing, the world is simultaneously working to combat climate change and its impacts. Electrification is additionally leading to an increase in high power demanding power electronic devices. Increased clean electricity production is crucial if the global temperature rise should be limited to 1.5 °C [1], and renewable energy is a key part in achieving this. The expanding integration of VREs, however, requires a more flexible power system compared to how the traditional system is built. Additionally, the implementation of DERs is complexifying the grid and challenges the role of system operators. Efficient operation of the changing power system is dependent on an increase in system flexibility. Flexibility resources can be viewed as a valuable alternative to expensive grid reinforcements, and the mapping and analysis of these resources is therefore vital.

The consumer plays a key role in the new Electricity Directive of the European Parliament to achieve the goals set out in the European Green Deal [2]. The implementation of EVs, rooftop photovoltaic (PV)s and smart household devices leads to an increased flexibility potential at the end-user level. The customers need to be stimulated to become more active market participants, to contribute to keeping the power system in balance.

The municipality of Utsira is expecting a sharp rise in power demand due to increasing industry activity and electrification, amplifying the already existing voltage issues induced by the island's weak grid and varying wind power generation. Flexibility could in this system be of great value in ensuring sufficient quality of grid operation. In this thesis, the potential of and need for various flexibility solutions related to different aspects of this grid is therefore investigated.

Main objectives

This thesis investigates how flexibility solutions can improve future voltage conditions in the distribution network on Utsira. The conditions are expected to be problematic, caused by increased electrification combined with pre-existing problems. The main objectives of the work in this thesis are:

- Analyze the potential and need for flexibility in the distribution system on Utsira.
- Develop a model of the distribution network on Utsira to simulate scenarios for how electrification and increased power demand will affect the existing distribution grid.
- Investigate how flexibility resources such as demand side response (DSR) and energy storage can contribute to voltage stability in the distribution grid on Utsira.

Structure of thesis

The thesis has the following structure:

Chapter 1, *A power system in change*, provides a brief overview of the traditional power system and electricity markets, and how technologies such has renewable energy introduces new challenges to overcome. The chapter ends with an introduction to flexibility and its value in the modern grid.

Chapter 2, *Analysis of flexibility potential and need on Utsira*, presents the distribution system on Utsira and the difficulties it is facing. The potential of utilizing different flexible resources to improve system conditions is explored.

Chapter 3, *Simulation model for the Utsira distribution network*, describes how a model of the Utsira network was constructed to perform simulations for different scenarios. The workings of the model, the data used as well as simplifications and assumptions are further detailed in this chapter

Chapter 4, *Flexibility scenarios at Utsira*, contains scenarios that have been constructed to reflect possible future states of the Utsira distribution grid. Simulations have been done to research the impact of flexible resources on the grid in these scenarios, focusing on changes in voltage profiles, and the results are then discussed for further analysis.

Chapter 5, *Conclusions*, draws the main conclusions of the thesis, and proposes possible avenues for further work.

Chapter 1

A power system in change

Electrical power systems have seen tremendous development since the first one was built in 1881, to power the 34 incandescent streetlights of the English town of Godalming [3]. They are now usually vast, complex grids consisting of many electrical components, power producers and power consumers. The power system can traditionally be divided into the three main levels: generation, transmission and distribution. The generation of power has usually been centralized in large power plants, such as thermal, nuclear and hydro [4]. As illustrated in Figure 1.1 the power is then supplied to end users through the transmission grid and then the distribution grid. The overall system needs to be in constant balance, as the production of power always has to equal the consumption of power.

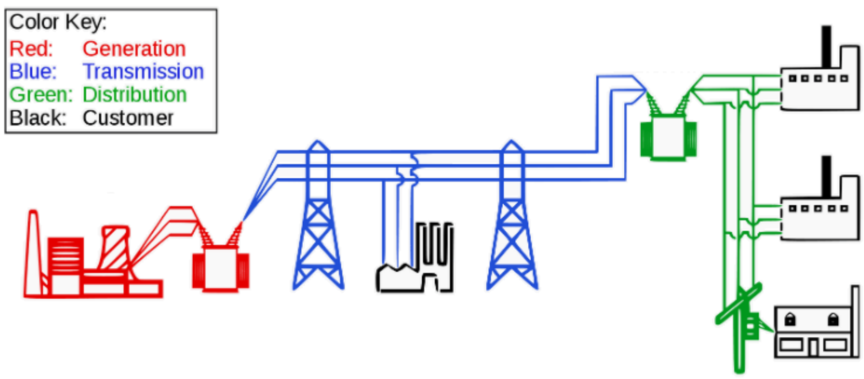

Figure 1.1: Simple illustration of the traditional power system [5]

As the world is working to combat the crisis of climate change, renewable energy production is increasing and is replacing traditional, flexible, polluting power generation: the Clean energy for all Europeans package, a 2019 update to the EU energy policy framework, sets a target for the share of renewables in the European Union (EU) energy mix of 32% by 2030 [6]. This is further escalated by the rapid electrification of industry and the transport sector, increasing the demand for clean, electric power. The total European plug-in-hybrid- and battery- electric vehicle (EV) stock increased from about 1,25 to 1,75 million vehicles from 2018 to 2019, constituting an approximately 40% growth in EVs [7]. Additionally, technology is evolving, leading to new grid components, new ways for power to be distributed in the grid and new methods of grid operation. The traditional model is no longer an accurate representation of the modern power system.

1.1 Variable renewables and distributed energy resources

Variable renewable energy

The ambitious EU target of being climate-neutral in 2050 will cause a total elimination of the European coal industry, and a major reduction of the gas industry[8]. Wind and solar power will produce a significant portion of the power lost from these industries; the implementation of solar PV and wind power to the power grid and the replacement of polluting, thermal power plants is a necessary step to reduce carbon emissions. It does, however, introduce new difficulties in regards to the key properties of VREs, which wind and solar generation is categorized as [9].

- **Variability:** The power production of VREs is dependent on resources such as wind and sunlight, which are by nature sporadic and unreliable, making it impossible to have full control over the power production of these facilities. This contrasts with conventional generation, which uses stored resources like water, coal and gas to generate electricity, such that controlling the power production is possible through increasing or decreasing the flow of the resource to the plant. VREs can be curtailed to reduce power output, but the dispatchabiity of conventional power is missing. An analysis of the future European power system by the Norwegian regulator Norges vassdrags- og energidirektorat (NVE) predicts that adjustable power resources will be reduced from 80% to 50% in 2040 as more wind and solar energy is introduced to the energy mix [10]

- **Uncertainty:** It is difficult to accurately forecast weather conditions, and therefore not possible to create completely reliable power production prognoses and plans for wind and solar power production. As non-VRE power producers rely on a resource reserve for generation, their production can, on the other hand, be planned ahead of time such that a combination of generators can be scheduled to meet projected demand.

- **Non- synchronous:** VREs are not directly connected to the power system through a spinning mass, such as for conventional generation, but through power electronics. They are therefore non- synchronous, providing no innate inertia to the grid. A system with a high penetration of VREs can therefore have frequency and stability issues if no steps are taken to remedy this.

- **Locational restrictions:** VREs are constrained by location. To efficiently utilize VREs, they should be implemented in locations were the conditions are adequate, i.e open areas with high amounts of wind, or places with low cloud coverage and strong solar radiation. These areas may be located far from demand and not in optimal places for grid connection, which may cause long electricity travel distances, negatively affect grid stability, and require comprehensive grid expansion. Conventional generation like thermal and nuclear is, on the other hand, not overly dependent on location and can thus be placed more conveniently in regards to the power grid.

The total energy generated by VREs is increasing, and will do so for the foreseeable future. Because of these key properties, this increase is making power systems more complex and introduces new challenges, such as grids becoming less flexible in their power supply. New technologies and further developments are key to ensure sufficient power system operation with VREs supplying a larger and larger share of the global electricity production.

Distributed energy resources

In contrast to traditional, large power plants such as coal and nuclear, wind and solar plants are often smaller and directly connected to the distribution grid [11]. A common term used for small-scale technologies producing electricity close to the end-user, like rooftop PVs and micro wind turbines, is distributed generation (DG). Generation of energy closer to where it is used can increase energy efficiency by avoiding large transmission losses over long distances and bottlenecks by optimal location of the power plants [12]. The increasing implementation of renewable energy sources is leading to an increase in the volume of distributed generation. As illustrated in Figure 1.2, the global share of wind and solar PV installation capacity will increase and surpass natural gas and coal within 2025 according to The International Energy Agency (IEA)s analysis of renewables from 2020 [13]. A high share of this increased capacity will be part of in the distribution grid.

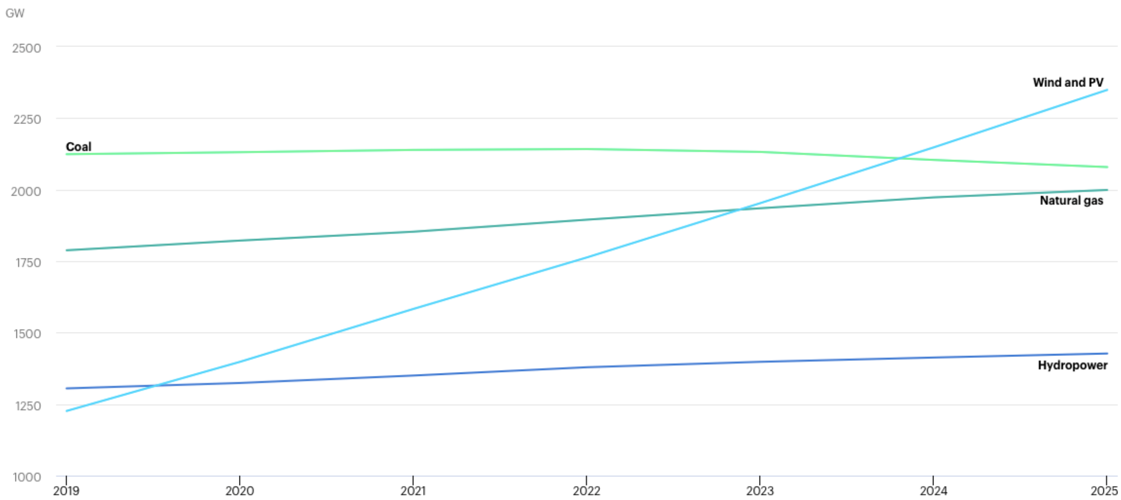

Figure 1.2: Total installed power capacity by fuel and technology, 2019-2025 [14].

The term DER includes DG as well as other distributed grid resources, such as battery energy storage system (BESS), plug-in EVs, and controllable loads (through for instance load shifting and curtailment). DERs can be implemented at the customer level in the grid, creating greater consumer participation and making the customer a so called ”prosumer” [15]. This changes the operation of the power system, which traditionally was designed for power flowing from large, centralized plants to the end-users. Introducing DERs makes for a more complex distribution system, with many uncertain components that challenges the role of the distribution system operator (DSO). Figure 1.3 illustrates how the implementation of DERs changes the power system structure, from one way power flow, to power flowing bi -directionally in the grid.

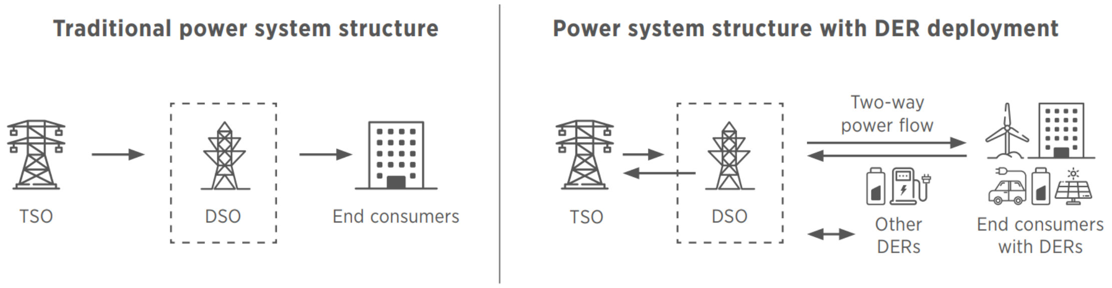

Figure 1.3: Illustration of how the implementation of distributed energy resources changes the power system [16].

To utilize the DERs connected to the distribution system, the DSO should be an active system operator by aggregating these resources, making the distribution system more flexible [16]. Generally, the regulatory framework does not allow the DSO to have direct access to all the DERs available. The DSO could then act as a market facilitator, providing price signals to the prosumers or the owner of the DERs.

Voltage quality in the distribution network

One of the main challenges facing the DSO by the increased penetration of VREs in the distribution grid is to ensure a stable and high voltage quality. The traditional distribution grid is made to distribute power from large power plants to the end-users, and the voltage is expected to decrease further out into the distribution network. Introducing DG will increase the voltage at some points in the grid. If the distributed power generation is variable, the voltage will be varying and sometimes unpredictable. The increase in more power-intensive and complex power electronic devices such as fast EV chargers creates further challenges and requirements for good voltage quality in the distribution network [17]. Implementing VREs and increasing demand in an already weak distribution grid may result in transient over voltages, voltage oscillations and system instability [18].

The Norwegian DSOs are responsible for keeping the voltage within in the limits of quality of electric supply given by NVE [19]. The Norwegian quality of supply regulation includes i.a. minimum requirements for voltage frequency, supply voltage variations, rapid voltage variations, short- and long-term flickering and voltage unbalances [20]. The regulation of supply voltage variations includes a limit of $\pm 10\%$ change of the RMS value of the voltage in the LV grid for a given time interval.

However, planning and coordination of these new components in the distribution network can contribute to an increased capability of voltage regulation.

1.2 Electricity prices and markets

While the transmission and distribution of energy is naturally monopolistic, an electricity market is established to ensure efficient use of the energy resources.

A restructuring of the energy industry in European countries started in England with a new Electricity Act in 1989 [21]. The Norwegian parliament followed with the Energy Act of 1990, which was the beginning of today's Nord Pool [22]. Nord Pool is a marketplace for power trading spanning across 16 European countries [23].

Nord Pool offers trading for both day-ahead and intraday markets. The day-ahead market is called the Elspot market and is the marketplace where the majority of the power in Nord Pool is traded. In the electricity market, there must be an instant balance between generation and consumption, and that makes the basis for the electricity price. In the Elspot market, the Nordic and Baltic countries are divided into areas [24]. The price is calculated for every hour for each area based on one aggregated demand curve and one aggregated supply curve for every hour of the next day. The Intraday market makes it possible to do corrections closer to the operating hour to achieve power balance.

To secure an instantaneous power balance the transmission system operator (TSO) operates a balancing market [25]. In case of unforeseen events in the operation hours, the TSO needs to ensure that there is sufficient regulative capacity available. Bidders in this market get paid in advance to guarantee they have reserves available if needed.

The area price is a result of providers and consumers in the area as well as transmission capacities between areas. The power will always flow from low price areas to high price areas. Traditionally, the Norwegian electricity prices have been low due to the high amount of hydropower, which is a flexible power source. With increased transmission capacity to other countries, electrification and higher taxes for fossil fuels, the Norwegian electricity prices are expected to rise in the coming years.

In 2019 advanced metering system (AMS)-meters were installed at all electricity consumers in Norway [26]. AMS-meters make it possible for customers to get information on their time-of-use (TOU) consumption and price, and can facilitate the customers to react to price signals and participate more actively in the market. As a part of the EU's long-term strategy of achieving carbon neutrality by 2050, an update of the Clean Energy Package (CEP) in 2019 stated new electricity market rules. To be able to meet the needs of renewable energies *"the market must provide the right incentives for consumers to become more active and to contribute to keeping the electricity system stable"* [2]. It is clear in paragraph 10 of the directive that [27]:

> *Consumers have an essential role to play in achieving the flexibility necessary to adapt the electricity system to variable and distributed renewable electricity generation.*

In 2020 NVE suggested introducing new grid tariffs in the Norwegian electricity market to facilitate better utilization of the power grid [28]. The new tariff is suggested based on TOU models, to better stimulate the customers to use electricity when the system demand is low.

1.3 Flexibility in the distribution grid

To be able to effectively utilize DERs the distribution system needs to be flexible. Flexibility is defined as *"the ability to change or be changed easily according to the situation"*[29]. A flexible power system is able to react and respond to changes in the system. In 2021 SINTEF Energy Research developed a precise definition of power system flexibility [30]:

> *The ability of power system operation, power system assets, loads, energy storage assets and generators, to change or modify their routine operation for a limited duration, and responding to external service request signals, without inducing unplanned disruptions.*

A resource that has this ability can be defined as a flexibility resource. Flexibility resources can be adapted into the ancillary services to improve the efficiency of system operation, and as an alternative to grid investments [31]. Flexibility can contribute to support voltage regulation, solve bottlenecks in the distribution grid and as a balancing service [32]. With the increasing integration of VREs to the distribution system, the mapping and utilization of flexibility and flexible resources will greatly benefit system operation.

Classification

There are many types of flexibility resources, differing in various ways. The characteristics of these resources can be generalized in order to give a better overview and allow for easier comparison and analysis. In [30], the characteristics have been separated into two aspects, technical and economic, which are then further expanded upon. This is illustrated in the following chart:

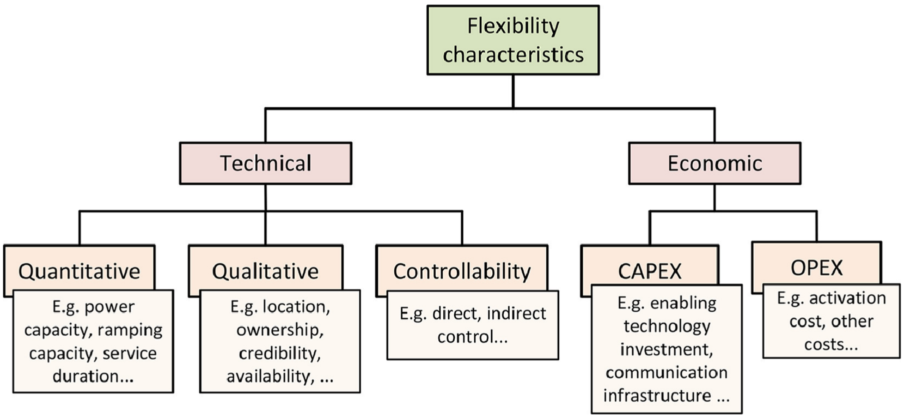

Figure 1.4: A classification of flexibility resource characteristics. [30]

Here, three separate characteristics defines the resource's technical capabilities, qualities and controllability. The economic aspect has been, simply put, divided into long- term investments (CAPEX) and day-to-day operative costs (OPEX). By reducing flexibility resources into these base characteristics, a more general description of the subject is achieved.

In [33], a flexibility classification is applied to system flexibility as a whole. The article presents four dimensions of a flexible power system, three technical and one economic:

- Time: how fast the system responds to deviations and returns to the desired state, in a time period from seconds to months. A system might be flexible on the short term but not long term, for instance.
- Control functions: the span of available corrective response measures, depending on the time interval; the set of choices to handle flexibility needs. A greater flexibility arsenal can increase control and decrease operative costs.
- Uncertainty: the degree of a lack of future system information; a declaration of how much flexibility is needed in the system. Uncertainty is present in conventional systems through varying market prices, outages and inaccurate power forecasts, and the increasing integration of VREs and DERs further boosts uncertainty and thus the value of flexibility.

- Cost: the system operator will always attempt to minimize the costs of system operation. This includes the overall flexibility costs, which are dependent on factors such as the flexibility resource type and economic risk (the cost of a lack of flexibility). For instance, if the costs related to the resource are high but the economic risk is low, high system flexibility investments might not be financially justifiable.

Additional classification of flexibility can be made to provide a better outline. In [34] there is made a distinction between technical flexibility and operational flexibility. Here, technical flexibility is related to the physical structure of the power system; the connected technologies/ components that provide inherent flexibility to the system. This includes resources such as energy storage and shiftable loads. Operational flexibility is defined as how these assets are operated and utilized. It is dependent on both the constraints of the assets/ technologies, and the surrounding regulations and market environment.

Flexibility resources are needed in different levels of the grid and for different applications:

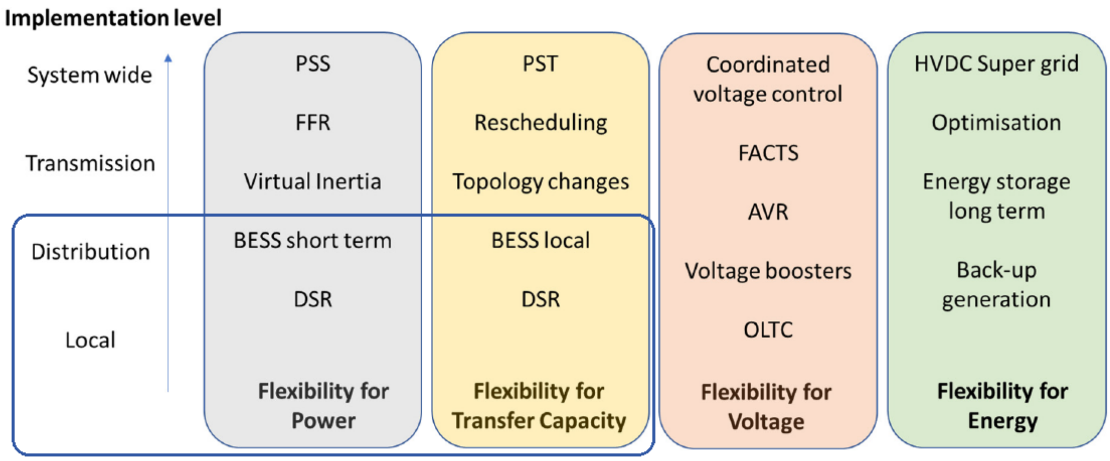

Figure 1.5: An overview of flexibility resources for different grid level implementations and areas of use. The highlighted area is in focus for this thesis. [35]

As presented in Figure 1.5, these flexibility needs can be split into four categories: power, transfer capacity, voltage and energy. Flexibility assets for various implementation levels in the grid can thus be categorized. In this thesis there is a focus on flexibility in the distribution network, and flexible resources that can improve problems related to transfer capacity and high power demand.

Chapter 2

Analysis of flexibility potential and need on Utsira

Utsira is a small island in the North Sea with just under 200 residents, located 18 km from the mainland of the western coast of Norway, close to and directly west of Karmøy [36]. The island has its own municipality, Utsira municipality, and contains an administration centre, school, supermarket and other businesses/ services, making it a small community. Most of these buildings, as well as many households, are located along a 2 km road that crosses from the northern to the southern port of Utsira, which can be seen in Figure 2.1. A ferry traveling between Utsira's northern port and Haugesund connects the island to the mainland, arriving and departing between two and four times a day.

Haugaland Kraft is the DSO of the power grid on Utsira. In the current situation, a 17 km long sea cable with an operational capacity of 1,1 MW is feeding the island with power from the mainland distribution grid, which is also operated by Haugaland Kraft. Additionally, there are two windmills generating power on the north- east side of the island, with a total production capacity of 1,2 MW. The island also has great potential for solar power. The DSO has currently active projects to build PV DG in strategical grid locations, to compensate for periods with poor wind conditions and increase renewable energy production.

Due to plans of building an energy-intensive fish industry, electrification of the ferry and integration of EV's at the island the electricity demand is expected to increase and be more intensive in the coming years [37]. In the coldest winter days the island power demand is already close to the cable's maximum power capacity. The sea cable is not dimensioned for an increase in load considering for instance the variable nature of wind power. Replacing it, however, would be expensive; the DSO has estimated the cost of building a new, feasible sea cable to be about 40 000 000 NOK. Alternative solutions to this construction are therefore being investigated, with one field of interest being power system flexibility. In this chapter the potential and need for flexibility solutions in the distribution system on Utsira will be further investigated.

Figure 2.1: Map of Utsira collected from Kartverket [38].

2.1 Existing voltage problems

The grid is in its current state experiencing notable voltage variations, due to a combination of multiple factors.

The 22kV distribution system on Utsira includes 13 substations transforming the voltage to 400V or 230V, supplying the lower voltage side with power, or receiving power from this side in the case of the wind power plants. These stations and the lines connecting them lie close to and follow the main road, while the 230/400V grid expand outwards to meet customer loads. The power supply from the windmills and the sea cable is located at the eastern end of the network. This radial structure causes increasing voltage difficulties further out in the grid, with the growing distance to the power supply, leading to these voltages being sensitive to changes in power consumption.

The windmills on Utsira produces varying amounts of power, as is the nature of VREs. The load of the island is relatively small compared to its wind production, and the power flowing in the sea cable therefore varies greatly with wind conditions. Voltages are generally low when there is little to no wind, and high when wind conditions are strong. Wind power is often greater than Utsira's own power demand, resulting in Utsira producing power for the mainland and reverse power flow in the sea cable. All in all, this has a big impact on voltages, resulting in large amounts of voltage fluctuations. Wind power must therefore be limited to a total production of 1 MW, half of the actual capacity.

The cable from the mainland has a thermal limit of 5 MW, but is as previously mentioned constrained to 1,1 MW of power flow, as a consequence of the voltage issues stated above and the cable's relatively high impedance. The expected load increase and implementation of more VREs on Utsira will inflate the current voltage problems as power flows will increase, and power production gain more irregularity and other negative effects from the planned PV.

2.2 Potential flexibility resources

As presented in section 1.2, customers play an essential role in achieving a flexible distribution system. With DSR, customers are stimulated to change their electricity use based on a price signal given by a market or the DSO through tariffs, to alleviate grid tension and improve conditions. Figure 2.2 illustrates how DSR can improve problematic load profiles by peak load reduction and valley filling.

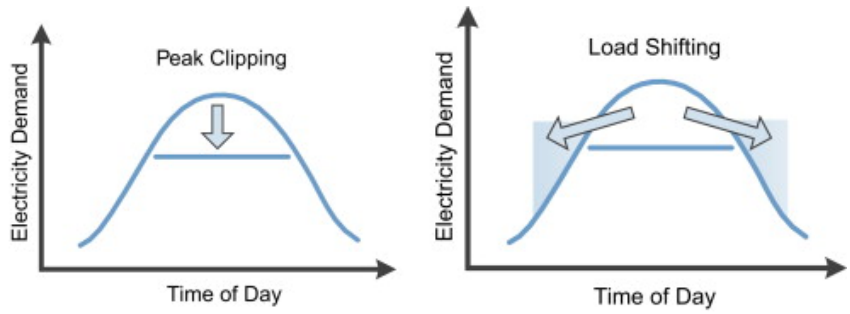

Figure 2.2: Illustration of load profile manipulation through DSR [39].

Household load profiles have typical peaks in the morning and in the afternoon, caused by morning routines and high evening activity. In areas dominated by households, customers could experience low- voltage problems at these times. Through surveys done in 2017 and 2020 among a representative group of Norwegian households, SINTEF Energy Research has mapped that 3 out of 5 households could be willing to change how they use electricity [40].

If flexibility resources are available when electricity consumption is close to the maximum grid capacity they can be used as an alternative to grid reinforcements. Sources in traditional households that can contribute to flexibility in peak demand periods are:

- Delay the start of atomic loads like dishwashers, washing machines, clothes dryers etc.
- Remote control of electrical water heaters (EWH)
- Manually reducing general consumption

2.2.1 Thermal loads

EWHs are large loads that use electricity to heat up and store energy in water. They have large thermal storage capacities and can be turned off for 2-4 hours without negative consequences for the customer's comfort. These properties make EWHs beneficial flexible resources for peak periods. Normal EWHs for households have a capacity of 2 kW, and tests show that the potential for load reduction can be estimated to 0,6 kWh/h in peak periods [41]. [40] showed that 61% of Norwegian households are willing to accept remote control of their water heater.

There are approximately 130 household customers on Utsira. From the total hourly load profile presented in Figure 2.3 for the coldest day in 2021, a morning peak can be observed at around 08:00. If 61% of the water heaters are disconnected in this period, around 48 kWh/h of elasticity could be achieved. As seen in the figure, 48 kWh/h approximately corresponds to the power increase of this peak. Using remote control of the water heaters, peak shaving can be accomplished by shifting loads to lower demand periods.

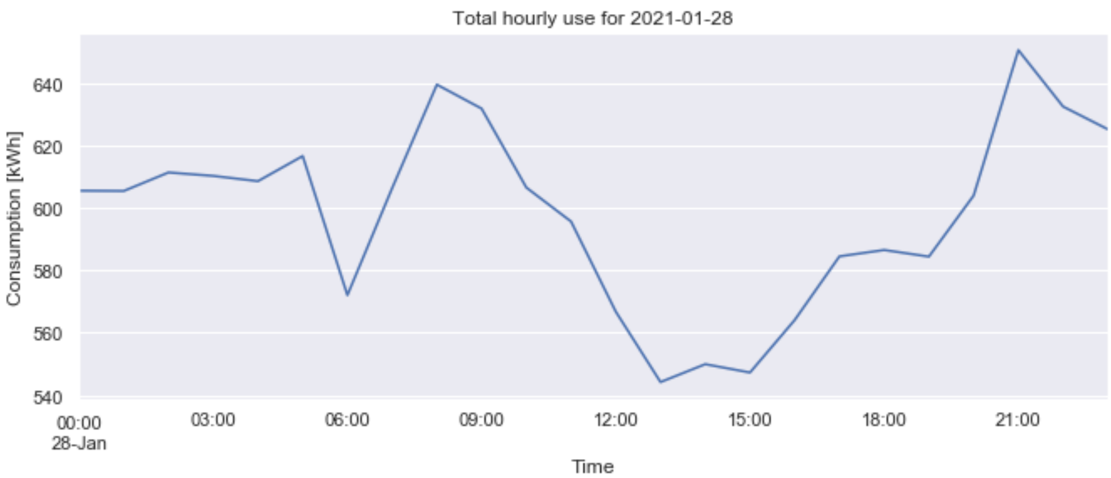

Figure 2.3: Hourly load profile for the total consumption at Utsira on the peak demand day in 2021

Utsira has an administration center where large electric water boilers are used for space heating of the school, sports hall, swimming pool and office building. These electric water boilers have a large thermal capacity and could be turned off if needed in peak demand periods [42]. The substation where these loads are connected has been chosen for further analysis in this thesis.

2.2.2 Estimating potential related to EV charging

As mentioned in the introduction of chapter 1 the electrification of the transport sector has accelerated in recent years. The amount of EVs in Norway has increased by 319,8% from 2015 to 2020 [43]. The Norwegian Parliament has an ambitious goal of all newly sold passenger cars being zero-emission vehicles by 2025 [44]. With this goal fulfilled it can be assumed that close to all cars will need to be charged from the power grid in 2040 [45]. 85-90% of this will be home charging. An average Norwegian household has 1,15 cars, resulting in a high amount of energy-intensive EV chargers in the Norwegian power grid. In areas with an already weak distribution grid, such as Utsira, these high power consuming devices can have a huge impact, and grid reinforcements or improvements will be needed to achieve proper integration.

A survey done by the Norwegian EV association [46] shows that the majority of the home charging in 2020 was done in the afternoon or night. With a trend of increasing range of the EVs and larger batteries, more energy intensive chargers will be in demand. If too many of these high power consuming chargers are used at the same time, it will create huge problems for the grid at Utsira as it stands today. 69% of the current home charging in Norway is done through a charge box, a significant increase from 43% in 2018 [47]. If these charge boxes are installed with smart charging, it would facilitate DSR. Additionally, many new EVs have the opportunity to manage the time of charging through controlling when the process begins and ends. Through price signals from the electricity market, the EV owners or smart chargers could be stimulated to use power when system demand is low. When a smart charger is connected it can communicate with the car, the charging operator and the utility company to optimize the charging process [48]. Results from the ModFlex project done by SINTEF showed that 90% of a representative group of Norwegian EV drivers were willing to change their charging routines if it had no negative effects for the user.

As EVs include batteries, they are classified as storable loads. In principle, electricity can flow both into and out of an EV with it having a bidirectional charger, referred to as vehicle to grid (V2G). In high-demand periods the EV can deliver power to the grid, or the household can be completely disconnected from the grid in critical periods using the EV as a battery. For prosumers with rooftop PV or micro windmills, it can work as an additional storage resource as electricity can be stored in high producing periods and used or supplied to the market in high demand periods. This way, EV charging can strengthen DSR opportunities and allow for greater integration of VREs in the energy mix [49].

A scenario with increased EV population at Utsira and how this will affect the existing grid is further analyzed and discussed in section 4.2.

2.2.3 Estimating potential related to electrification of the ferry

As mentioned previously, the current ferry connecting Utsira to the mainland will be electrified. The ferry has a carrying capacity of 150 passengers and 25 passenger cars [50], and the crossing time is approximately 70 minutes [51]. Also taking into account that the crossing often experiences rough weather conditions, it can be understood that the ferry requires a high amount of energy. It arrives and departs three to four times a day, and according to the current time table the electric ferry will sometimes require a full recharge at Utsira in 20 minutes. The power required in these 20 minutes will drastically increase the total load of the island for the period. Grid reinforcements for handling this enormous peak demand will most likely be very expensive for the DSO and the ferry company, and the large dimensions would most of the time be excessive. In similar cases, such as for the ferry Ampere in Sognefjorden, there has been installed lithium batteries at each side of the route [52]. The batteries are used as intermediate storage, continuously charging from the grid when the ferry is not alongside the quay, and discharging when the ferry is charging from the grid as a complementary source. A similar solution is intended for the Utsira ferry, to alleviate the high grid tension the charging would cause, but the details are not entirely laid out.

Including additional storage in the Utsira grid is an interesting concept, as it can act as storage when the windmills are producing too much power. Taking the plans of PV integration into account, there will be periods with great potential for energy storage. The energy stored can be used as grid support, preventing voltage issues, provide frequency regulation, reduce peak loads or for black starts [53]. [54] describes a similar case as Utsira, where battery storage is used as grid support in a weak distribution grid with very high demand in short periods of the day. As it stands today, the DSO is planning to implement a BESS on Utsira for ancillary purposes, separate from the ferry related BESS.

Different scenario cases for the charging of the planned electric Utsira ferry are simulated, analyzed and discussed in section 4.3.

2.3 Flexibility market opportunities

To utilize the flexibility resources available at Utsira it could be beneficial to develop a marketplace for buying and selling flexibility. In a digital marketplace, flexibility providers or aggregators can offer their assets, and the DSO can buy the feasible type of flexibility needed in the area [55]. Different competing technologies ensure that the DSO can purchase flexibility at the lowest price available. The EU Commission promotes flexibility markets as an essential part of the EU becoming climate neutral in 2050 [56]. There are many different approaches to flexibility markets, and the EU has registered more than 20 projects in this area [57]. NODES is an independent market provider, established by Agder Energi and Nord Pool, which can facilitate optimal use of flexibility by setting up a marketplace and settle the transaction between buyer and seller in a continuous market or in long term contracts [58][59][60].

For Utsira a flexible market could be very valuable in the high demand periods, such as when the electric ferry is recharging at the port. The DSO can map and request the flexibility needed in these periods, and high demand customers such as Utsira municipality can offer their flexibility by disconnecting loads in the critical periods. Loads that can be disconnected for 20 minuets and provide flexibility needed at the ferry charging can be for instance electric water boilers used for heating in the school and offices, ventilation, EWHs, heating cables and swimming pool heating.

The pilot project Norflex has performed successful end-to-end tests of the market chain in a flexibility market [61]. First, the DSO calculated the need for flexibility and the price they were willing to pay for it. The power retailer provided the flexibility available at the end-users at a flexibility platform, Flextools, provided by Enfo [62]. The marketplace provider NODES settled the transactions between the DSO and the owner of the flexibility asset. In this way the owners of the flexibility assets can set the value of the assets they are providing. A similar case has been performed in a weak distribution grid in the Smart Senja project [63].

The Ecogrid project was another market initiative, running from 2011 to 2015 on the island of Bornholm, Denmark [64] [4]. The goal was to develop and demonstrate a market for real-time DSR in the island's distribution grid, providing needed flexibility to a grid that, like Utsira, was heavily affected by wind power. The project's fundamental concept was to balance supply and demand by issuing price signals to flexible resources in the system, which costumers could then respond to. Participant households/buildings were installed with different types of smart home technology that could control the power consumption of household devices, such as heating and lighting. The results of the EcoGrid project showed a peak load reduction of 1.2% with 10% consumer participation, and significant reduction in participant power consumption when prices increased and the grid was under high tension.

To implement a market for flexibility which includes DSR, it is valuable to have knowledge on how consumers react to price signals. Flexibility market projects have operated on and given insight to today's price sensitivity, but it is difficult to predict how this sensitivity will change in the future. In the iFleks project [65], research is being done into future price sensitivity for different consumer types. It is predicted that price sensitivity in Norway will increase, due to expected increases in power price fluctuations and planned introduction of power tariffs, as well as a growth in technologies for consumer side load management. Obtaining such information would be helpful if a market were to be established on/ that includes Utsira.

A drawback of a flexibility market on Utsira is that there might not be enough flexibility asset owners to create a sizable and competitive market.

Chapter 3

Simulation model for the Utsira distribution network

As described in chapter 2 there is a potential and need for flexibility solutions in the Utsira power system. To investigate this potential and need, a simulation model of the 22kV grid at Utsira is built. This grid is connected to the mainland through a sea cable, which is then indirectly connected to the regional grid further inland (a simplification of this grid is included). One substation is analyzed more closely, at end-user level. This substation will be referred to as substation 215(s215) further on in this thesis. This radial is of interest because it includes the municipality building, school and kindergarten, and is assumed to have significant flexibility potential. There are also several households with a long distance/ high impedance connection to this substation, which are therefore sensitive to load changes and highly prone to voltage problems. These problems are highlighted and can thus be properly analyzed.

The simulation tool used is PSS®E 34, which is a software developed by Siemens used for simulating, analyzing and optimizing power system performance [66]. A description of the PSSE model and the data used is presented in this chapter.

3.1 Power flow analysis

Power flow, or load flow, is an important tool in the operation, maintenance and analysis of power systems, and is fundamental to simulation software such as PSSE. It is a steady state study of an AC- system model, using the relevant network, load and generation data. It is used to find power system information like power flows and line losses for cases such as real- time data analysis, contingency scenarios and load & generation forecasts.

Power flow analysis is based on a one- phase model of the network, where each bus in the system is dependent on four variables: the voltage magnitude $|V|$, the phase angle δ, and the reactive and active power P and Q. Two of these variables is known for every bus, depending on the bus type: the slack bus, or the reference bus, is unique in the network and has voltage and angle equal to $|V| = 1$ and $\delta = 0$ (in p.u.). The PV- bus has, as the name suggests, known P and $|V|$ values, and normally represents generation buses. The last bus type is the PQ- bus, or load bus, where the P and Q values are known. The unknowns are solved for using the power balance equations below, derivated using the basic network matrix equations [67]:

$$\text{Active Power} = P_k = |V_k| \sum_{n=1}^{N} |Y_{kn}||V_n| \cos(\delta_k - \delta_n - \theta_{kn}) \tag{3.1}$$

$$\text{Reactive Power} = Q_k = |V_k| \sum_{n=1}^{N} |Y_{kn}||V_n| \sin(\delta_k - \delta_n - \theta_{kn}) \tag{3.2}$$

Where:

k	- the specified bus.
n	- one of the buses in the network.
N	- the total number of buses.
Y_{kn}	- the admittance between bus k and n.
θ_{kn}	- the angle of the bus admittance Y_{kn}.

Solving these equations for each bus with known P and/ or Q values will lead to all angles and voltage magnitudes of the network being known, and the unknown P and Q values can then be directly calculated, opening up for further analysis of the network. However, as the equations are non- linear, numerical methods must be used to solve them. There are several numerical methods implemented in PSSE to solve the equations, with the Newton- Raphson (NR) method being the default and the one chosen in this analysis.

3.1.1 The Newton- Raphson method

The NR method is an iterative algorithm used to numerically estimate the roots of real- valued functions. The power balance equations for buses with known P and Q values can be solved through this method by the following expressions [67]:

$$\vec{x}_i = \begin{bmatrix} \vec{\delta}_i \\ |\vec{V}|_i \end{bmatrix} \tag{3.3}$$

$$\begin{bmatrix} \vec{P} - \vec{P}(\vec{x}_i) \\ \vec{Q} - \vec{Q}(\vec{x}_i) \end{bmatrix} = \begin{bmatrix} \Delta\vec{P}_i \\ \Delta\vec{Q}_i \end{bmatrix} = \mathbf{J}(\vec{x}_i) \begin{bmatrix} \Delta\vec{\delta}_i \\ \Delta|\vec{V}|_i \end{bmatrix} \tag{3.4}$$

$$\vec{x}_{i+1} = \begin{bmatrix} \vec{\delta}_{i+1} \\ |\vec{V}|_{i+1} \end{bmatrix} = \vec{x}_i + \begin{bmatrix} \Delta\vec{\delta}_i \\ \Delta|\vec{V}|_i \end{bmatrix} \tag{3.5}$$

Where:

i	- Current iteration.
$\vec{x}_i$	- Line vector of current angles and voltages.
$\vec{P}, \vec{Q}$	- Line vector of real P, Q for each bus.
$\vec{P}(\vec{x}_i), \vec{Q}(\vec{x}_i)$	- Line vector of calculated P, Q using $\vec{x}_i$ and power balance equations.
$\mathbf{J}(\vec{x}_i)$	- Jacobian matrix of the power balance equations calculated with $\vec{x}_i$.
$\Delta\vec{\delta}_i, \Delta|\vec{V}|_i$	- Difference between current and new values.
$\vec{x}_{i+1}$	- Updated angle and voltage values.

The algorithm is completed when the power mismatches $\Delta\vec{P}_i$ and $\Delta\vec{Q}_i$ are within acceptable values, which depends on the application. These values were in PSSE set to 0,001 MVA. The algorithm is started by guessing all angle and voltage values, often done with a flat start where all angles are 0 and voltages 1 (in p.u.).

The method will however converge faster the closer the starting values are to the solution, so values from a previous solution with similar load and generation values are often preferred to a flat start.

3.2 Data used

The model was built using network data exported from NETBAS [68], provided by the DSO using an export to PSSE function. This served as the fundamentals of the model. The data contained most of the necessary grid parameters, such as all network buses and connections, line impedance data and transformer data, from the viewpoint of the mainland substation directly connected to Utsira through the sea cable. All load connections were also provided, along with their yearly maximum power demand calculated using Velander's formula. However, the load values used were in stead gathered from meter readings.

The load data for Utsira used in the model is gathered from AMS-data collected by the DSO, provided for the period of the 1st of January 2020 to the 28th of January 2021. The AMS-data set consists of measurements from 254 meters, where ten of these are substation meters. Substation meters measures the total load of its radial, on the low voltage side of the transformer. The active and reactive power consumption is measured at the start of each hour every day, and is for each hour presented in the data set as the total consumption from the installation date of the meters. The hourly load is thus equal to the current value subtracted by the previous value. Voltage values are also provided, measured on a daily basis. From December 2020 the voltage measurements became more useful, increasing from daily to hourly metering. The meter voltage values are given as the maximum, minimum and average voltage during the metering period for each phase.

Some hourly measurements were missing in the data set. According to the DSO that could be due to data corruption, power outages, meter resets or missing entries or an unknown reason. To counteract this, the data is simply removed, and the difference in total power measured at the first usable entry after the problematic data point and the last entry leading up to it, is averaged over the time period. As the data faults are few and mostly far between, this has little impact on the accuracy of the load profiles.

The AMS-data is processed using Python, so that it can be implemented into the simulation model. Additionally, load profiles and voltage profiles are made in Python and used to investigate the loads behaviour, identify peak periods and analyze voltage variations for the current situation. The peak demand day for the area is found to be 28th of January by using a maximum function in Python. This was also the day with the lowest temperature in the measurement period, most likely correlated with increased heating use [69].

For the data used in the simulations the total load for a radial is summarized using Python for those substations which do not have a meter installed.

For this thesis there has been given access to iAM Viewer, a service provided by Powel that gives information of all grid components and connections for Haugaland Kraft operated grids, in the form of an interactive map[70]. It also gives a physical understanding of how the grid and all of its components are connected.

In addition, a data set of the power production of the windmills is given by the DSO. This data set consists of hourly measured power produced for each windmill, given in kWh. A significant part of this data were missing values, which could be due to maintenance of the wind turbines or metering errors. It is therefore used a constant value for the windmill production in the simulations, which will be specified further on.

The power system on Utsira is not an isolated system, and its network conditions are therefore not only dependent on island activity, but also on the situation on the mainland. Therefore, it is desirable to include parts of this grid in the model as well to achieve more accurate simulations. A simplified representation of the grid data between the sea cable substation and the regional grid was provided by the DSO to accomplish this. This data included intermediary substations between this substation and the regional grid, data for the lines between them, as well as the average hourly load for each of these stations, for each hour and day of the year. This load data was given as a percentage of the maximum substation load, and was an average of 2019-2021 measurements.

All of this data was anonymized and combined, and used to model the Utsira power grid and facilitate simulations of different system scenarios. The model and its application are further described in the following section.

3.3 Modeling approach

The model used in this thesis is a one-line representation of the three-phase distribution grid on Utsira as seen from the regional grid connection on the mainland, constructed in PSSE to look into possible scenarios of the Utsira power system. It consists of three parts of the real network that have been combined to form a network of 67 buses, where 42 of these are load buses.

The first part is a simplified 22kV mainland grid, as described in section 3.2, starting with the connection to the regional grid, which serves as the slack bus of the complete network model. There are 21 total buses in this section, where each bus (apart from the slack bus) is connected to a load. These loads are simplifications of the total load on the low voltage side of the substation, in the sense that they are connected directly to the bus and not through a transformer. The buses are connected in a line, with the final bus connecting to the 22kV Utsira grid.

The second part is the 22kV Utsira grid, starting from the island sea cable substation and encompassing all other Utsira substations, for a total of 11 substations and 23 buses. Each 22kV substation bus is connected, through a transformer, to a 230V bus on the low voltage side. The sum of the grid costumers in the 230V radial connected to the substation is used as the load, which is connected to the corresponding 230V bus (not the case for bus 215). The two windmills are connected to the 22kV grid through transformers and modeled as PV buses.

The third and last part is the 230V radial of one specific substation, 215 (s215), containing 23 buses. Each costumer is modeled as one load, resulting in 14 load buses.

3.3.1 Simplifications and assumptions

Several simplifications and assumptions have been made in the modeling process, which will be described in this subsection.

As the model is a one-phase representation of the grid, all phases are assumed to be symmetric. This includes voltages, currents, loads, line data, etc. The real network is, however, not entirely balanced, as loads are not distributed completely evenly across the phases, network data might differ between phases, and there will be slight variations in regional grid phase voltages. The model will therefore not showcase potential uneven voltage problems.

Some substation loads, as mentioned in section 3.2, are modeled as a sum of the individual loads in their radial instead of with a direct substation meter. Line losses for these radials are therefore not included in the sums. This has little effect on bus voltages, however, as these losses are small compared to the loads and do not constitute a significant part of the total power usage. Additionally, the simplification only applies to a few number of substations.

The temporal resolution of the load data provided and used in the model is one hour. The hourly value for a load in the simulations is the difference in total consumption of the current and the previous hour. The power consumption and generation of the buses are therefore not instantaneous values, but can in stead be viewed as one hour averages. The effect of this on the voltage profiles is that the curve will be smoother than in reality, and there will be no sudden spikes in voltage. This also means that changes in the curve represents a broader deviation in voltage, as it is an estimate of the average voltage value.

The wind turbines are modeled as PV- buses with no reactive power production or consumption. This assumption is confirmed with the DSO to be mostly accurate, and will therefore have little impact on the accuracy of the results.

The network data the model is built upon is based on data sheets from the manufacturer, and does not take component aging into account. Impedances and losses in the lines and transformers will therefore most likely be lower in the model than for the real grid.

3.3.2 Network model overview

By using power flow analysis in the PSSE network model, voltage magnitudes and angles for all buses can be found for different load combinations.

An overview of all network buses is presented in Table 3.1:

Utsira network model, bus overview					
Mainland grid		**Utsira, 22kV grid**		**Utsira, 230V, s215 radial**	
Bus nr.	**Bus description**	**Bus nr.**	**Bus type**	**Bus nr.**	**Bus type**
101	Slack bus	201	Open bus	301	Branching node
102	Substation + load	202	Substation 230V Load	302	Branching node
103	Substation + load	203	Substation	303	Load
104	Substation + load	204	Substation	304	Load
105	Substation + load	205	Substation, wind	305	Branching node
106	Substation + load	206	Wind power plant	306	Load
107	Substation + load	207	Substation	307	Branching node
108	Substation + load	208	Substation 230V Load	308	Load
109	Substation + load	209	Substation	309	Load
110	Substation + load	210	Substation 230V Load	310	Load
111	Substation + load	211	Substation	311	Branching node
112	Substation + load	212	Substation 230V Load	312	Load
113	Substation + load	213	Substation	313	Branching node
114	Substation + load	214	Substation 230V Load	314	Load
115	Substation + load	215	Substation (s215)	315	Load
116	Substation + load	216	Substation	316	Branching node
117	Substation + load	217	Substation 230V Load	317	Branching node
118	Substation + load	218	Substation	318	Load
119	Substation + load	219	Substation	319	Load
120	Substation + load	220	Substation 230V Load (ferry)	320	Branching node
121	Substation + load	221	Substation 230V Load	321	Load
		222	Substation, wind	322	Load
		223	Wind power plant	323	Load

Table 3.1: An overview of all buses in the model of the Utsira grid. Bus 101 is the slack bus, bus 306 & 323 are PV- buses, while the remaining buses are PQ- buses.

The network line diagram for the radial in focus (s215) is presented below in Figure 3.1. The shape of the grid does not accurately depict the real grid, but the components and connections are the same. The green bus, 215, is the radial substation and thus part of the 22kV grid, connected to the radial through a transformer. The loads are represented by the arrow- shapes.

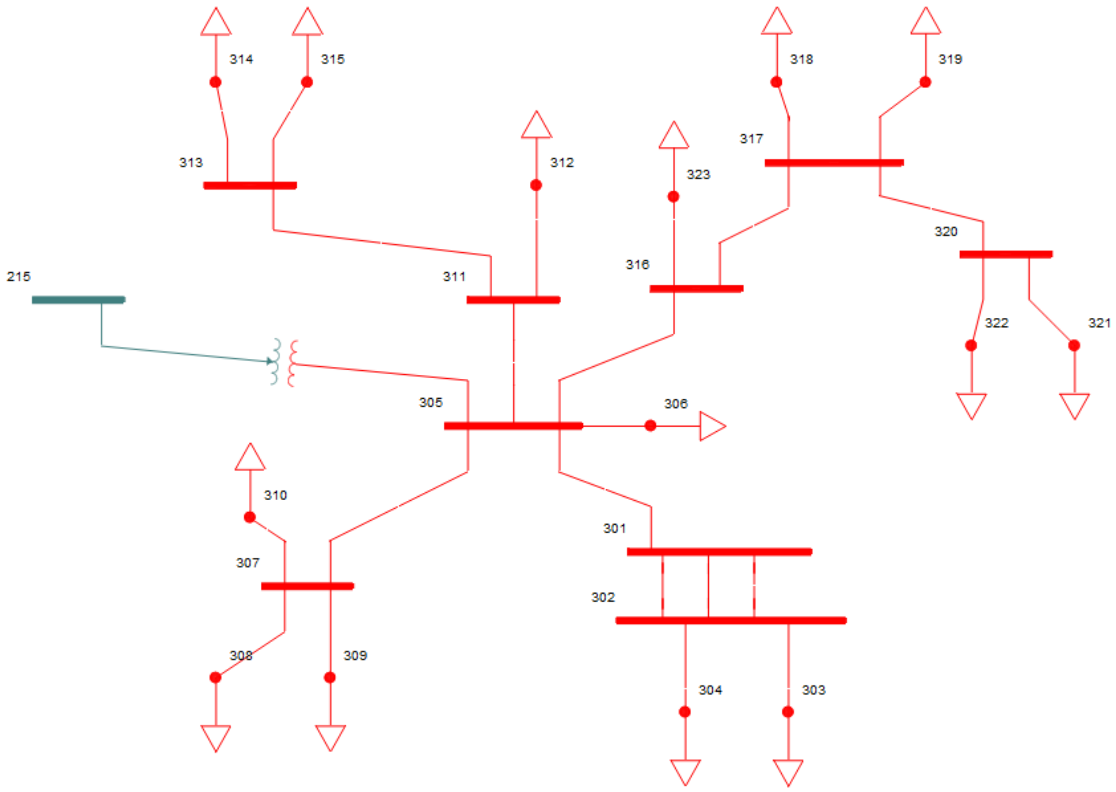

Figure 3.1: The model of the radial connected to substation 215 (bus 215), with the associated bus numbers.

The network line diagram for the 22kV Utsira grid is presented below in Figure 3.2. The shape of the grid does not accurately depict the real grid, but the components and connections are the same. The wind power plants are represented by the circles located in the top right, connected to bus 206 and 223. The red bus bar in the bottom left, 305, is the first bus in the s215 radial, which can be seen in further detail in Figure 3.1.

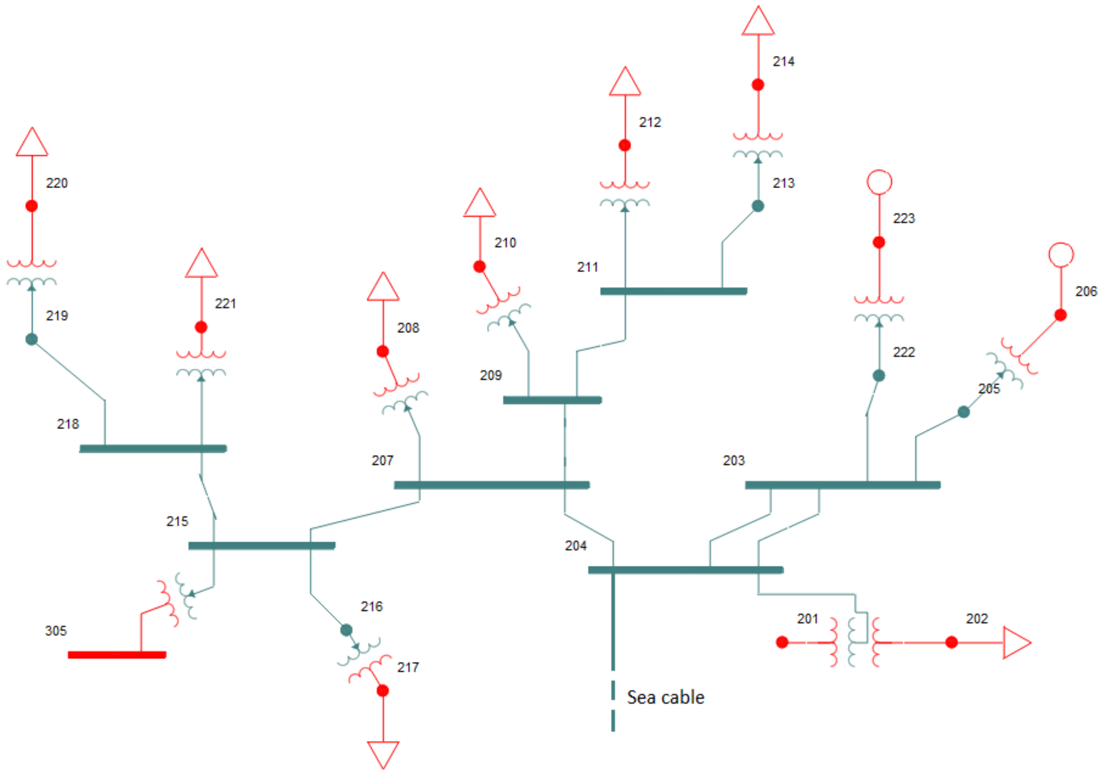

Figure 3.2: The model of the 22kV grid on Utsira with the associated bus numbers.

Chapter 4

Flexibility scenarios at Utsira

To identify and analyze the future need and potential for flexibility solutions in the distribution network at Utsira some scenarios are developed. These scenarios reflect the increased electrification of the industry and transport sector that is planned on Utsira, in Norway, and in the rest of Europe in the coming years. The scenarios look into how the power system situation can potentially be on Utsira in 2025, including a general increase in load. The first scenario simulates a situation with increased household EVs on Utsira, and how DSR can facilitate EV integration by improving the related charging process in regards to grid operation. The second scenario simulates how charging of the planned electric ferry on the island will affect the existing distribution grid, focusing on potential voltage problems, and how storage can provide load leveling and contribute to an adequate charging process. Both scenarios include three different cases which are compared. In subsection 4.2.3, subsection 4.3.3 and section 4.4 possible flexibility solutions are discussed.

4.1 Scenario 0: Base case

The day with the highest power demand in 2021 is chosen as the reference scenario, or the base case. This day, January 28th, had variable wind conditions, seen from the windmill power production data. The power production was zero in the night hours and slowly increased from 07:00 until 19:00. In the last five hours of the day, the hourly windmill production was approximately 200-250 kWh. As wind power varies from day to day, it is difficult to predict how much of the Utsira power demand is covered by it. To be able to better compare the simulation cases, some assumptions and simplifications of the windmills are made, as described later in this section.

The load profile for the total island demand for the 28th is presented in Figure 2.3. The system peak demand hour occurs in the hour 20-21 and is 651 kWh.

The load profile for the actual power used in the radial under substation 215 at the peak demand day is presented in Figure 4.1.

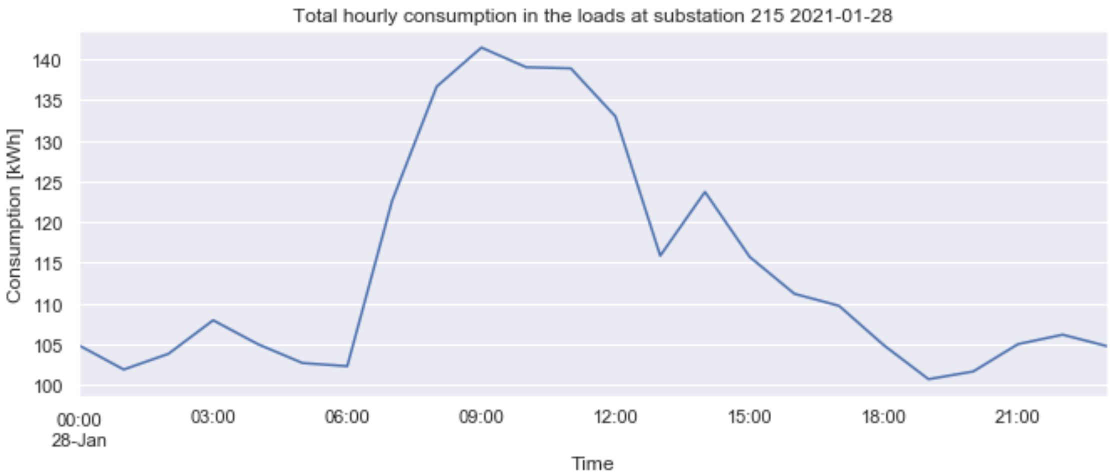

Figure 4.1: Hourly load profile for the total consumption at the radial under substation 215 for the peak demand day in 2021

The peak in load demand occurs in the hour 08:00-09:00 and is 141 kWh. This means that the average power demand is 141 kW during that hour, so load peaks within the hour might be even higher. The peak can indicate that this is when the heating in the school and office building, which are located in the area, are at their maximum, and in the same hour, people are doing their morning routines at home. It can be assumed that this area is dominated by the school and office building since the high demand period occurs from 08:00-12:00, which is typical for such loads.

The steep slope during the morning hours in the graph in Figure 4.1 indicates that there is a drop in voltage at this time. The loads located furthest away from the transformer are most sensitive to this fast change in consumption and are more exposed to experiencing voltage issues. Figure 4.2 illustrates the measured hourly voltage values at the loads in the LV grid at the radial under substation 215.

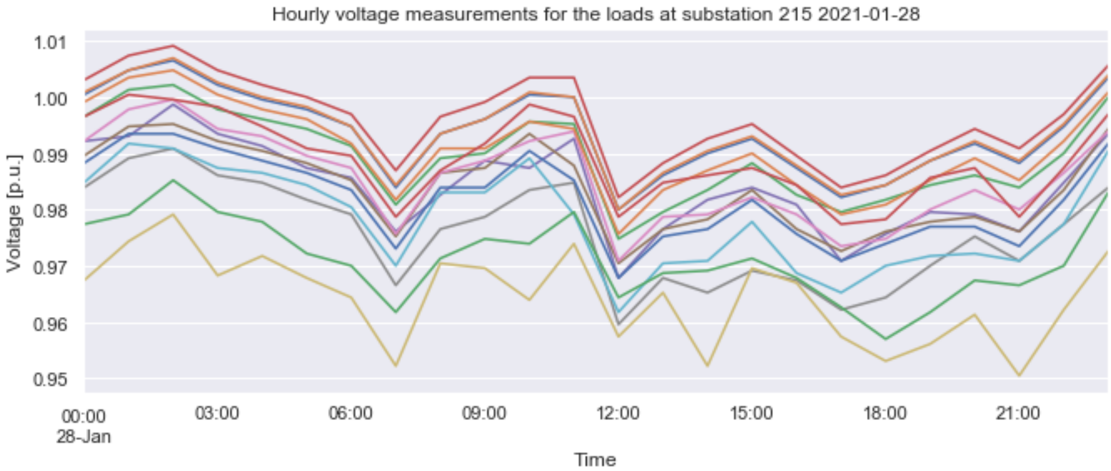

Figure 4.2: Hourly voltage profile for the loads at the radial under substation 215 for the peak demand day in 2021.

One can see from Figure 4.2 that there is a drop in the voltage at 07:00, which is expected as this is where the steepest increase in load occurs. For some of the loads, there is also a voltage drop at 21:00, indicating that these are probably households. However, the lowest voltage value is approximately 0,95 p.u. which is within acceptable values.

Simplifications and assumptions

Both scenarios use 2025 as the year of analysis. To give more general simulation results and allow for better comparisons, the base case described above has been altered.

As explained in chapter 2 the electricity demand is expected to increase on Utsira in the coming years. Therefore, there has been introduced a load increase in the following scenarios to simulate how the situation will look in 2025. The load increase is assumed to be 8% on Utsira, excluding the increase in load due to electrification of the transport sector. This assumption is based on [10] and the planned increase in industry activity at Utsira. The mainland load increase is set to 10%, as this part includes the transport sector increase. The hourly load values for all loads in the network are attached in Appendix A.

As the power produced by the windmills is different from day to day and even from hour to hour, their production has been set to a constant value that reflects a day with medium wind conditions. This way the voltage profiles are partially normalized and not dominated by a somewhat random factor, and simulations therefore provide more applicable information. This value was chosen to be 200 kW for each turbine, for a total of 400kW, determined by observing windmill power production over the total period of 2020.

The transformer step ratios are kept the same as today. They would most likely be increased with the increasing load, but this impact is in stead discussed later on.

Figure 4.3 illustrates how the average hourly voltage values would be on a high demand day in 2025, with an average island and mainland load increase of 8% & 10%, respectively, and constant wind production of 0,2 MW for each windmill. This is used as a reference case for the following scenarios. Hourly voltage values for all the loads in the network for the reference scenario are attached in Appendix A. The impact of the alterations to the real case is apparent, but is expected due to the simplified and generalized nature of the model and base case changes.

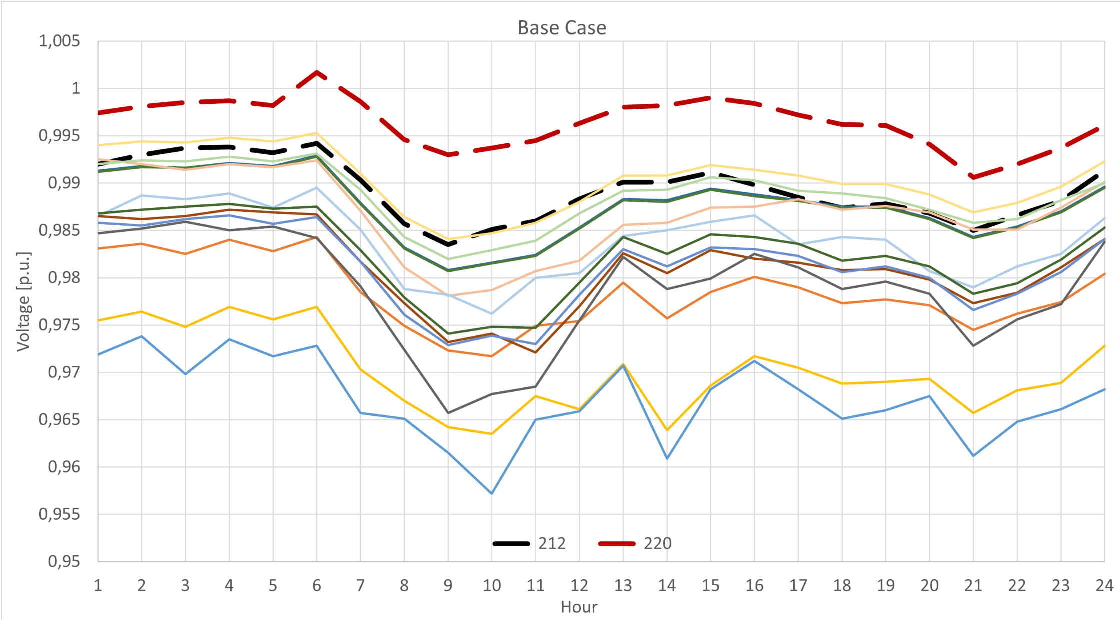

Figure 4.3: The voltage profile for the base case, for the loads in the 215 substation radial, the ferry substation (220) and the substation with most households(212).

By comparing the simulated voltage profiles in Figure 4.3 and the voltage profiles based on the measured values in Figure 4.2, it can be seen that the simulated values are in some ways better than the measured values, even when the total load is increased. A major reason for this is that the real windmill power production differs from and is lower than the simulated production, especially for the first part of the day, which in a vacuum leads to higher and more stable voltage values for the simulated case compared to the actual case. When analyzing the simulation cases it should therefore be kept in mind that the simulated values might give a better impression than the actual case.

4.2 Scenario 1: EV charging in households

Based on the ambitious goal of the Norwegian Parliament and the increase of EVs in Norway in the last five years, as presented in subsection 2.2.2, it is estimated a share of 50% EVs in the Norwegian passenger car park in 2025. In this scenario, it has therefore been simulated cases where 50% of the households on Utsira have an

EV charger, and how this will affect the existing distribution grid on the island. It has been simulated three different cases with varying DSR participation, to observe how DSR can improve the voltage situation. The EV loads have in these cases been modeled as constant loads, where the charging power is even for the entire charging period. The loads are additionally modeled as pure active power loads, so the change of reactive load is ignored. The voltages of all loads in the 215 radial are observed, as well as for bus 212, as this substation is connected to the highest amount of households (30) and therefore expected to be impacted the most of all substations.

4.2.1 Scenario description

Case 1.1: Afternoon charging

In the first simulation case, it is assumed that all households have a "dumb" EV charger. A dumb charger is in this case a charger without smart charging capabilities. It is assumed that all of these chargers have a power capacity of 7,2 kW, as this is the highest possible capacity for chargers for a 230V, 1- phase connection [45], and that they are charging at their maximum capacity for four hours once they are connected. This will approximately give a driving range of 150 km, which is significantly more than the average daily driving length of passenger cars, which was 30 km in 2020 [71][72]. The reason that 7,2 kW of charging for four hours was simulated is that it corresponds to the size of the battery of a Nissan Leaf, which is today's most popular EV in Norway [73]. It can not be known if drivers charge their car every day or if they charge when the battery is near empty, and it is therefore simulated a worst-case situation where every driver needs to charge 28,8 kWh or approximately 150 km. This high charging need also reflects the constantly increasing battery capacity of new EVs, as the charging demand is expected to increase with battery size. It is assumed that all EVs start charging at 17:00, assuming that this is the hour people most commonly come home from work, and that it is fully charged at 21:00.

The EV load is found by multiplying the charging power by half of the number of households in a substation radial. For the 230V grid, where each load is modeled, half of the households were chosen as EV loads by selecting the buses with the most problematic voltages, as seen in the base case. The load change is thus the following:

Load increase, 100% afternoon charging		
Bus nr.	**Afternoon (17-21) [kW]**	**Households**
202	43,2	12
208	61,2	17
210	46,8	13
212	108	30
214	25,2	7
217	32,4	9
220	21,6	6
221	97,2	27
308	7,2	1
315	7,2	1
318	7,2	1
319	7,2	1
323	7,2	1
Total	471,6	

Table 4.1: Demand caused by EV afternoon charging, from 17:00 to 21:00, as well as the number of households at each bus

Case 1.2: 66,7 % smart night charging

As presented in subsection 2.2.2 90% of Norwegian EV owners can be willing to change their charging routines from daytime to nighttime if it has no negative consequences for the user. For practical reasons this requires that the users own a smart charging box. In this case it is therefore assumed that two out of three EV households have a charging box that supports smart charging at home and accepts that their charging is shifted into the night, as long as their EV is fully charged the next morning. If the user allows it, the DSO can optimize the charging according to the grid capacity through DSR. In this case it is assumed that this smart charging starts at 21:00. The power needed for charging is evenly distributed during the night, in the hours 21:00-06:00, which also ensures most users have a fully charged vehicle at the start of their day. One out of three of the EVs still has a dumb charger, charging in the afternoon as in the previous case.

Smart loads are shifted to nighttime and will charge in 9 hours in stead of 4, so the power demand is then $P_{night} = 7,2\text{kW} \cdot \frac{4\text{hours}}{9\text{hours}} = 3,2\text{kW}$. The loads are distributed as DSR loads as following: For substation loads, the total EV load, as presented in subsection 4.2.1, is simply multiplied by the fraction of DSR charging, 2/3, for nighttime and 1/3 for the afternoon. For the 230V grid loads, 2 of the 4 EV loads use smart charging while the other two still charges in the afternoon. The loads with the most problematic voltages were chosen to not use smart charging in this grid, as a worst-case. This results in the following EV loads for each hour of charging:

Load increase, 67% DSR, 33% afternoon charging		
Bus nr.	**Afternoon(17-21) [kW]**	**Night(21-6) [kW]**
202	14,40	12,80
208	20,40	18,13
210	15,60	13,87
212	36,00	32,00
214	8,40	7,47
217	10,80	9,60
220	7,20	6,40
221	32,40	28,80
308	0,00	3,20
318	0,00	3,20
319	7,20	0,00
323	7,20	0,00
Total	159,6	135,47

Table 4.2: Demand caused by EV charging, from 17:00 to 21:00 for regular chargers and 21:00 to 06:00 for smart chargers

Case 1.3: 100% smart night charging

In this scenario, it is assumed that all EV owners have a smart charger. All the EV charging is evenly distributed during the hours 21:00-06:00. This scenario is a "best-case scenario" for smart charging, assuming all customers accept that their car is charged when there is capacity in the grid thus creating a 100% DSR participation rate.

The load increase is now only for the hours of 21:00-06:00, as no EVs are charged in the afternoon. This results in the following load increase:

Load increase, 100% DSR	
Bus nr.	**Night (21-06) [kW]**
202	19,2
208	27,2
210	20,8
212	48
214	11,2
217	14,4
220	9,6
221	43,2
308	3,2
318	3,2
319	3,2
323	3,2
Total	206,4

Table 4.3: Demand caused by EV charging, with all charging shifted to 21:00-06:00

4.2.2 Simulation results

The resulting hourly voltage values for all buses in the network on Utsira after the simulations of the cases in this scenario are attached in Appendix B.

Case 1.1: Afternoon charging

In Figure 4.4 the voltage profiles for all loads in the radial under substation 215 are presented, as well as the voltage at substation 212, as a result of the simulation of afternoon charging at 50% of the households on Utsira.

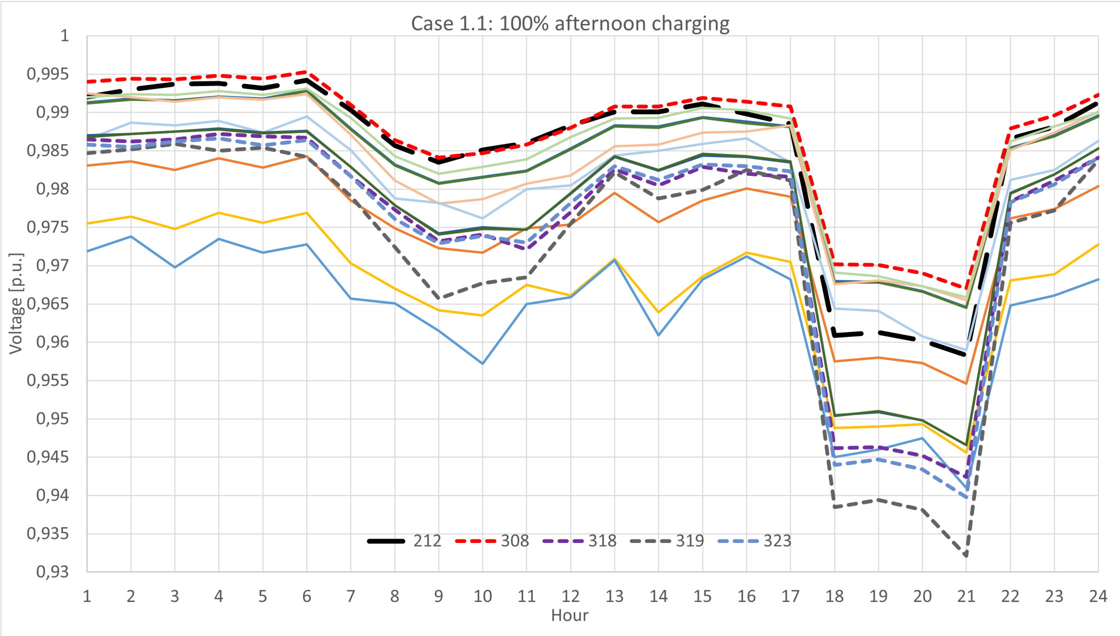

Figure 4.4: Voltage profiles of all loads in the 215 radial for the 1.1 case, as well as the 212 substation. Buses with EV charging have stapled voltage lines.

From Figure 4.4 it can be seen that the charging of all EVs simultaneously in the afternoon will cause a significant voltage drop in these hours. Bus 319 has a voltage drop of approximately 0,05 p.u. and a minimum value of 0,932 p.u. Substation 212 has a voltage drop of 0,03 p.u., and the minimum value is close to 0,960 p.u., indicating significant voltage drops for the loads in this radial.

Case 1.2: 66,7 % smart night charging

Figure 4.5 presents the voltage results of the simulation of 66,7 % smart night charging introduced and 33,3 % afternoon charging of the EVs expected at Utsira in 2025.

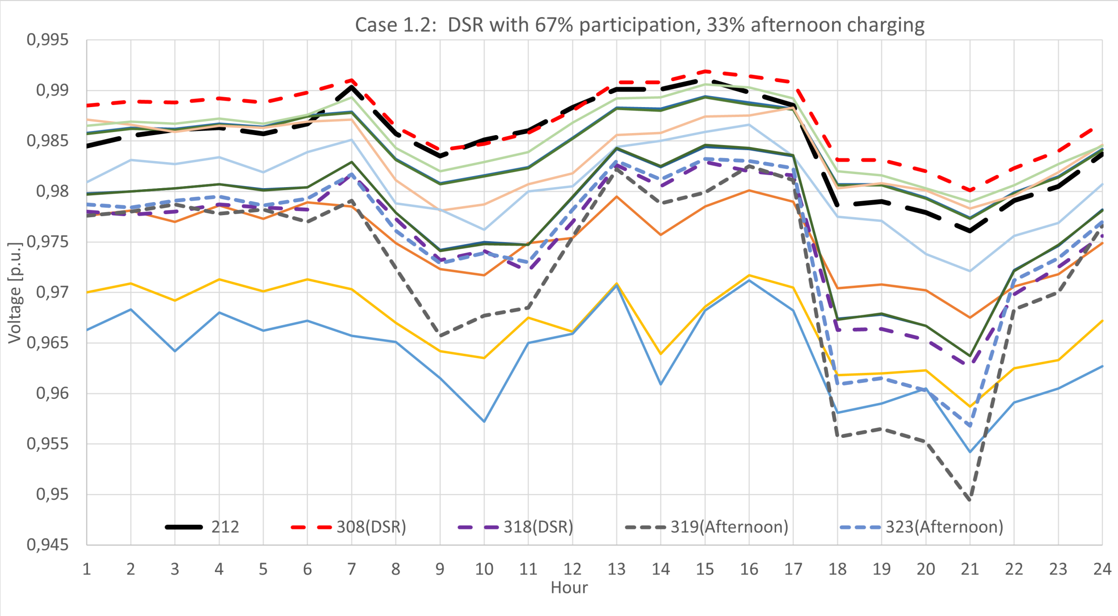

Figure 4.5: Voltage profiles of all loads in the 215 radial for the 1.2 case, as well as the 212 substation. Buses with EV charging have stapled voltage lines, and DSR and afternoon charging is distinguished between.

It can be observed from Figure 4.5 that bus 319 has a voltage drop of approximately 0,03 p.u. and a minimum value of 0,950 p.u. Substation 212 has a voltage drop of 0,015 p.u. and a minimum value of 0,976 p.u. The loads with DSR have seen significant improvements compared to their profiles before it was implemented.

Case 1.3: 100% smart night charging

The voltage profiles from the results of simulating 100% smart night charging of the EVs expected at Utsira are presented in Figure 4.6.

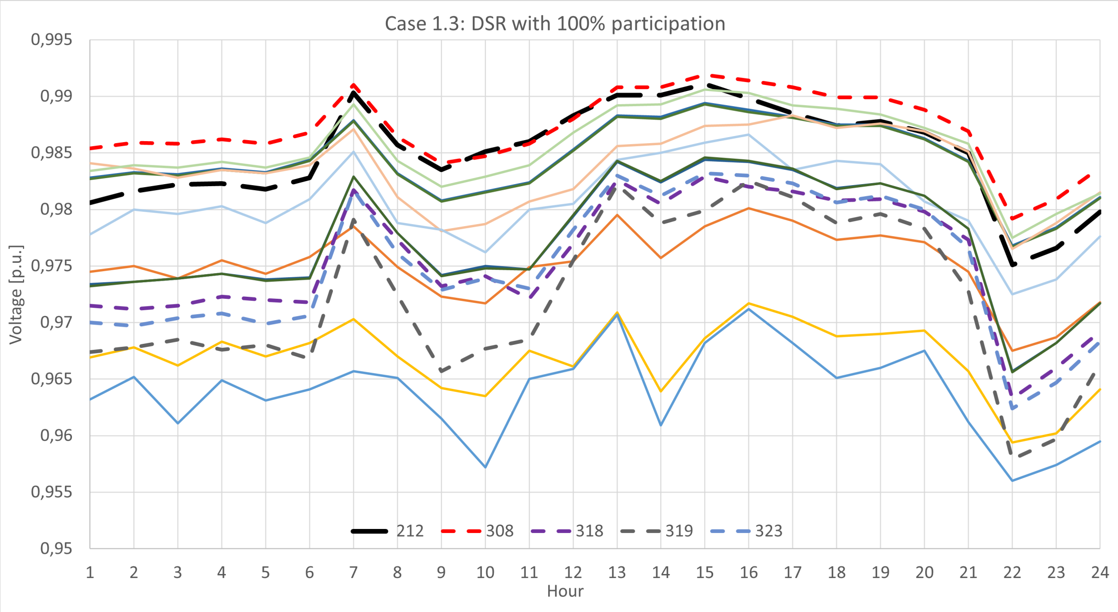

Figure 4.6: Voltage profiles of all loads in the 215 radial for the 1.3 case, as well as the 212 substation. Buses with EV charging have stapled voltage lines.

The results in Figure 4.6 illustrates that bus 319 has a voltage drop of 0,025 p.u. and a minimum value of 0,958 p.u. The bus with the lowest voltage value reaches a minimum value of 0,956 p.u. Substation 212 has a voltage drop of 0,015 p.u. and a minimum value of 0,975 p.u.

4.2.3 Discussion

Case 1.1: Afternoon charging

As seen from the voltage profile all EV owners charging their car in the afternoon will cause a significant drop in voltage. It can be seen that several of the profiles go lower than 0,95 p.u. which is seen as a critical value. It should be noticed that this is the average hourly voltage, and that even lower voltage values can occur within these hours. The voltage profile for substation 212 has a voltage drop of approximately 0,025, and it should be noticed that the loads located further into the LV grid under this substation will experience higher voltage drops, and be more exposed for voltage variations and reaching the critical values presented in section 1.1. It is assumed that some points in the grid will experience higher voltage variations and lower voltage values than illustrated in these results.

The total load of the island will in the charging period reach upwards of 1,1 MW, reaching its highest peak at 21:00 and breaching the operative limit of the sea cable. When also considering losses, this limit is potentially breached for the entire period. With a combined wind power production of 400 kW, however, power flow in the cable is reduced by roughly this amount, but a day with close to no wind will have problems regarding this limit.

It might not be realistic that all EV owners need to charge their car with 7,2 kW for four hours at the same day. However, it should be noted that if all the chargers are connected to the grid at the same time for a shorter period and are not smart chargers, there will be capacity problems in the grid and customers will experience unacceptable voltage problems as the grid stands today.

Case 1.2: 66,7 % smart night charging

When introducing smart charging it can be seen from Figure 4.5 that the voltage profile is much smoother. Though, there is still one load where the voltage is dropping under the critical value of 0,95 p.u. This is a load with afternoon EV charging located in the s215 LV grid, which indicates that loads located in weak network radials, with high impedance in the connection to the transformer, will be sensitive to this kind of load increase and more frequently experience voltage variations.

Case 1.3: 100% smart night charging

By introducing 100% smart charging in the system, it can be seen from Figure 4.6 that the voltage curve is very much flattened, and none of the loads are experiencing critical voltage values. The minimum value occurs in the hour 21:00-22:00, and the maximum value occurs in the hour 06:00-07:00. Probably not all cars are needed at 06:00, so some of the charging could therefore have been moved to early morning in a smart charging system, which could have resulted in an even more smooth voltage profile.

As explained in the scenario description a scenario with 100% DSR participation is a best-case scenario. There will probably always be a situation where some customers can not be stimulated to demand response by price signals, for various reasons.

Comparing the cases

Figure 4.7 presents the voltage profiles for bus 308 and bus 319 for each of the three cases, to be able to compare the results from the cases. These buses are chosen for comparison as these have the lowest and highest voltage values in radial 215.

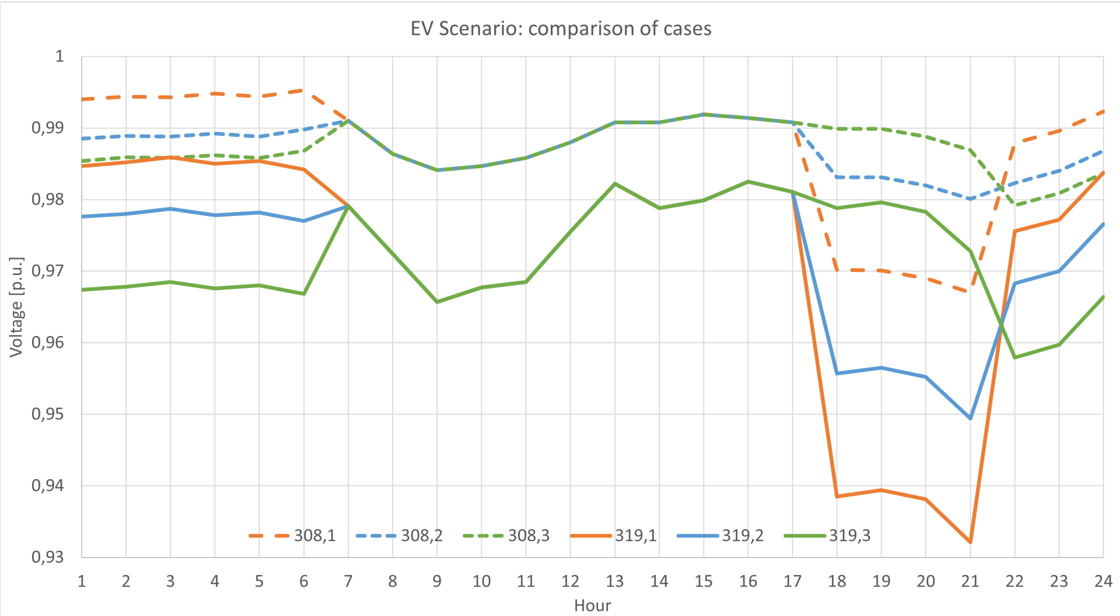

Figure 4.7: Comparison of voltage profiles for bus 308 & 319, the buses with the highest and lowest voltages, respectively.

It can be seen in Figure 4.7 how shifting the load through DSR affects the voltage profiles, resulting in a small drop at night with longer duration and reducing the steeper, shorter drop in the afternoon. By this comparison, it is apparent that case 1.3 gives the most stable voltage profiles. The voltage drop is significantly higher for case 1.1 than 1.3 for bus 319, that is 0,050 p.u. and 0,025 p.u., respectively. The results gives an impression that incentives for high DSR participation and smart charging will provide better voltage conditions to secure adequate grid operation for the DSO at Utsira. Furthermore, the power flow in the cable will be within its limit for both case 1.2 and 1.3, unlike for case 1.1.

100% DSR participation leads to an overall higher load increase for the island compared to 67% in case 1.2: 206,4 v.s. 159,6 kW. This is due to all loads being connected at night, leading to lower voltage values in these hours for case 1.3 compared to the other cases. Furthermore, when the EVs are connected with DSR and the charging process is initiated, there is still a relatively high overall power demand caused by a early night peak. Shifting the charging even later into the night could therefore be considered, but would then result in the vehicles completing their charging later in the morning. Alternatively, some EV charging could be started later, such that the start and end ramping would be less steep, but stretch over a longer period.

Common discussion

In the simulation cases the reactive power values for the loads are not changed from the base case. This is a simplification done in this thesis. In a real case the reactive power injected or consumed in the EV charger is decided by the power factor (PF) of the charger and can have a significant contribution to the grid voltage variations [74]. By injecting reactive power during EV charging, i.e. implementing a capacitive PF in the charger, the reactive power can be used to support the grid and compensate for the voltage drop during charging. However, this is entirely dependent on charger type and scheme and was therefore not included in the simulations.

It should be noticed that the charging schemes developed in this model are simplified. A smart charger will have a complex charging scheme dependent on power needed and power available in the grid. However, it should give an impression of how load shifting by DSR can benefit the situation.

Challenges with implementing DSR with EV charging

As explained in section 1.2 the Norwegian electricity prices have traditionally been low, and the variation in spot prices during a day might not be big enough to stimulate end-users to use smart night charging. Local capacity problems could also appear if several EVs in the same neighbourhood start charging when the electricity price is expected to be at its lowest value. This could be prevented by introducing new TOU tariffs, as suggested by NVE in 2020. In this way, the DSO could stimulate several EV owners to use smart charging, and charge their EVs over longer and lower demand periods.

4.3 Scenario 2: Ferry charging

As presented in chapter 2 the ferry from Utsira to the mainland is planned to be electrified. According to the DSO, the electric ferry will require a power capacity of 4 MW during the most intensive charging periods. In this scenario it is assumed that the future electric ferry will use the same time table as today, as seen in Figure 4.8, and have the same crossing time as today's ferry of 70 minutes. This requires that the ferry gets fully charged in 20 minutes two times a day, in addition to two longer charging periods in the afternoon and at night. From this information it is assumed that the ferry has an energy capacity of $4\text{MW} \cdot 20\text{minutes} = 1,33\text{MWh}$. Different implementations of ferry charging are simulated in this scenario, to investigate potential solutions that secure good grid operation.

FRA UTSIRA	FRA HAUGESUND
MAN./ ONS./FRE.	MAN./ ONS./FRE.
06.30	08.00
09.30	11.00
14.45	16.15
17.45	19.15

Figure 4.8: Ferry time table, showing departures from both Utsira and the mainland. [75]

4.3.1 Scenario description

Case 2.0: Ferry charged directly from the grid

Assuming that no actions for improving the charging process are taken, the electric ferry will recharge directly from the Utsira distribution grid. For the intensive charging periods of 20 minutes the power demand would be 4MW, an increase in total island load for these hours in 2025 of over 600%. In this case an unrealistically high power capacity is therefore required, which is not possible to deliver with the current sea cable. It would require huge reinforcements in the grid, which would have been unnecessary for most of the operating time outside of the charging process. Moreover, attempting to simulate this scenario did not give a power flow solution that converged. Due to these reasons, it is necessary to consider different solutions for charging, such as implementing a BESS to achieve load shifting. This is the focus of case 2.1 and 2.2.

Case 2.1: Ferry charged from battery and grid

According to the DSO, the ferry company is planning to install a battery at the ferry quay used for charging in addition to the grid connection. The DSO has estimated that the power required from the grid will be 1 MW in the most intensive charging periods. This implies that a battery with a power capacity of 3MW needs to be installed.

In this scenario it is therefore simulated a case where the ferry gets charged 0,33 MWh from the grid and 1 MWh from the battery. In the night hours (from 20:25 to 06:30) the ferry charges directly from the grid at the same time as the battery is recharging. In the daytime hours, when the ferry is not alongside the quay, the battery is constantly recharging. Table 4.4 gives an overview of when the ferry is charging from the grid, and when the battery is charging and discharging. The battery is modeled in a way that it is charging at a constant power rate when it is not connected to the ferry.

Charging time table			
Time	**Ferry grid charging [MWh]**	**Battery ferry charging [MWh]**	**Battery grid charging [MW]**
06:30-09:10	0	0	x
09:10-09:30	0,333	1,000	0
09:30-12:10	0	0	x
12:10-14:45	0,333	1,000	0
14:45-17:25	0	0	x
17:25-17:45	0,333	1,000	0
17:45-20:25	0	0	x
20:25-06:30	1,333	0	x

Table 4.4: Time table for charging the ferry and battery

The constant charging rate for the battery is found by dividing the total battery energy needed by the total battery charging time, x = $\frac{3\text{MWh}}{20{,}75\text{h}} = 0,1446\text{MW}$.

The minimum size of the battery is given by the charging rate and time, and is equal to the largest difference in charge during its 24 hour cycle. This excludes the potential need for a minimum reserve. Assuming the battery is fully charged at 09:10 after a night of charging, the lowest point in the curve will be at 17:45, which gives a capacity of C= Discharge - Charge, for 09:10 to 17:45:

$$\begin{aligned} C &= 3\text{MWh} - x((12{:}10\text{h} - 09{:}30\text{h}) + (17{:}25\text{h} - 14{:}45\text{h}))\text{MWh} \\ \rightarrow C &= 3\text{MWh} - 0,1446\text{MW}(2,67\text{h} + 2,67\text{h}) = 2,23\text{MWh} \end{aligned} \tag{4.1}$$

Table 4.5 presents how much hourly capacity from the grid the charging of the battery and the charging of the ferry will require in this case.

Grid demand			
Hour	**Ferry [kWh]**	**Battery [kWh]**	**Total [kWh]**
01:00	132,2	144,6	276,8
02:00	132,2	144,6	276,8
03:00	132,2	144,6	276,8
04:00	132,2	144,6	276,8
05:00	132,2	144,6	276,8
06:00	132,2	144,6	276,8
07:00	66,1	144,6	210,7
08:00	0	144,6	144,6
09:00	0	144,6	144,6
10:00	333,3	96,4	429,7
11:00	0	144,6	144,6
12:00	0	144,6	144,6
13:00	107,5	24,1	131,6
14:00	129,0	0	129,0
15:00	53,8	21,7	75,4
16:00	0	144,6	144,6
17:00	0	144,6	144,6
18:00	333,3	96,4	429,7
19:00	0	144,6	144,6
20:00	0	144,6	144,6
21:00	77,1	144,6	221,7
22:00	132,2	144,6	276,8
23:00	132,2	144,6	276,8
24:00	132,2	144,6	276,8

Table 4.5: Hourly demand caused by ferry charging with one battery, seen from the grid's point of view. Note that the demand will be 1MW in the fast charging periods.

Case 2.2: Ferry charged from two batteries and grid

As 1 MW power capacity from the grid will create a significant spike in the demand of the island it is decided to do a simulation case where an additional battery is used as grid support to level out the load. A case has been modeled with an additional battery of 1 MW replacing the grid charging during daytime. In the nighttime, both of the batteries are recharging at the same time as the ferry is directly charged from the grid. In this way the ferry is demanding most of its power from the grid during nighttime when the rest of the island has low demand.

In the daytime, when the ferry is charging from the batteries, the demand from the grid's point of view will be zero. In the hours when the ferry is not charging the recharging of the batteries is modeled as a constant load. The charging table for the case with two batteries is presented in Table 4.6. The total power needed from the battery replacing the grid charging during daytime will be $0,333\text{MWh} \cdot 3 = 1\text{MWh}$

Charging time table			
Time	**Ferry grid charging [MWh]**	**Batteries ferry charging [MWh]**	**Batteries grid charging [MW]**
06:30-09:10	0	0	x
09:10-09:30	0	1,333	0
09:30-12:10	0	0	x
12:10-14:45	0	1,333	0
14:45-17:25	0	0	x
17:25-17:45	0	1,333	0
17:45-20:25	0	0	x
20:25-06:30	1,333	0	x

Table 4.6: Time table for charging the ferry and the two batteries

The original battery remains unchanged, and the second is modeled using the same methodology. The charging rate of this battery is given by:
$\frac{1\text{MWh}}{20{,}75\text{h}} = 0,04819\text{MW}.$

The minimum size of the battery is thus given by:

$$\begin{aligned} C &= 1\text{MWh} - x((12{:}10\text{h} - 09{:}30\text{h}) + (17{:}25\text{h} - 14{:}45\text{h}))\text{MWh} \\ \rightarrow C &= 1\text{MWh} - 0,04819\text{MW}(2,67\text{h} + 2,67\text{h}) = 0,743\text{MWh} \end{aligned} \tag{4.2}$$

As seen from Table 4.6 this charging scheme demands higher power during night hours but lower during the day, smoothing out the high load of the fast charging periods.

Table 4.7 gives a presentation of how much hourly power is required from the grid in the case with two batteries.

Grid demand				
Hour	**Ferry [kWh]**	**Battery 1 [kWh]**	**Battery 2 [kWh]**	**Total [kWh]**
01:00	132,2	144,6	48,2	325,0
02:00	132,2	144,6	48,2	325,0
03:00	132,2	144,6	48,2	325,0
04:00	132,2	144,6	48,2	325,0
05:00	132,2	144,6	48,2	325,0
06:00	132,2	144,6	48,2	325,0
07:00	66,1	144,6	48,2	258,9
08:00	0	144,6	48,2	192,8
09:00	0	144,6	48,2	192,8
10:00	0	96,4	32,1	128,5
11:00	0	144,6	48,2	192,8
12:00	0	144,6	48,2	192,8
13:00	0	24,1	8,0	32,1
14:00	0	0	0	0
15:00	0	21,7	7,2	28,9
16:00	0	144,6	48,2	192,8
17:00	0	144,6	48,2	192,8
18:00	0	96,4	32,1	128,5
19:00	0	144,6	48,2	192,8
20:00	0	144,6	48,2	192,8
21:00	77,1	144,6	48,2	269,9
22:00	132,2	144,6	48,2	325,0
23:00	132,2	144,6	48,2	325,0
24:00	132,2	144,6	48,2	325,0

Table 4.7: Demand caused by ferry charging with two batteries, seen from the grid's point of view

4.3.2 Simulation results

The resulting hourly voltage values at all buses on Utsira after the simulation of the cases in this scenario are attached in Appendix C.

Case 2.1: Ferry charged from battery and grid

Figure 4.9 presents the voltage profiles of the buses in the s215 radial and the ferry substation(220), as a result of simulating the ferry charging from one battery and the grid. For the 20 minute charging periods, the increase in load at bus 220 was set to 1 MW.

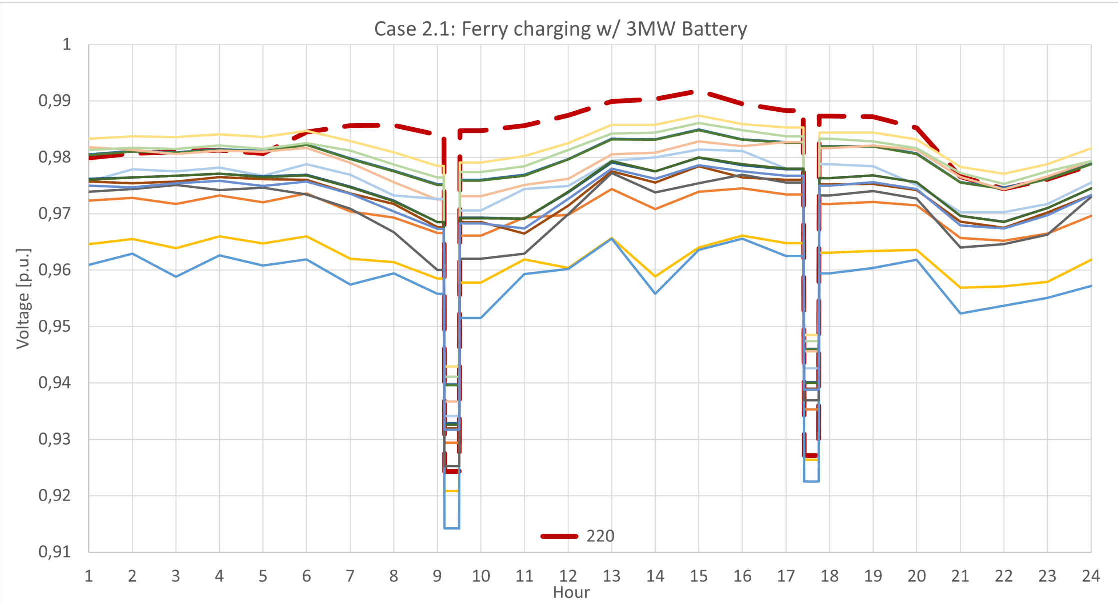

Figure 4.9: Voltage profiles of all loads in the 215 radial for the 1.3 case, as well as the ferry substation (220).

A large drop in voltage can be seen for all buses for the two fast charging periods, 09:10-09:30 and 17:25-17:45, where 1 MW is demanded from the grid for charging. For the ferry substation(220), the drop in voltage value is approximately 0,06 p.u.

Case 2.2: Ferry charged from two batteries and grid

Figure 4.10 presents the voltage profiles as a result of simulations of the ferry charging from two batteries at daytime and directly from the grid at nighttime. In the 09:10-09:30 and 17:25-17:45 charging periods, the grid demand for charging is zero, as all power comes from the batteries.

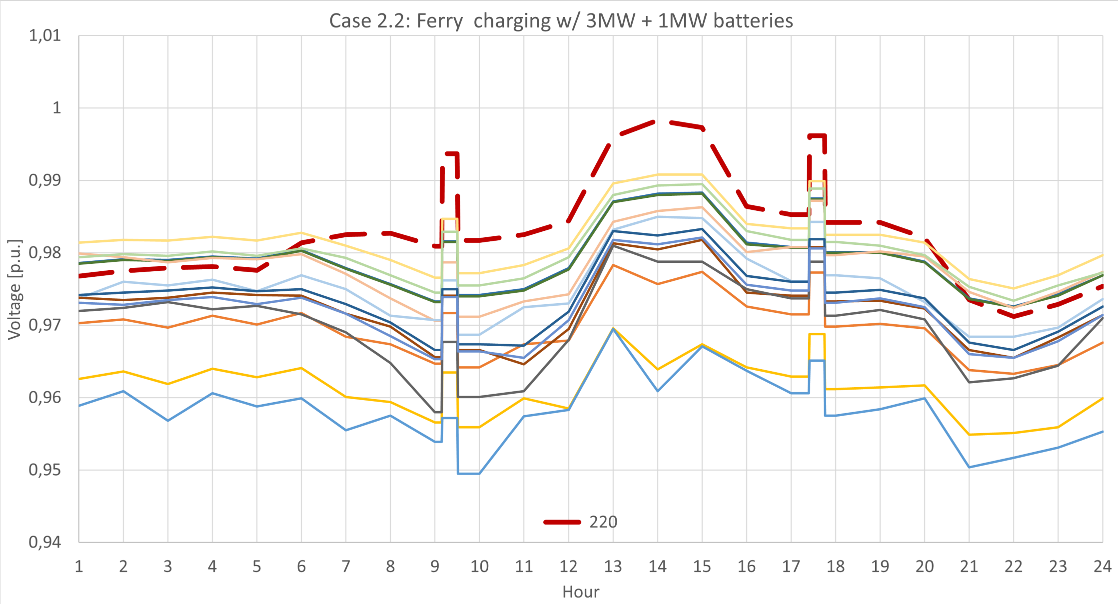

Figure 4.10: Voltage profiles of all loads in the 215 radial for the 2.2 case, as well as the ferry substation (220).

It can be seen from Figure 4.10 that bus 220 has three voltage peaks of approximately 0,02 p.u. in height, due to the batteries disconnecting from the grid to recharge the electric ferry.

4.3.3 Discussion

Case 2.1: Ferry charged from battery and grid

From Table 4.5, it can be observed that the demand seen from the grid caused by the ferry is leveled out in comparison to the case when the ferry is directly charged from the grid. This is an application of peak shaving by using storage. It can be seen that there are still two hours during the day with significantly higher load in comparison to the rest of the day. This can also be observed in the voltage profile, indicated by two voltage drops during the day. This indicates that there is a potential for better managed peak shaving if the amount of storage is increased.

The total load on Utsira will in the 20 minute ferry charging periods reach over 1,5 MW. The currently used 400 kW of wind power production is not enough to ensure that the 1,1 MW operative limit of the sea cable is complied with, let alone for days with worse wind conditions, meaning other measures must be taken to achieve adequate grid operation.

The ferry grid demand during the most intensive charging periods is 1 MW. This peak demand may be reduced using flexibility. To avoid a peak, approximately 700 kW of flexibility is needed in these periods. In a flexibility market, some of this flexibility could be obtained by the DSO. Flexibility providers in these periods could be Utsira municipality, which uses large electrical water boilers for space heating at the school, swimming pool, and sports hall. There are also most likely water heaters used for the showers and the swimming pool, which could provide flexibility in these periods. Based on the load values attached in Appendix A, these loads are estimated to be approximately 50 kW. In section 2.2 it was estimated a potential of 48 kW from all EWHs in the households on the island. Utilization of these flexibility resources will improve the situation, but the mapping and investigation of several other flexibility resources should be done to search for an optimal solution.

Case 2.2: Ferry charged from two batteries and grid

When the ferry is charged from two batteries at daytime and directly from the grid at nighttime it can be seen from Table 4.7 that the load peaks are avoided, and the grid demand has increased in the night hours. In general the demand is lower during the night, so this solution can be characterized as load leveling by peak shaving and valley filling. The electricity demand seen from the grid is low and zero in some of the hours in the middle of the day. As seen from Figure 2.3 the system demand is low in these hours. Therefore, in an optimal solution the demand seen from the grid's point of view could have been increased in these hours to better level out the load.

Comparing the cases

The power demanded from the grid in the two cases are combined in Table 4.8 in order to better see the differences.

Grid demand		
Hour	**case 2.1 [kWh]**	**case 2.2 [kWh]**
01:00	276,8	325,0
02:00	276,8	325,0
03:00	276,8	325,0
04:00	276,8	325,0
05:00	276,8	325,0
06:00	276,8	325,0
07:00	210,7	258,9
08:00	144,6	192,8
09:00	144,6	192,8
10:00	429,7	128,5
11:00	144,6	192,8
12:00	144,6	192,8
13:00	131,6	32,1
14:00	129,0	0
15:00	75,4	28,9
16:00	144,6	192,8
17:00	144,6	192,8
18:00	429,7	128,5
19:00	144,6	192,8
20:00	144,6	192,8
21:00	221,7	269,9
22:00	276,8	325,0
23:00	276,8	325,0
24:00	276,8	325,0

Table 4.8: The overall ferry grid demand for case 2.1 and case 2.1., as a measurement of consumption from the previous to the current hour.

Additionally, in the fast charging periods, the demand will be 1 MW v.s. 0 MW.

To better visualize the impact of a second battery, the ferry substation voltage curves for both cases are superimposed in Figure 4.11.

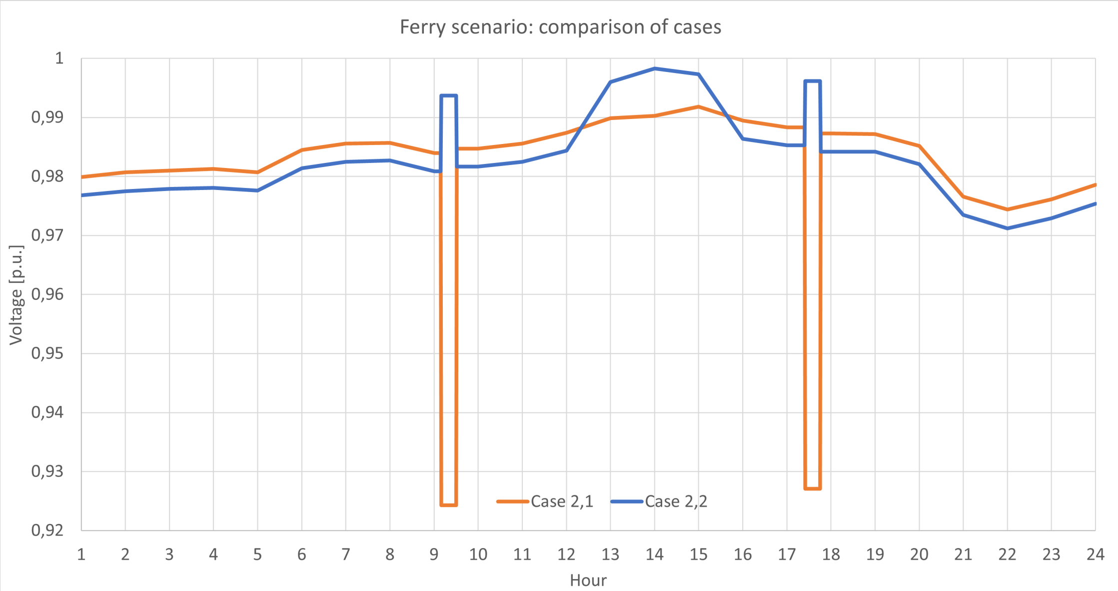

Figure 4.11: A comparison of the voltage profile at the ferry substation (bus 220) for case 2.1 and 2.2.

The case with two installed batteries will give a more stable load curve, but also increase the demand during night hours. By comparing the voltage variations in case 2.1 and case 2.2 in Figure 4.11 it can be observed that case 2.2 will have a significantly flatter voltage profile. The voltage drops in bus 220 are calculated to be approximately 0,07 p.u. and 0,02 p.u. for case 2.1 and case 2.2, respectively.

Considering the variability of wind power in the real case, case 2.2 gives more stability in the fast charging periods as wind fluctuations here can further worsen case 2.1 values, reaching as low as 0,9 p.u. with no wind.

The current transformer rating for the ferry substation is 315 kVA. This limit is breached for both case 2.1 and 2.2, and so the transformer must be replaced no matter the solution implemented for the integration of the electric ferry. However, as the change in maximum load is 1 MW v.s. 0,325 MW for case 2.1 vs.s 2.2, the size of the new transformer would need to be significantly larger for case 2.1. This capacity would be needed for the short, fast charging periods, but be overkill for the remainder of the day. Contrarily, less additional transformer capacity would be needed for case 2.2, and it would not be underutilized for long periods.

It can be observed that for an optimal solution the energy storage should be at such a size that the load curve is perfectly leveled out. The cost of increasing the storage capacity has to be seen in the context of grid investments. The costs for lithium-ion batteries, normally used for stationary storage, have decreased the recent years [76]. Using current cost data the costs for introducing a second battery as simulated in case 2.2 could be estimated to be 3-4,5 MNOK. The battery costs can continue to decrease as it becomes more common to use in grid operation. Therefore, the size of storage solutions has to be continuously considered in the context of alternative costs of grid operation.

Common discussion

The voltage value of bus 220 was most heavily impacted in the simulation, as this is where the ferry is indirectly connected. Costumers in the radial connected to this substation, including the ferry, will experience magnified voltage problems, as the voltage dips will increase further out into the radial due to line voltage losses. This effect can also be seen in the s215 radial voltages, where the lowest curves in the graphs are generally positioned the furthest out into the network.

The battery recharging scheme is as stated in the scenario descriptions modeled as a constant load. However, other charging methods could be implemented in stead of this, potentially further improving grid conditions. For instance, if the battery recharging were to increase and decrease with available grid capacity, the BESS would more heavily utilize periods of high capacity, for instance when wind conditions are strong, such that low capacity periods would not be loaded as much, resulting in smoother load curves for the distribution system. On the other hand, such schemes might be more expensive and complex to realize.

4.4 Discussion of scenarios

As the load is expected to increase in the future, transformer step ratios will also be tuned to accommodate for higher power flows. However, increasing transformer step ratios would not solve the voltage problems demonstrated in case 1.1 and 2.1. Changing the ratio to increase the lowest value of the dips could then result in the voltages being too high outside of the affected periods. There would similarly be introduced problems related to the variable wind productions effect on voltage values, when loads are low and generation high.

In both case 1.2 and case 2.2 the best solution seemed to be to move most of the load to the night. If both scenarios are combined, however, the total load increase during night hours would be 530 kWh/h, which is higher than the highest hourly consumption for the ferry in case 2.1. Both case 1.3 and case 2.2 have low voltage values at 21:00-22:00, so combining these scenarios would probably result in too poor conditions for the island in these hours. As can be observed in Figure 2.3 the load demand during the night hours in the existing network is high as well. This is mostly because of the docking of today's ferry, and it is not known how this will change with its electrification.

The power production at the island should also be increased if these scenarios are realized in 2025. The power demand will almost be doubled according to today's demand. As mentioned in chapter 2 the sea cable is already close to its maximum capacity, and the increase in load should be covered by energy resources at Utsira. To utilize the wind and solar potential at the island BESS solutions have to be considered. A combination of storage used for ferry charging and storing power from windmill or PV production could be beneficial. Also, for end-users, the EV battery can be used as additional storage for rooftop PV. An investigation of the possibilities for locating DG in a combination with BESS in weak areas of the distribution network at Utsira would be valuable.

Chapter 5

Conclusions

In this thesis, flexibility solutions in the distribution network on Utsira have been studied.

A general literature analysis on how the power system is changing has been done. Increasing electrification, decentralization, and integration of VREs will change the operation of existing power systems, and the integration of flexibility resources are necessary to improve and maintain operational conditions.

Current and expected problems in the distribution system on the island municipality of Utsira have been investigated. Existing voltage problems are forecasted to increase due to growing industry and the electrification of the ferry, and flexibility potential has therefore been explored as a remedy.

An analysis of the AMS data given by the DSO, Haugaland Kraft, was done to give an overview of the need and potential for flexibility solutions on the island. A model of the network on Utsira was built in PSSE to simulate scenarios on how changes in power consumption, due to i.a. increased electrification, would affect the existing grid. Power flow analyses were done in PSSE to predict the voltage profiles in the scenarios.

In the first scenario, three different cases of how an increased EV population on the island would affect the existing distribution grid have been studied. The simulation results indicated that simultaneous high intensive charging of several EVs could result in voltage issues for some end-users. It was concluded that incentives for achieving a high DSR participation rate should be implemented to secure adequate grid operation.

In the second scenario, three different charging schemes for the planned electric ferry have been investigated. It was clear that charging the ferry directly from the distribution grid would be an unrealistic solution according to the existing grid capacity. Therefore, two different scenarios for shifting the load by using BESS were in focus. It was observed that the size and power capacity of the combined battery solution was important for flattening the load curve, but cost analysis has to be done to secure the optimal solution for grid operation in the context of investment and operational costs for the DSO.

Key takeaways:

- Achieving a high DSR participation rate for smart charging of EVs will reduce voltage variations.
- Load shifting by using appropriate BESS for charging the planned electric ferry will reduce voltage variations and reduce needed reinforcements in the distribution grid.
- The increase of load due to electrification of the transport sector at Utsira will demand an increase of power supply from the VRES available on the island.
- There is a potential for flexibility in the thermal loads on Utsira, but that is alone not sufficient to cover the predicted increase in power demand.

5.1 Further work

The work done in this thesis indicates that there is a potential for flexibility solutions in the distribution grid at Utsira. Due to limited time and available data some of the analysis is based on statistics and prognoses. A more detailed analysis and exact mapping of the flexibility resources could be done. In addition, the further work of this thesis can include the following aspects:

- Perform further analysis on a more detailed network model of Utsira, reducing simplifications and assumptions to obtain more accurate simulation results.

- Include a more realistic variation in windmill power production in the model; investigate the impact of wind power variations in more detail.
- Investigate how BESS used for ferry charging could be combined with storage for windmill or PV power production.
- Develop a more detailed charging scheme for the planned electric ferry, including different methods of charging and discharging the BESS.
- Analyze how reactive power injections from EV chargers can be used as grid support by improving the voltage.
- The potential of DG could be analyzed by mapping the optimal location and size of the energy resources.
- Do a survey among the population on Utsira to investigate the possible flexibility potential of the loads, and their willingness to participate in DSR.
- Investigate the possibilities for island operation in critical situations by analyzing the potential for storage and the operation time without any wind and PV power production.
- Perform a cost-benefit analysis of implementing BESS in weak areas of the distribution network versus conventional network planning.

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Appendix A

Scenario 0: Base case

Bus/hour	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
102	26,26	25,11	24,60	24,51	24,80	25,69	27,94	30,83	32,91	33,31	32,95	32,32	31,56	30,98	30,27	30,16	30,89	31,75	32,16	32,18	31,88	31,14	29,66	27,66
103	20,70	19,79	19,39	19,32	19,55	20,25	22,02	24,30	25,94	26,26	25,97	25,47	24,88	24,42	23,86	23,77	24,35	25,03	25,35	25,37	25,13	24,55	23,38	21,80
104	127,51	121,93	119,49	119,05	120,45	124,78	135,69	149,73	159,84	161,76	160,00	156,95	153,28	150,47	147,01	146,45	150,02	154,21	156,17	156,29	154,81	151,24	144,06	134,32
105	167,71	160,36	157,16	156,58	158,42	164,12	178,47	196,94	210,23	212,75	210,45	206,42	201,61	197,91	193,35	192,62	197,31	202,82	205,40	205,55	203,61	198,92	189,47	176,67
106	50,35	48,14	47,18	47,01	47,56	49,27	53,58	59,12	63,11	63,87	63,18	61,97	60,52	59,41	58,04	57,82	59,23	60,89	61,66	61,71	61,12	59,72	56,88	53,04
107	354,24	338,72	331,95	330,74	334,61	346,64	376,96	415,97	444,05	449,37	444,50	436,00	425,83	418,03	408,40	406,84	416,76	428,39	433,84	434,17	430,06	420,16	400,19	373,16
108	106,06	101,41	99,39	99,02	100,18	103,79	112,86	124,54	132,95	134,54	133,08	130,54	127,50	125,16	122,28	121,81	124,78	128,26	129,89	129,99	128,76	125,80	119,82	111,72
109	436,10	416,99	408,66	407,16	411,93	426,74	464,07	512,09	546,66	553,21	547,21	536,75	524,23	514,62	502,77	500,85	513,06	527,38	534,09	534,50	529,44	517,24	492,67	459,38
110	116,16	111,07	108,85	108,45	109,72	113,66	123,60	136,40	145,60	147,35	145,75	142,97	139,63	137,07	133,91	133,40	136,66	140,47	142,25	142,36	141,02	137,77	131,22	122,36
111	135,29	129,37	126,78	126,32	127,80	132,39	143,97	158,87	169,60	171,63	169,77	166,52	162,64	159,66	155,98	155,39	159,17	163,62	165,69	165,82	164,25	160,47	152,85	142,52
112	677,99	648,28	635,33	633,01	640,42	663,45	721,48	796,13	849,89	860,06	850,74	834,48	815,01	800,07	781,65	778,67	797,65	819,91	830,33	830,97	823,11	804,15	765,94	714,19
113	136,00	130,04	127,44	126,97	128,46	133,08	144,72	159,69	170,48	172,52	170,65	167,39	163,48	160,48	156,79	156,19	160,00	164,46	166,55	166,68	165,11	161,30	153,64	143,26
114	135,53	129,59	127,01	126,54	128,02	132,63	144,23	159,15	169,90	171,93	170,07	166,82	162,92	159,94	156,25	155,66	159,45	163,90	165,99	166,11	164,54	160,75	153,12	142,77
115	135,92	129,96	127,37	126,90	128,39	133,00	144,64	159,60	170,38	172,42	170,55	167,29	163,39	160,39	156,70	156,10	159,91	164,37	166,46	166,59	165,01	161,21	153,55	143,18
116	39,07	37,36	36,61	36,48	36,91	38,23	41,58	45,88	48,98	49,57	49,03	48,09	46,97	46,11	45,05	44,88	45,97	47,25	47,85	47,89	47,44	46,34	44,14	41,16
117	227,43	217,46	213,12	212,34	214,82	222,55	242,02	267,06	285,09	288,50	285,38	279,92	273,39	268,38	262,20	261,20	267,57	275,04	278,53	278,74	276,11	269,75	256,93	239,57
118	152,09	145,43	142,52	142,00	143,66	148,83	161,84	178,59	190,65	192,93	190,84	187,19	182,83	179,48	175,34	174,67	178,93	183,93	186,26	186,41	184,64	180,39	171,82	160,21
119	285,98	273,45	267,99	267,01	270,13	279,85	304,32	335,81	358,49	362,78	358,85	351,99	343,78	337,48	329,70	328,45	336,45	345,84	350,24	350,51	347,19	339,19	323,08	301,25
120	147,85	141,37	138,55	138,04	139,65	144,68	157,33	173,61	185,33	187,55	185,52	181,97	177,73	174,47	170,45	169,80	173,94	178,80	181,07	181,21	179,49	175,36	167,03	155,74
121	68,24	65,25	63,94	63,71	64,46	66,77	72,61	80,13	85,54	86,56	85,62	83,99	82,03	80,52	78,67	78,37	80,28	82,52	83,57	83,63	82,84	80,93	77,09	71,88
202	41,56	40,24	42,66	42,12	50,32	44,52	48,82	50,12	44,88	47,78	45,18	36,82	36,60	38,78	43,10	48,88	46,32	53,42	51,24	52,42	52,42	47,34	48,68	42,52
208	23,13	23,24	22,85	22,55	22,85	20,75	23,31	23,41	23,04	22,90	21,53	19,99	20,39	20,85	20,39	24,18	26,81	22,78	24,30	25,43	25,64	25,46	26,65	24,09
210	39,04	40,96	38,08	39,68	40,64	46,72	46,72	44,16	40,64	39,04	38,08	39,36	35,52	32,64	39,68	39,04	42,56	42,24	42,24	40,96	41,60	41,60	42,24	41,28
212	118,08	115,20	112,64	112,96	112,96	114,56	122,24	130,88	136,64	125,44	123,52	117,44	115,52	118,40	115,52	124,16	126,40	127,68	120,00	120,96	121,60	117,76	119,36	112,64
214	54,98	55,04	54,00	53,27	58,00	57,57	57,54	66,86	61,55	59,44	57,18	55,90	56,36	50,65	51,24	50,03	55,09	52,65	57,91	58,36	57,45	57,68	55,02	54,76
217	41,40	45,90	44,70	46,50	41,40	40,80	41,10	45,60	40,20	37,80	40,20	41,40	39,90	36,30	35,10	35,40	39,60	37,80	41,40	40,50	43,20	40,80	39,90	39,30
220	73,60	73,92	74,88	74,24	75,20	25,92	23,36	22,40	24,00	23,68	22,72	21,44	21,12	19,52	19,84	20,80	20,48	24,32	22,08	42,88	79,36	74,56	71,68	76,48
221	110,80	111,20	111,20	110,80	111,20	118,00	118,80	119,20	121,20	114,00	110,40	102,80	104,40	111,20	107,60	111,60	115,60	119,20	122,80	119,20	122,00	120,00	115,60	107,60
303	18,66	16,32	16,26	15,72	14,28	10,74	19,26	19,50	18,36	13,08	8,04	6,54	4,68	3,96	4,08	8,40	10,92	6,30	8,04	9,90	10,92	8,88	11,58	16,74
304	39,12	38,96	40,24	39,84	38,88	39,84	44,72	48,24	50,32	50,96	61,04	51,12	46,24	50,00	47,84	46,40	43,60	43,60	41,76	43,04	44,24	43,28	42,80	40,08
306	9,50	14,00	16,60	15,80	14,80	16,50	21,40	31,20	33,60	33,60	29,50	36,20	31,40	30,00	27,20	22,50	15,90	16,50	13,70	11,70	10,90	15,70	12,90	13,10
308	0,83	0,83	0,84	0,84	0,83	0,83	0,83	0,83	0,83	0,83	0,83	0,83	0,83	0,83	1,05	1,53	1,52	1,52	1,53	1,53	1,53	1,54	1,55	0,83
309	3,74	2,86	3,05	2,93	3,46	2,95	2,94	3,77	2,87	4,16	2,85	3,74	3,14	2,88	2,96	2,38	3,60	2,78	2,93	4,00	3,90	3,31	3,50	2,99
310	1,03	1,04	1,09	1,04	1,10	1,15	0,90	1,10	1,10	0,91	0,95	0,64	0,83	0,77	0,65	0,55	0,80	0,56	0,78	0,85	0,57	0,89	0,70	1,21
312	1,97	2,33	2,34	2,14	2,56	2,04	2,42	2,34	2,33	2,57	2,15	2,37	1,97	2,01	2,51	2,07	2,09	2,43	2,13	2,50	2,13	2,21	2,38	2,47
314	5,50	5,50	5,32	5,28	5,27	5,32	5,86	6,20	6,11	5,42	5,63	7,71	7,12	8,87	8,18	6,86	6,58	6,32	6,54	6,26	6,17	5,96	6,44	5,42
315	3,03	2,52	3,64	2,85	3,10	3,21	3,54	2,35	2,70	4,24	2,52	1,89	1,74	3,51	2,07	1,85	2,63	3,22	2,94	2,29	3,58	2,98	2,83	3,43
318	3,28	4,10	4,18	3,28	3,12	3,96	4,53	3,28	3,98	4,01	7,46	6,78	5,07	5,92	4,67	6,31	5,70	4,50	5,01	4,86	4,04	4,50	3,56	4,58
319	2,58	2,30	1,98	3,02	2,34	3,50	3,76	5,06	7,36	6,52	5,56	3,68	2,08	3,50	4,10	1,90	2,44	3,22	2,84	2,94	5,02	3,88	4,36	1,94
321	0,33	0,33	0,32	0,32	0,32	0,32	0,31	0,32	0,31	0,31	0,31	0,30	0,31	0,31	0,31	0,31	0,31	0,31	0,31	0,32	0,31	0,32	0,32	0,32
322	2,09	1,62	1,61	1,60	1,89	1,83	1,58	1,64	1,62	2,08	1,49	1,01	0,90	1,26	0,77	0,86	1,02	1,83	1,42	1,43	1,44	1,92	1,47	1,61
323	3,00	3,51	3,01	3,00	3,61	2,97	2,98	3,75	3,06	2,94	3,61	2,73	2,60	2,87	2,71	2,63	2,69	3,15	2,80	2,90	3,48	2,97	2,98	2,92

Table A.1: Base case load: Active power consumed from previous hour [kWh]

Bus/hour	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
102	5,34	5,10	5,00	4,98	5,04	5,22	5,68	6,27	6,69	6,77	6,70	6,57	6,41	6,30	6,15	6,13	6,28	6,45	6,54	6,54	6,48	6,33	6,03	5,62
103	4,20	4,02	3,94	3,92	3,97	4,11	4,47	4,93	5,27	5,33	5,27	5,17	5,05	4,96	4,85	4,83	4,94	5,08	5,15	5,15	5,10	4,98	4,75	4,43
104	25,89	24,76	24,27	24,18	24,46	25,34	27,56	30,41	32,46	32,85	32,49	31,87	31,13	30,56	29,85	29,74	30,46	31,31	31,71	31,74	31,44	30,71	29,25	27,28
105	55,70	53,26	52,19	52,00	52,61	54,50	59,27	65,40	69,82	70,66	69,89	68,55	66,95	65,73	64,21	63,97	65,53	67,36	68,21	68,27	67,62	66,06	62,92	58,67
106	10,23	9,78	9,58	9,55	9,66	10,01	10,88	12,01	12,82	12,97	12,83	12,59	12,29	12,07	11,79	11,74	12,03	12,37	12,52	12,53	12,41	12,13	11,55	10,77
107	77,95	74,53	73,04	72,77	73,63	76,27	82,94	91,53	97,71	98,88	97,81	95,94	93,70	91,98	89,86	89,52	91,70	94,26	95,46	95,53	94,63	92,45	88,06	82,11
108	21,54	20,59	20,18	20,11	20,34	21,08	22,92	25,29	27,00	27,32	27,03	26,51	25,89	25,42	24,83	24,74	25,34	26,05	26,38	26,40	26,15	25,55	24,33	22,69
109	139,57	133,46	130,79	130,31	131,84	136,58	148,53	163,90	174,96	177,06	175,14	171,79	167,78	164,71	160,91	160,30	164,21	168,79	170,94	171,07	169,45	165,55	157,68	147,03
110	37,89	36,23	35,50	35,37	35,79	37,07	40,32	44,49	47,49	48,06	47,54	46,63	45,54	44,71	43,68	43,51	44,57	45,82	46,40	46,43	45,99	44,94	42,80	39,91
111	51,16	48,92	47,95	47,77	48,33	50,07	54,45	60,08	64,14	64,90	64,20	62,97	61,50	60,38	58,99	58,76	60,19	61,87	62,66	62,71	62,12	60,68	57,80	53,90
112	178,86	171,02	167,60	166,99	168,94	175,02	190,33	210,02	224,20	226,89	224,43	220,14	215,00	211,06	206,20	205,41	210,42	216,30	219,04	219,21	217,14	212,14	202,06	188,41
113	52,57	50,26	49,26	49,08	49,65	51,44	55,94	61,73	65,90	66,68	65,96	64,70	63,19	62,03	60,60	60,37	61,85	63,57	64,38	64,43	63,82	62,35	59,39	55,37
114	45,00	43,02	42,16	42,01	42,50	44,03	47,88	52,84	56,40	57,08	56,46	55,38	54,09	53,10	51,87	51,68	52,94	54,41	55,11	55,15	54,63	53,37	50,83	47,40
115	44,53	42,57	41,72	41,57	42,06	43,57	47,38	52,28	55,81	56,48	55,87	54,80	53,52	52,54	51,33	51,14	52,38	53,85	54,53	54,57	54,06	52,81	50,30	46,90
116	7,93	7,59	7,44	7,41	7,50	7,76	8,44	9,32	9,95	10,07	9,96	9,77	9,54	9,36	9,15	9,11	9,34	9,60	9,72	9,73	9,63	9,41	8,96	8,36
117	46,18	44,16	43,28	43,12	43,62	45,19	49,14	54,23	57,89	58,59	57,95	56,84	55,52	54,50	53,24	53,04	54,33	55,85	56,56	56,60	56,07	54,78	52,17	48,65
118	49,37	47,20	46,26	46,09	46,63	48,31	52,53	57,97	61,88	62,63	61,95	60,76	59,34	58,26	56,92	56,70	58,08	59,70	60,46	60,51	59,93	58,55	55,77	52,00
119	66,48	63,57	62,30	62,07	62,79	65,05	70,74	78,06	83,33	84,33	83,42	81,82	79,91	78,45	76,64	76,35	78,21	80,39	81,42	81,48	80,71	78,85	75,10	70,03
120	44,63	42,68	41,82	41,67	42,16	43,68	47,50	52,41	55,95	56,62	56,01	54,93	53,65	52,67	51,46	51,26	52,51	53,98	54,66	54,70	54,19	52,94	50,42	47,02
121	0,37	0,35	0,35	0,35	0,35	0,36	0,39	0,43	0,46	0,47	0,46	0,46	0,44	0,44	0,43	0,43	0,44	0,45	0,45	0,45	0,45	0,44	0,42	0,39
202	0,80	1,00	0,62	0,62	0,80	0,80	0,74	0,86	0,90	1,46	1,40	1,02	1,08	1,28	1,44	1,20	1,34	1,28	1,40	1,34	1,58	1,46	1,60	0,68
208	1,76	1,73	1,74	1,68	1,58	1,47	1,49	1,79	1,73	1,65	1,65	1,49	1,42	1,60	1,54	1,40	1,71	1,82	1,83	1,71	1,53	1,69	1,46	1,67
210	0,96	0,64	0,96	0,96	0,96	0,96	0,96	0,64	1,28	1,28	1,28	0,64	0,96	0,64	0,96	0,64	1,92	1,60	1,28	1,28	0,96	1,28	0,96	0,96
212	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
214	2,02	2,14	2,39	2,21	2,24	2,43	2,32	2,63	2,70	2,48	2,36	2,14	2,26	1,79	1,85	2,21	2,04	2,23	2,20	1,92	2,18	2,57	2,62	2,11
217	2,40	3,00	5,70	5,70	3,30	2,40	2,40	2,70	1,80	1,80	2,10	4,80	4,80	3,60	1,80	2,70	2,10	2,40	2,70	2,40	2,40	2,10	1,80	1,80
220	20,48	20,48	20,80	20,16	19,84	5,12	3,52	3,84	3,52	3,20	2,88	2,88	2,24	2,56	2,56	3,20	2,88	3,20	1,28	8,32	18,88	19,84	20,16	20,48
221	3,20	3,20	3,20	2,80	3,20	3,60	2,80	3,20	4,80	4,00	4,40	2,80	3,20	3,60	3,60	3,20	2,80	3,20	2,40	3,60	2,00	2,40	2,80	2,80
303	0,00	0,00	0,06	0,00	0,00	0,00	0,00	0,06	0,00	0,00	0,00	0,00	0,06	0,00	0,00	0,00	0,00	0,06	0,00	0,00	0,00	0,00	0,06	0,00
304	16,72	16,80	16,88	16,56	16,40	17,04	16,72	17,04	17,68	18,64	19,76	16,80	17,20	16,88	17,04	17,20	16,48	16,56	16,96	17,20	16,96	17,44	17,84	16,64
306	1,80	4,00	6,30	5,70	5,50	6,30	7,50	6,00	8,80	9,20	6,10	8,00	4,90	4,60	4,60	5,20	2,70	3,70	2,90	2,90	2,90	5,20	4,30	4,50
308	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
309	0,37	0,34	0,15	0,08	0,09	0,11	0,21	0,38	0,36	0,34	0,34	0,29	0,32	0,27	0,29	0,24	0,28	0,27	0,22	0,26	0,26	0,25	0,31	0,36
310	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
312	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,04	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01
314	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
315	0,01	0,01	0,00	0,01	0,02	0,01	0,03	0,03	0,01	0,02	0,01	0,00	0,01	0,00	0,00	0,02	0,00	0,00	0,02	0,00	0,00	0,02	0,00	0,00
318	0,00	0,00	0,00	0,03	0,00	0,03	0,15	0,00	0,00	0,02	0,00	0,00	0,00	0,00	0,03	0,03	0,17	0,03	0,06	0,07	0,04	0,12	0,00	0,00
319	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,02	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,02	0,00	0,00	0,00	0,00
321	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
322	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
323	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00

Table A.2: Base case load: Reactive power consumed from previous hour [kVarh]

Bus/hour	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
201	1,0123	1,0131	1,0135	1,0137	1,013	1,0142	1,0109	1,0068	1,0052	1,0058	1,0066	1,0086	1,0102	1,0104	1,0111	1,0104	1,0093	1,0083	1,008	1,0071	1,0054	1,0068	1,0084	1,0111
202	0,9752	0,976	0,9764	0,9765	0,9758	0,977	0,9737	0,9698	0,9683	0,9688	0,9697	0,9716	0,9732	0,9733	0,974	0,9733	0,9722	0,9712	0,971	0,97	0,9684	0,9698	0,9713	0,974
203	0,9762	0,977	0,9774	0,9775	0,977	0,9781	0,9749	0,9711	0,9694	0,9701	0,9709	0,9726	0,9741	0,9744	0,9751	0,9745	0,9734	0,9725	0,9723	0,9714	0,9697	0,971	0,9726	0,9751
204	0,9762	0,977	0,9774	0,9775	0,977	0,9781	0,9749	0,9711	0,9694	0,9701	0,9709	0,9726	0,9741	0,9744	0,9751	0,9745	0,9734	0,9725	0,9723	0,9714	0,9697	0,971	0,9726	0,9751
205	0,9767	0,9774	0,9778	0,978	0,9774	0,9785	0,9754	0,9715	0,9699	0,9705	0,9713	0,973	0,9746	0,9748	0,9756	0,975	0,9739	0,973	0,9727	0,9718	0,9702	0,9715	0,973	0,9755
206	1,0532	1,054	1,0545	1,0546	1,0541	1,0552	1,0518	1,0477	1,0459	1,0466	1,0474	1,0493	1,051	1,0512	1,052	1,0514	1,0502	1,0492	1,049	1,048	1,0462	1,0476	1,0493	1,052
207	0,976	0,9767	0,9771	0,9773	0,9767	0,9778	0,9747	0,9708	0,9692	0,9698	0,9706	0,9724	0,9739	0,9741	0,9749	0,9743	0,9732	0,9723	0,972	0,9711	0,9695	0,9708	0,9723	0,9748
208	0,9989	0,9997	1,0001	1,0003	0,9998	1,0011	0,9976	0,9936	0,992	0,9927	0,9936	0,9955	0,9971	0,9972	0,9981	0,9972	0,9958	0,9951	0,9948	0,9938	0,9921	0,9934	0,9949	0,9977
209	0,9759	0,9766	0,977	0,9772	0,9766	0,9777	0,9745	0,9707	0,9691	0,9697	0,9705	0,9722	0,9738	0,974	0,9748	0,9742	0,9731	0,9722	0,9719	0,971	0,9694	0,9706	0,9722	0,9747
210	0,9978	0,9985	0,9991	0,9991	0,9985	0,9992	0,9959	0,9922	0,9907	0,9915	0,9923	0,9942	0,996	0,9965	0,9967	0,9962	0,9945	0,9937	0,9935	0,9927	0,991	0,9922	0,9938	0,9965
211	0,9758	0,9766	0,977	0,9771	0,9766	0,9777	0,9745	0,9706	0,969	0,9697	0,9704	0,9722	0,9737	0,974	0,9747	0,9742	0,973	0,9721	0,9719	0,971	0,9693	0,9706	0,9721	0,9747
212	0,992	0,993	0,9937	0,9938	0,9932	0,9942	0,9903	0,9857	0,9835	0,9851	0,986	0,9883	0,9901	0,9901	0,9911	0,9898	0,9885	0,9874	0,9878	0,9868	0,985	0,9866	0,9881	0,9913
213	0,9758	0,9766	0,977	0,9771	0,9766	0,9777	0,9745	0,9706	0,969	0,9697	0,9704	0,9722	0,9737	0,974	0,9747	0,9741	0,973	0,9721	0,9719	0,9709	0,9693	0,9706	0,9721	0,9746
214	1,0002	1,001	1,0013	1,0015	1,0009	1,002	0,9988	0,9947	0,993	0,9938	0,9946	0,9965	0,998	0,9984	0,9992	0,9985	0,9973	0,9964	0,9961	0,9952	0,9935	0,9947	0,9963	0,999
215	0,9758	0,9766	0,977	0,9771	0,9766	0,9777	0,9745	0,9707	0,969	0,9697	0,9705	0,9722	0,9738	0,974	0,9748	0,9742	0,9731	0,9722	0,9719	0,971	0,9693	0,9706	0,9722	0,9747
216	0,9758	0,9766	0,977	0,9771	0,9766	0,9777	0,9745	0,9706	0,969	0,9697	0,9705	0,9722	0,9738	0,974	0,9748	0,9742	0,973	0,9721	0,9719	0,971	0,9693	0,9706	0,9721	0,9747
217	0,9988	0,9993	0,9994	0,9994	0,9994	1,0007	0,9974	0,9932	0,9919	0,9927	0,9933	0,9947	0,9964	0,997	0,998	0,9973	0,996	0,9951	0,9947	0,9938	0,992	0,9935	0,9951	0,9977
218	0,9757	0,9765	0,9769	0,977	0,9765	0,9777	0,9745	0,9706	0,969	0,9696	0,9704	0,9722	0,9737	0,9739	0,9747	0,9741	0,973	0,9721	0,9718	0,9709	0,9692	0,9705	0,9721	0,9746
219	0,9757	0,9765	0,9769	0,977	0,9765	0,9776	0,9745	0,9706	0,969	0,9696	0,9704	0,9722	0,9737	0,9739	0,9747	0,9741	0,973	0,9721	0,9718	0,9709	0,9692	0,9705	0,972	0,9746
220	0,9974	0,9981	0,9985	0,9987	0,9982	1,0017	0,9986	0,9946	0,993	0,9937	0,9945	0,9963	0,998	0,9982	0,999	0,9984	0,9972	0,9962	0,9961	0,9941	0,9906	0,992	0,9937	0,9961
221	0,9919	0,9926	0,993	0,9933	0,9926	0,9932	0,99	0,9859	0,9837	0,9851	0,9861	0,9888	0,9903	0,9899	0,991	0,9901	0,9887	0,9874	0,987	0,9861	0,9844	0,9859	0,9877	0,991
222	0,9766	0,9774	0,9778	0,9779	0,9774	0,9785	0,9753	0,9715	0,9698	0,9705	0,9713	0,973	0,9745	0,9748	0,9755	0,9749	0,9738	0,9729	0,9727	0,9718	0,9701	0,9714	0,973	0,9755
223	1,0532	1,054	1,0544	1,0546	1,054	1,0552	1,0518	1,0476	1,0459	1,0466	1,0474	1,0492	1,0509	1,0512	1,052	1,0514	1,0711	1,0702	1,0699	1,0689	1,0671	1,0476	1,0492	1,0519
301	0,994	0,9944	0,9944	0,9948	0,9944	0,9954	0,991	0,9865	0,9841	0,9847	0,9858	0,9881	0,9908	0,9908	0,9919	0,9914	0,9908	0,99	0,9899	0,9889	0,987	0,9879	0,9896	0,9924
302	0,9913	0,9918	0,9917	0,9921	0,9918	0,9929	0,988	0,9832	0,9808	0,9817	0,9825	0,9853	0,9883	0,9882	0,9894	0,9888	0,9882	0,9875	0,9875	0,9863	0,9843	0,9854	0,987	0,9897
303	0,9913	0,9918	0,9916	0,9921	0,9918	0,9929	0,9879	0,9832	0,9808	0,9816	0,9824	0,9853	0,9883	0,9882	0,9894	0,9888	0,9882	0,9875	0,9875	0,9863	0,9843	0,9854	0,987	0,9896
304	0,9912	0,9917	0,9916	0,992	0,9917	0,9928	0,9878	0,9831	0,9807	0,9815	0,9823	0,9852	0,9882	0,988	0,9893	0,9886	0,9881	0,9874	0,9874	0,9862	0,9842	0,9853	0,9869	0,9895
305	0,9942	0,9946	0,9945	0,9949	0,9945	0,9955	0,9912	0,9866	0,9843	0,9849	0,9859	0,9882	0,9909	0,9909	0,992	0,9915	0,991	0,9901	0,9901	0,989	0,9871	0,9881	0,9898	0,9925
306	0,9925	0,992	0,9914	0,992	0,9917	0,9924	0,9871	0,9811	0,9781	0,9787	0,9807	0,9818	0,9856	0,9858	0,9874	0,9875	0,9883	0,9872	0,9876	0,9869	0,9851	0,9851	0,9874	0,9901
307	0,994	0,9944	0,9944	0,9948	0,9944	0,9953	0,991	0,9864	0,9841	0,9847	0,9858	0,988	0,9908	0,9908	0,9919	0,9914	0,9908	0,9899	0,9899	0,9888	0,9869	0,9879	0,9896	0,9923
308	0,994	0,9944	0,9943	0,9948	0,9944	0,9953	0,991	0,9864	0,9841	0,9847	0,9858	0,988	0,9908	0,9908	0,9919	0,9914	0,9908	0,9899	0,9899	0,9888	0,9869	0,9879	0,9896	0,9923
309	0,9865	0,9887	0,9883	0,9889	0,9874	0,9895	0,9851	0,9788	0,9782	0,9762	0,98	0,9805	0,9844	0,985	0,9859	0,9866	0,9835	0,9843	0,984	0,9807	0,979	0,9812	0,9825	0,9863
310	0,992	0,9924	0,9923	0,9928	0,9923	0,9931	0,9893	0,9843	0,982	0,9829	0,9839	0,9868	0,9892	0,9893	0,9906	0,9903	0,9892	0,9889	0,9884	0,9872	0,9858	0,9862	0,9882	0,99
311	0,9837	0,9842	0,9832	0,9847	0,9836	0,9849	0,9792	0,9756	0,973	0,9725	0,9756	0,9761	0,98	0,9763	0,9792	0,9807	0,9796	0,978	0,9783	0,9779	0,9751	0,9768	0,9781	0,9811
312	0,9831	0,9836	0,9825	0,984	0,9828	0,9843	0,9785	0,9749	0,9723	0,9717	0,9749	0,9754	0,9795	0,9757	0,9785	0,9801	0,979	0,9773	0,9777	0,9771	0,9745	0,9762	0,9774	0,9804
313	0,9782	0,9791	0,9774	0,9794	0,9782	0,9794	0,9731	0,9701	0,9672	0,9661	0,9703	0,9699	0,9743	0,9683	0,9725	0,9751	0,9737	0,9718	0,9722	0,9723	0,9687	0,971	0,972	0,9754
314	0,9755	0,9764	0,9748	0,9769	0,9756	0,9769	0,9703	0,967	0,9642	0,9635	0,9675	0,9661	0,9709	0,9639	0,9686	0,9717	0,9705	0,9688	0,969	0,9693	0,9657	0,9681	0,9689	0,9728
315	0,9719	0,9738	0,9698	0,9735	0,9717	0,9728	0,9657	0,9651	0,9615	0,9572	0,965	0,9659	0,9707	0,9609	0,9682	0,9712	0,9682	0,9651	0,966	0,9675	0,9612	0,9648	0,9661	0,9682
316	0,9881	0,9882	0,9885	0,9889	0,9885	0,9887	0,984	0,979	0,9753	0,9762	0,9759	0,9803	0,985	0,9834	0,9852	0,985	0,9844	0,983	0,9833	0,9822	0,9793	0,9807	0,9829	0,9864
317	0,9879	0,988	0,9884	0,9887	0,9883	0,9885	0,9838	0,9788	0,975	0,9759	0,9755	0,9801	0,9848	0,9832	0,985	0,9848	0,9842	0,9828	0,9831	0,982	0,9791	0,9804	0,9827	0,9862
318	0,9865	0,9862	0,9865	0,9872	0,9869	0,9867	0,9817	0,9773	0,9732	0,9741	0,9721	0,977	0,9826	0,9805	0,9829	0,982	0,9816	0,9808	0,9809	0,9798	0,9773	0,9784	0,9811	0,9841
319	0,9847	0,9852	0,9859	0,985	0,9854	0,9842	0,9791	0,9724	0,9657	0,9677	0,9685	0,9755	0,9822	0,9788	0,9799	0,9825	0,9811	0,9788	0,9796	0,9783	0,9728	0,9756	0,9772	0,9838
320	0,9873	0,9876	0,9879	0,9882	0,9877	0,988	0,9833	0,9783	0,9745	0,9753	0,9751	0,9797	0,9845	0,9828	0,9848	0,9846	0,9838	0,9823	0,9827	0,9816	0,9787	0,9799	0,9822	0,9857
321	0,987	0,9872	0,9875	0,9879	0,9874	0,9876	0,9829	0,9779	0,9742	0,975	0,9747	0,9794	0,9842	0,9824	0,9844	0,9842	0,9835	0,9819	0,9823	0,9812	0,9783	0,9795	0,9819	0,9853
322	0,9868	0,9872	0,9875	0,9878	0,9873	0,9875	0,9829	0,9779	0,9741	0,9748	0,9747	0,9795	0,9843	0,9825	0,9846	0,9843	0,9836	0,9818	0,9823	0,9812	0,9783	0,9794	0,9819	0,9853
323	0,9858	0,9855	0,9862	0,9866	0,9857	0,9864	0,9817	0,9761	0,9729	0,9739	0,973	0,9782	0,983	0,9812	0,9832	0,983	0,9823	0,9806	0,9812	0,98	0,9766	0,9783	0,9806	0,9841

Table A.3: Base case: voltages for Utsira 22kV and 230V grid [p.u.]

Appendix B

Scenario 1: EV charging

Bus/hour	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
201	1,0123	1,0131	1,0135	1,0137	1,013	1,0142	1,0109	1,0068	1,0052	1,0058	1,0066	1,0086	1,0102	1,0104	1,0111	1,0104	1,0093	0,9898	0,9896	0,9886	0,9868	1,0068	1,0084	1,0111
202	0,9752	0,976	0,9764	0,9765	0,9758	0,977	0,9737	0,9698	0,9683	0,9688	0,9697	0,9716	0,9732	0,9733	0,974	0,9733	0,9722	0,9529	0,9527	0,9517	0,95	0,9698	0,9713	0,974
203	0,9762	0,977	0,9774	0,9775	0,977	0,9781	0,9749	0,9711	0,9694	0,9701	0,9709	0,9726	0,9741	0,9744	0,9751	0,9745	0,9734	0,9552	0,9549	0,954	0,9523	0,971	0,9726	0,9751
204	0,9762	0,977	0,9774	0,9775	0,977	0,9781	0,9749	0,9711	0,9694	0,9701	0,9709	0,9726	0,9741	0,9744	0,9751	0,9745	0,9734	0,9552	0,9549	0,954	0,9523	0,971	0,9726	0,9751
205	0,9767	0,9774	0,9778	0,978	0,9774	0,9785	0,9754	0,9715	0,9699	0,9705	0,9713	0,973	0,9746	0,9748	0,9756	0,975	0,9739	0,9556	0,9554	0,9545	0,9528	0,9715	0,973	0,9755
206	1,0532	1,054	1,0545	1,0546	1,0541	1,0552	1,0518	1,0477	1,0459	1,0466	1,0474	1,0493	1,051	1,0512	1,052	1,0514	1,0502	1,0305	1,0303	1,0293	1,0274	1,0476	1,0493	1,052
207	0,976	0,9767	0,9771	0,9773	0,9767	0,9778	0,9747	0,9708	0,9692	0,9698	0,9706	0,9724	0,9739	0,9741	0,9749	0,9743	0,9732	0,9548	0,9545	0,9536	0,9518	0,9708	0,9723	0,9748
208	0,9989	0,9997	1,0001	1,0003	0,9998	1,0011	0,9976	0,9936	0,992	0,9927	0,9936	0,9955	0,9971	0,9972	0,9981	0,9972	0,9958	0,9726	0,9723	0,9712	0,9694	0,9934	0,9949	0,9977
209	0,9759	0,9766	0,977	0,9772	0,9766	0,9777	0,9745	0,9707	0,9691	0,9697	0,9705	0,9722	0,9738	0,974	0,9748	0,9742	0,9731	0,9545	0,9543	0,9534	0,9516	0,9706	0,9722	0,9747
210	0,9978	0,9985	0,9991	0,9991	0,9985	0,9992	0,9959	0,9922	0,9907	0,9915	0,9923	0,9942	0,996	0,9965	0,9967	0,9962	0,9945	0,9722	0,972	0,9711	0,9693	0,9922	0,9938	0,9965
211	0,9758	0,9766	0,977	0,9771	0,9766	0,9777	0,9745	0,9706	0,969	0,9697	0,9704	0,9722	0,9737	0,974	0,9747	0,9742	0,973	0,9544	0,9542	0,9532	0,9515	0,9706	0,9721	0,9747
212	0,992	0,993	0,9937	0,9938	0,9932	0,9942	0,9903	0,9857	0,9835	0,9851	0,986	0,9883	0,9901	0,9901	0,9911	0,9898	0,9885	0,9609	0,9613	0,9602	0,9583	0,9866	0,9881	0,9913
213	0,9758	0,9766	0,977	0,9771	0,9766	0,9777	0,9745	0,9706	0,969	0,9697	0,9704	0,9722	0,9737	0,974	0,9747	0,9741	0,973	0,9544	0,9542	0,9532	0,9515	0,9706	0,9721	0,9746
214	1,0002	1,001	1,0013	1,0015	1,0009	1,002	0,9988	0,9947	0,993	0,9938	0,9946	0,9965	0,998	0,9984	0,9992	0,9985	0,9973	0,9781	0,9778	0,9769	0,9751	0,9947	0,9963	0,999
215	0,9758	0,9766	0,977	0,9771	0,9766	0,9777	0,9745	0,9707	0,969	0,9697	0,9705	0,9722	0,9738	0,974	0,9748	0,9742	0,9731	0,9545	0,9543	0,9534	0,9516	0,9706	0,9722	0,9747
216	0,9758	0,9766	0,977	0,9771	0,9766	0,9777	0,9745	0,9706	0,969	0,9697	0,9705	0,9722	0,9738	0,974	0,9748	0,9742	0,973	0,9545	0,9543	0,9533	0,9516	0,9706	0,9721	0,9747
217	0,9988	0,9993	0,9994	0,9994	0,9994	1,0007	0,9974	0,9932	0,9919	0,9927	0,9933	0,9947	0,9964	0,997	0,998	0,9973	0,996	0,9757	0,9753	0,9744	0,9724	0,9935	0,9951	0,9977
218	0,9757	0,9765	0,9769	0,977	0,9765	0,9777	0,9745	0,9706	0,969	0,9696	0,9704	0,9722	0,9737	0,9739	0,9747	0,9741	0,973	0,9544	0,9542	0,9532	0,9514	0,9705	0,9721	0,9746
219	0,9757	0,9765	0,9769	0,977	0,9765	0,9776	0,9745	0,9706	0,969	0,9696	0,9704	0,9722	0,9737	0,9739	0,9747	0,9741	0,973	0,9544	0,9542	0,9532	0,9514	0,9705	0,972	0,9746
220	0,9974	0,9981	0,9985	0,9987	0,9982	1,0017	0,9986	0,9946	0,993	0,9937	0,9945	0,9963	0,998	0,9982	0,999	0,9984	0,9972	0,9775	0,9775	0,9754	0,9718	0,992	0,9937	0,9961
221	0,9919	0,9926	0,993	0,9933	0,9926	0,9932	0,99	0,9859	0,9837	0,9851	0,9861	0,9888	0,9903	0,9899	0,991	0,9901	0,9887	0,9617	0,9613	0,9603	0,9585	0,9859	0,9877	0,991
222	0,9766	0,9774	0,9778	0,9779	0,9774	0,9785	0,9753	0,9715	0,9698	0,9705	0,9713	0,973	0,9745	0,9748	0,9755	0,9749	0,9738	0,9556	0,9554	0,9544	0,9527	0,9714	0,973	0,9755
223	1,0532	1,054	1,0544	1,0546	1,054	1,0552	1,0518	1,0476	1,0459	1,0466	1,0474	1,0492	1,0509	1,0512	1,052	1,0514	1,0711	1,0511	1,0508	1,0498	1,0479	1,0476	1,0492	1,0519
301	0,994	0,9944	0,9944	0,9948	0,9944	0,9954	0,991	0,9865	0,9841	0,9847	0,9858	0,9881	0,9908	0,9908	0,9919	0,9914	0,9908	0,9704	0,9704	0,9693	0,9673	0,9879	0,9896	0,9924
302	0,9913	0,9918	0,9917	0,9921	0,9918	0,9929	0,988	0,9832	0,9808	0,9817	0,9825	0,9853	0,9883	0,9882	0,9894	0,9888	0,9882	0,968	0,968	0,9667	0,9646	0,9854	0,987	0,9897
303	0,9913	0,9918	0,9916	0,9921	0,9918	0,9929	0,9879	0,9832	0,9808	0,9816	0,9824	0,9853	0,9883	0,9882	0,9894	0,9888	0,9882	0,968	0,9679	0,9667	0,9646	0,9854	0,987	0,9896
304	0,9912	0,9917	0,9916	0,992	0,9917	0,9928	0,9878	0,9831	0,9807	0,9815	0,9823	0,9852	0,9882	0,988	0,9893	0,9886	0,9881	0,9678	0,9678	0,9666	0,9645	0,9853	0,9869	0,9895
305	0,9942	0,9946	0,9945	0,9949	0,9945	0,9955	0,9912	0,9866	0,9843	0,9849	0,9859	0,9882	0,9909	0,9909	0,992	0,9915	0,991	0,9706	0,9706	0,9695	0,9675	0,9881	0,9898	0,9925
306	0,9925	0,992	0,9914	0,992	0,9917	0,9924	0,9871	0,9811	0,9781	0,9787	0,9807	0,9818	0,9856	0,9858	0,9874	0,9875	0,9883	0,9676	0,9681	0,9673	0,9655	0,9851	0,9874	0,9901
307	0,994	0,9944	0,9944	0,9948	0,9944	0,9953	0,991	0,9864	0,9841	0,9847	0,9858	0,988	0,9908	0,9908	0,9919	0,9914	0,9908	0,9702	0,9702	0,969	0,967	0,9879	0,9896	0,9923
308	0,994	0,9944	0,9943	0,9948	0,9944	0,9953	0,991	0,9864	0,9841	0,9847	0,9858	0,988	0,9908	0,9908	0,9919	0,9914	0,9908	0,9702	0,9701	0,969	0,967	0,9879	0,9896	0,9923
309	0,9865	0,9887	0,9883	0,9889	0,9874	0,9895	0,9851	0,9788	0,9782	0,9762	0,98	0,9805	0,9844	0,985	0,9859	0,9866	0,9835	0,9644	0,9641	0,9608	0,959	0,9812	0,9825	0,9863
310	0,992	0,9924	0,9923	0,9928	0,9923	0,9931	0,9893	0,9843	0,982	0,9829	0,9839	0,9868	0,9892	0,9893	0,9906	0,9903	0,9892	0,9691	0,9686	0,9673	0,9659	0,9862	0,9882	0,99
311	0,9837	0,9842	0,9832	0,9847	0,9836	0,9849	0,9792	0,9756	0,973	0,9725	0,9756	0,9761	0,98	0,9763	0,9792	0,9807	0,9796	0,9582	0,9586	0,9581	0,9552	0,9768	0,9781	0,9811
312	0,9831	0,9836	0,9825	0,984	0,9828	0,9843	0,9785	0,9749	0,9723	0,9717	0,9749	0,9754	0,9795	0,9757	0,9785	0,9801	0,979	0,9575	0,958	0,9573	0,9546	0,9762	0,9774	0,9804
313	0,9782	0,9791	0,9774	0,9794	0,9782	0,9794	0,9731	0,9701	0,9672	0,9661	0,9703	0,9699	0,9743	0,9683	0,9725	0,9751	0,9737	0,9519	0,9523	0,9524	0,9487	0,971	0,972	0,9754
314	0,9755	0,9764	0,9748	0,9769	0,9756	0,9769	0,9703	0,967	0,9642	0,9635	0,9675	0,9661	0,9709	0,9639	0,9686	0,9717	0,9705	0,9488	0,949	0,9493	0,9456	0,9681	0,9689	0,9728
315	0,9719	0,9738	0,9698	0,9735	0,9717	0,9728	0,9657	0,9651	0,9615	0,9572	0,965	0,9659	0,9707	0,9609	0,9682	0,9712	0,9682	0,945	0,946	0,9475	0,941	0,9648	0,9661	0,9682
316	0,9881	0,9882	0,9885	0,9889	0,9885	0,9887	0,984	0,979	0,9753	0,9762	0,9759	0,9803	0,985	0,9834	0,9852	0,985	0,9844	0,9519	0,9523	0,9511	0,948	0,9807	0,9829	0,9864
317	0,9879	0,988	0,9884	0,9887	0,9883	0,9885	0,9838	0,9788	0,975	0,9759	0,9755	0,9801	0,9848	0,9832	0,985	0,9848	0,9842	0,9514	0,9518	0,9506	0,9475	0,9804	0,9827	0,9862
318	0,9865	0,9862	0,9865	0,9872	0,9869	0,9867	0,9817	0,9773	0,9732	0,9741	0,9721	0,977	0,9826	0,9805	0,9829	0,982	0,9816	0,9462	0,9463	0,9452	0,9424	0,9784	0,9811	0,9841
319	0,9847	0,9852	0,9859	0,985	0,9854	0,9842	0,9791	0,9724	0,9657	0,9677	0,9685	0,9755	0,9822	0,9788	0,9799	0,9825	0,9811	0,9385	0,9394	0,9381	0,9321	0,9756	0,9772	0,9838
320	0,9873	0,9876	0,9879	0,9882	0,9877	0,988	0,9833	0,9783	0,9745	0,9753	0,9751	0,9797	0,9845	0,9828	0,9848	0,9846	0,9838	0,9509	0,9513	0,9502	0,947	0,9799	0,9822	0,9857
321	0,987	0,9872	0,9875	0,9879	0,9874	0,9876	0,9829	0,9779	0,9742	0,975	0,9747	0,9794	0,9842	0,9824	0,9844	0,9842	0,9835	0,9505	0,9509	0,9498	0,9466	0,9795	0,9819	0,9853
322	0,9868	0,9872	0,9875	0,9878	0,9873	0,9875	0,9829	0,9779	0,9741	0,9748	0,9747	0,9795	0,9843	0,9825	0,9846	0,9843	0,9836	0,9504	0,951	0,9498	0,9466	0,9794	0,9819	0,9853
323	0,9858	0,9855	0,9862	0,9866	0,9857	0,9864	0,9817	0,9761	0,9729	0,9739	0,973	0,9782	0,983	0,9812	0,9832	0,983	0,9823	0,944	0,9447	0,9434	0,9398	0,9783	0,9806	0,9841

Table B.1: Scenario 1, case 1.1: EV 100% afternoon charging, Utsira bus voltages [p.u.]

Bus/hour	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
201	1,007	1,0078	1,0082	1,0084	1,0077	1,0089	1,0109	1,0068	1,0052	1,0058	1,0066	1,0086	1,0102	1,0104	1,0111	1,0104	1,0093	1,002	1,0018	1,0009	0,9991	1,0015	1,0031	1,0058
202	0,97	0,9708	0,9711	0,9713	0,9706	0,9718	0,9737	0,9698	0,9683	0,9688	0,9697	0,9716	0,9732	0,9733	0,974	0,9733	0,9722	0,965	0,9648	0,9639	0,9622	0,9645	0,966	0,9688
203	0,9713	0,9721	0,9724	0,9726	0,9721	0,9732	0,9749	0,9711	0,9694	0,9701	0,9709	0,9726	0,9741	0,9744	0,9751	0,9745	0,9734	0,9667	0,9664	0,9655	0,9638	0,9661	0,9676	0,9701
204	0,9713	0,9721	0,9724	0,9726	0,9721	0,9732	0,9749	0,9711	0,9694	0,9701	0,9709	0,9726	0,9741	0,9744	0,9751	0,9745	0,9734	0,9667	0,9664	0,9655	0,9638	0,9661	0,9676	0,9701
205	0,9718	0,9725	0,9729	0,9731	0,9725	0,9736	0,9754	0,9715	0,9699	0,9705	0,9713	0,973	0,9746	0,9748	0,9756	0,975	0,9739	0,9671	0,9669	0,966	0,9643	0,9665	0,9681	0,9706
206	1,0479	1,0487	1,0492	1,0493	1,0488	1,0499	1,0518	1,0477	1,0459	1,0466	1,0474	1,0493	1,051	1,0512	1,052	1,0514	1,0502	1,0429	1,0427	1,0417	1,0399	1,0423	1,0439	1,0467
207	0,971	0,9718	0,9721	0,9723	0,9718	0,9729	0,9747	0,9708	0,9692	0,9698	0,9706	0,9724	0,9739	0,9741	0,9749	0,9743	0,9732	0,9664	0,9661	0,9652	0,9635	0,9657	0,9673	0,9698
208	0,9925	0,9933	0,9937	0,9939	0,9934	0,9947	0,9976	0,9936	0,992	0,9927	0,9936	0,9955	0,9971	0,9972	0,9981	0,9972	0,9958	0,9876	0,9872	0,9862	0,9845	0,9869	0,9885	0,9913
209	0,9709	0,9716	0,972	0,9722	0,9716	0,9727	0,9745	0,9707	0,9691	0,9697	0,9705	0,9722	0,9738	0,974	0,9748	0,9742	0,9731	0,9662	0,966	0,9651	0,9634	0,9656	0,9671	0,9697
210	0,9917	0,9924	0,993	0,993	0,9924	0,9931	0,9959	0,9922	0,9907	0,9915	0,9923	0,9942	0,996	0,9965	0,9967	0,9962	0,9945	0,9865	0,9863	0,9854	0,9837	0,9861	0,9877	0,9904
211	0,9708	0,9715	0,9719	0,9721	0,9716	0,9727	0,9745	0,9706	0,969	0,9697	0,9704	0,9722	0,9737	0,974	0,9747	0,9742	0,973	0,9661	0,9659	0,965	0,9633	0,9655	0,9671	0,9696
212	0,9845	0,9855	0,9861	0,9863	0,9857	0,9867	0,9903	0,9857	0,9835	0,9851	0,986	0,9883	0,9901	0,9901	0,9911	0,9898	0,9885	0,9786	0,979	0,9779	0,9761	0,9791	0,9805	0,9837
213	0,9708	0,9715	0,9719	0,9721	0,9715	0,9727	0,9745	0,9706	0,969	0,9697	0,9704	0,9722	0,9737	0,974	0,9747	0,9741	0,973	0,9661	0,9659	0,965	0,9633	0,9655	0,9671	0,9696
214	0,995	0,9958	0,9961	0,9963	0,9957	0,9968	0,9988	0,9947	0,993	0,9938	0,9946	0,9965	0,998	0,9984	0,9992	0,9985	0,9973	0,9902	0,9899	0,9891	0,9873	0,9895	0,9911	0,9938
215	0,9708	0,9716	0,972	0,9721	0,9716	0,9727	0,9745	0,9707	0,969	0,9697	0,9705	0,9722	0,9738	0,974	0,9748	0,9742	0,9731	0,9662	0,966	0,965	0,9633	0,9656	0,9671	0,9697
216	0,9708	0,9716	0,9719	0,9721	0,9716	0,9727	0,9745	0,9706	0,969	0,9697	0,9705	0,9722	0,9738	0,974	0,9748	0,9742	0,973	0,9662	0,9659	0,965	0,9633	0,9655	0,9671	0,9696
217	0,9932	0,9937	0,9938	0,9939	0,9939	0,9952	0,9974	0,9932	0,9919	0,9927	0,9933	0,9947	0,9964	0,997	0,998	0,9973	0,996	0,9886	0,9881	0,9873	0,9854	0,9879	0,9896	0,9922
218	0,9707	0,9715	0,9719	0,972	0,9715	0,9726	0,9745	0,9706	0,969	0,9696	0,9704	0,9722	0,9737	0,9739	0,9747	0,9741	0,973	0,9661	0,9659	0,9649	0,9632	0,9654	0,967	0,9696
219	0,9707	0,9715	0,9718	0,972	0,9715	0,9726	0,9745	0,9706	0,969	0,9696	0,9704	0,9722	0,9737	0,9739	0,9747	0,9741	0,973	0,9661	0,9659	0,9649	0,9632	0,9654	0,967	0,9695
220	0,9921	0,9928	0,9932	0,9934	0,9929	0,9964	0,9986	0,9946	0,993	0,9937	0,9945	0,9963	0,998	0,9982	0,999	0,9984	0,9972	0,9899	0,9898	0,9878	0,9843	0,9867	0,9883	0,9908
221	0,9846	0,9853	0,9857	0,986	0,9853	0,9859	0,99	0,9859	0,9837	0,9851	0,9861	0,9888	0,9903	0,9899	0,991	0,9901	0,9887	0,9788	0,9785	0,9775	0,9758	0,9785	0,9804	0,9837
222	0,9717	0,9725	0,9728	0,973	0,9725	0,9736	0,9753	0,9715	0,9698	0,9705	0,9713	0,973	0,9745	0,9748	0,9755	0,9749	0,9738	0,9671	0,9668	0,9659	0,9643	0,9665	0,968	0,9705
223	1,0688	1,0697	1,0701	1,0703	1,0697	1,0709	1,0728	1,0476	1,0459	1,0466	1,0474	1,0492	1,0509	1,0512	1,052	1,0514	1,0711	1,0637	1,0635	1,0625	1,0606	1,0631	1,0648	1,0675
301	0,9886	0,989	0,9889	0,9894	0,989	0,9899	0,991	0,9865	0,9841	0,9847	0,9858	0,9881	0,9908	0,9908	0,9919	0,9914	0,9908	0,9831	0,9831	0,982	0,9801	0,9824	0,9842	0,9869
302	0,9858	0,9864	0,9862	0,9867	0,9864	0,9875	0,988	0,9832	0,9808	0,9817	0,9825	0,9853	0,9883	0,9882	0,9894	0,9888	0,9882	0,9807	0,9807	0,9795	0,9774	0,9799	0,9815	0,9842
303	0,9858	0,9863	0,9862	0,9867	0,9864	0,9875	0,9879	0,9832	0,9808	0,9816	0,9824	0,9853	0,9883	0,9882	0,9894	0,9888	0,9882	0,9807	0,9807	0,9794	0,9774	0,9799	0,9815	0,9842
304	0,9857	0,9862	0,9861	0,9866	0,9863	0,9874	0,9878	0,9831	0,9807	0,9815	0,9823	0,9852	0,9882	0,988	0,9893	0,9886	0,9881	0,9806	0,9806	0,9793	0,9773	0,9798	0,9814	0,9841
305	0,9888	0,9892	0,9891	0,9895	0,9891	0,9901	0,9912	0,9866	0,9843	0,9849	0,9859	0,9882	0,9909	0,9909	0,992	0,9915	0,991	0,9833	0,9833	0,9822	0,9803	0,9826	0,9843	0,9871
306	0,9871	0,9866	0,9859	0,9865	0,9863	0,9869	0,9871	0,9811	0,9781	0,9787	0,9807	0,9818	0,9856	0,9858	0,9874	0,9875	0,9883	0,9803	0,9808	0,9801	0,9783	0,9796	0,9819	0,9846
307	0,9885	0,9889	0,9888	0,9892	0,9888	0,9898	0,991	0,9864	0,9841	0,9847	0,9858	0,988	0,9908	0,9908	0,9919	0,9914	0,9908	0,9831	0,9831	0,982	0,9801	0,9823	0,984	0,9868
308	0,9885	0,9889	0,9888	0,9892	0,9888	0,9898	0,991	0,9864	0,9841	0,9847	0,9858	0,988	0,9908	0,9908	0,9919	0,9914	0,9908	0,9831	0,9831	0,982	0,9801	0,9823	0,984	0,9868
309	0,9809	0,9831	0,9827	0,9834	0,9819	0,9839	0,9851	0,9788	0,9782	0,9762	0,98	0,9805	0,9844	0,985	0,9859	0,9866	0,9835	0,9775	0,9771	0,9738	0,9721	0,9756	0,9769	0,9807
310	0,9865	0,9869	0,9867	0,9872	0,9867	0,9876	0,9893	0,9843	0,982	0,9829	0,9839	0,9868	0,9892	0,9893	0,9906	0,9903	0,9892	0,982	0,9816	0,9803	0,979	0,9806	0,9827	0,9845
311	0,9782	0,9787	0,9777	0,9792	0,9781	0,9794	0,9792	0,9756	0,973	0,9725	0,9756	0,9761	0,98	0,9763	0,9792	0,9807	0,9796	0,9711	0,9715	0,971	0,9682	0,9713	0,9725	0,9756
312	0,9776	0,9781	0,977	0,9786	0,9773	0,9789	0,9785	0,9749	0,9723	0,9717	0,9749	0,9754	0,9795	0,9757	0,9785	0,9801	0,979	0,9704	0,9708	0,9702	0,9675	0,9706	0,9718	0,9749
313	0,9726	0,9735	0,9718	0,9739	0,9726	0,9739	0,9731	0,9701	0,9672	0,9661	0,9703	0,9699	0,9743	0,9683	0,9725	0,9751	0,9737	0,9649	0,9653	0,9654	0,9617	0,9654	0,9665	0,9699
314	0,97	0,9709	0,9692	0,9713	0,9701	0,9713	0,9703	0,967	0,9642	0,9635	0,9675	0,9661	0,9709	0,9639	0,9686	0,9717	0,9705	0,9618	0,962	0,9623	0,9587	0,9625	0,9633	0,9672
315	0,9663	0,9683	0,9642	0,968	0,9662	0,9672	0,9657	0,9651	0,9615	0,9572	0,965	0,9659	0,9707	0,9609	0,9682	0,9712	0,9682	0,9581	0,959	0,9605	0,9542	0,9591	0,9605	0,9627
316	0,981	0,9811	0,9814	0,9818	0,9814	0,9816	0,984	0,979	0,9753	0,9762	0,9759	0,9803	0,985	0,9834	0,9852	0,985	0,9844	0,9687	0,969	0,9679	0,9649	0,9735	0,9758	0,9793
317	0,9808	0,9809	0,9812	0,9816	0,9811	0,9814	0,9838	0,9788	0,975	0,9759	0,9755	0,9801	0,9848	0,9832	0,985	0,9848	0,9842	0,9683	0,9687	0,9675	0,9645	0,9732	0,9755	0,979
318	0,978	0,9777	0,978	0,9787	0,9784	0,9782	0,9817	0,9773	0,9732	0,9741	0,9721	0,977	0,9826	0,9805	0,9829	0,982	0,9816	0,9663	0,9664	0,9653	0,9626	0,9698	0,9725	0,9756
319	0,9776	0,978	0,9787	0,9778	0,9782	0,977	0,9791	0,9724	0,9657	0,9677	0,9685	0,9755	0,9822	0,9788	0,9799	0,9825	0,9811	0,9557	0,9565	0,9552	0,9494	0,9683	0,97	0,9766
320	0,9802	0,9804	0,9807	0,9811	0,9806	0,9808	0,9833	0,9783	0,9745	0,9753	0,9751	0,9797	0,9845	0,9828	0,9848	0,9846	0,9838	0,9678	0,9682	0,9671	0,964	0,9726	0,975	0,9785
321	0,9798	0,98	0,9803	0,9807	0,9802	0,9804	0,9829	0,9779	0,9742	0,975	0,9747	0,9794	0,9842	0,9824	0,9844	0,9842	0,9835	0,9674	0,9678	0,9667	0,9637	0,9722	0,9746	0,9782
322	0,9797	0,98	0,9803	0,9807	0,9801	0,9804	0,9829	0,9779	0,9741	0,9748	0,9747	0,9795	0,9843	0,9825	0,9846	0,9843	0,9836	0,9673	0,9679	0,9667	0,9637	0,9721	0,9747	0,9781
323	0,9787	0,9784	0,9791	0,9795	0,9786	0,9793	0,9817	0,9761	0,9729	0,9739	0,973	0,9782	0,983	0,9812	0,9832	0,983	0,9823	0,9609	0,9615	0,9603	0,9568	0,9712	0,9734	0,977

Table B.2: Scenario 1, case 1.2: EV 67% DSR, 33% afternoon charging, Utsira bus voltages [p.u.]

Bus/hour	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
201	1,0043	1,0051	1,0055	1,0056	1,005	1,0062	1,0108	1,0068	1,0052	1,0058	1,0066	1,0086	1,0102	1,0104	1,0111	1,0104	1,0093	1,0083	1,008	1,0071	1,0054	0,9987	1,0003	1,003
202	0,9672	0,968	0,9684	0,9686	0,9678	0,9691	0,9737	0,9698	0,9683	0,9688	0,9697	0,9716	0,9732	0,9733	0,974	0,9733	0,9722	0,9712	0,971	0,97	0,9684	0,9618	0,9633	0,9661
203	0,9687	0,9695	0,9698	0,97	0,9695	0,9706	0,9749	0,9711	0,9694	0,9701	0,9709	0,9726	0,9741	0,9744	0,9751	0,9745	0,9734	0,9725	0,9723	0,9714	0,9697	0,9634	0,965	0,9675
204	0,9687	0,9695	0,9698	0,97	0,9695	0,9706	0,9749	0,9711	0,9694	0,9701	0,9709	0,9726	0,9741	0,9744	0,9751	0,9745	0,9734	0,9725	0,9723	0,9714	0,9697	0,9634	0,965	0,9675
205	0,9691	0,9699	0,9703	0,9705	0,9699	0,971	0,9754	0,9715	0,9699	0,9705	0,9713	0,973	0,9746	0,9748	0,9756	0,975	0,9739	0,973	0,9727	0,9718	0,9702	0,9639	0,9654	0,968
206	1,0451	1,0459	1,0463	1,0465	1,0459	1,0471	1,0518	1,0477	1,0459	1,0466	1,0474	1,0493	1,051	1,0512	1,052	1,0514	1,0502	1,0492	1,049	1,048	1,0462	1,0394	1,0411	1,0438
207	0,9684	0,9691	0,9695	0,9697	0,9691	0,9702	0,9747	0,9708	0,9692	0,9698	0,9706	0,9724	0,9739	0,9741	0,9749	0,9743	0,9732	0,9723	0,972	0,9711	0,9695	0,9631	0,9646	0,9672
208	0,9891	0,9899	0,9903	0,9906	0,99	0,9913	0,9976	0,9936	0,992	0,9927	0,9936	0,9955	0,9971	0,9972	0,9981	0,9972	0,9958	0,9951	0,9948	0,9938	0,9921	0,9835	0,9851	0,9879
209	0,9682	0,969	0,9693	0,9695	0,969	0,9701	0,9745	0,9707	0,9691	0,9697	0,9705	0,9722	0,9738	0,974	0,9748	0,9742	0,9731	0,9722	0,9719	0,971	0,9694	0,9629	0,9645	0,967
210	0,9885	0,9892	0,9898	0,9898	0,9892	0,9899	0,9959	0,9922	0,9907	0,9915	0,9923	0,9942	0,996	0,9965	0,9967	0,9962	0,9945	0,9937	0,9935	0,9927	0,991	0,9828	0,9844	0,9871
211	0,9681	0,9689	0,9693	0,9694	0,9689	0,97	0,9745	0,9706	0,969	0,9697	0,9704	0,9722	0,9737	0,974	0,9747	0,9742	0,973	0,9721	0,9719	0,971	0,9693	0,9628	0,9644	0,967
212	0,9806	0,9816	0,9822	0,9823	0,9818	0,9828	0,9903	0,9857	0,9835	0,9851	0,986	0,9883	0,9901	0,9901	0,9911	0,9898	0,9885	0,9874	0,9878	0,9868	0,985	0,9751	0,9766	0,9798
213	0,9681	0,9689	0,9693	0,9694	0,9689	0,97	0,9745	0,9706	0,969	0,9697	0,9704	0,9722	0,9737	0,974	0,9747	0,9741	0,973	0,9721	0,9719	0,9709	0,9693	0,9628	0,9644	0,9669
214	0,9923	0,993	0,9934	0,9936	0,993	0,9941	0,9988	0,9947	0,993	0,9938	0,9946	0,9965	0,998	0,9984	0,9992	0,9985	0,9973	0,9964	0,9961	0,9952	0,9935	0,9867	0,9883	0,9911
215	0,9682	0,9689	0,9693	0,9695	0,9689	0,9701	0,9745	0,9707	0,969	0,9697	0,9705	0,9722	0,9738	0,974	0,9748	0,9742	0,9731	0,9722	0,9719	0,971	0,9693	0,9629	0,9644	0,967
216	0,9681	0,9689	0,9693	0,9695	0,9689	0,9701	0,9745	0,9706	0,969	0,9697	0,9705	0,9722	0,9738	0,974	0,9748	0,9742	0,973	0,9721	0,9719	0,971	0,9693	0,9629	0,9644	0,967
217	0,9903	0,9908	0,9909	0,991	0,991	0,9923	0,9974	0,9932	0,9919	0,9927	0,9933	0,9947	0,9964	0,997	0,998	0,9973	0,996	0,9951	0,9947	0,9938	0,992	0,9849	0,9866	0,9893
218	0,968	0,9688	0,9692	0,9694	0,9688	0,97	0,9745	0,9706	0,969	0,9696	0,9704	0,9722	0,9737	0,9739	0,9747	0,9741	0,973	0,9721	0,9718	0,9709	0,9692	0,9628	0,9643	0,9669
219	0,968	0,9688	0,9692	0,9693	0,9688	0,97	0,9745	0,9706	0,969	0,9696	0,9704	0,9722	0,9737	0,9739	0,9747	0,9741	0,973	0,9721	0,9718	0,9709	0,9692	0,9627	0,9643	0,9669
220	0,9892	0,99	0,9904	0,9906	0,99	0,9936	0,9986	0,9946	0,993	0,9937	0,9945	0,9963	0,998	0,9982	0,999	0,9984	0,9972	0,9962	0,9961	0,9941	0,9906	0,9838	0,9855	0,988
221	0,9807	0,9815	0,9819	0,9822	0,9815	0,9821	0,99	0,9859	0,9837	0,9851	0,9861	0,9888	0,9903	0,9899	0,991	0,9901	0,9887	0,9874	0,987	0,9861	0,9844	0,9746	0,9765	0,9798
222	0,9691	0,9699	0,9702	0,9704	0,9699	0,971	0,9753	0,9715	0,9698	0,9705	0,9713	0,973	0,9745	0,9748	0,9755	0,9749	0,9738	0,9729	0,9727	0,9718	0,9701	0,9638	0,9654	0,9679
223	1,066	1,0668	1,0672	1,0674	1,0668	1,068	1,0728	1,0476	1,0459	1,0466	1,0474	1,0492	1,0509	1,0512	1,052	1,0514	1,0711	1,0702	1,0699	1,0689	1,0671	1,0602	1,0619	1,0647
301	0,9856	0,986	0,9859	0,9863	0,9859	0,9869	0,991	0,9865	0,9841	0,9847	0,9858	0,9881	0,9908	0,9908	0,9919	0,9914	0,9908	0,99	0,9899	0,9889	0,987	0,9794	0,9811	0,9839
302	0,9828	0,9833	0,9832	0,9837	0,9834	0,9845	0,988	0,9832	0,9808	0,9817	0,9825	0,9853	0,9883	0,9882	0,9894	0,9888	0,9882	0,9875	0,9875	0,9863	0,9843	0,9768	0,9785	0,9811
303	0,9828	0,9833	0,9831	0,9836	0,9833	0,9844	0,9879	0,9832	0,9808	0,9816	0,9824	0,9853	0,9883	0,9882	0,9894	0,9888	0,9882	0,9875	0,9875	0,9863	0,9843	0,9768	0,9784	0,9811
304	0,9827	0,9832	0,983	0,9835	0,9832	0,9843	0,9878	0,9831	0,9807	0,9815	0,9823	0,9852	0,9882	0,988	0,9893	0,9886	0,9881	0,9874	0,9874	0,9862	0,9842	0,9767	0,9783	0,981
305	0,9857	0,9861	0,986	0,9865	0,9861	0,9871	0,9912	0,9866	0,9843	0,9849	0,9859	0,9882	0,9909	0,9909	0,992	0,9915	0,991	0,9901	0,9901	0,989	0,9871	0,9795	0,9813	0,984
306	0,9841	0,9836	0,9828	0,9835	0,9832	0,9839	0,9871	0,9811	0,9781	0,9787	0,9807	0,9818	0,9856	0,9858	0,9874	0,9875	0,9883	0,9872	0,9876	0,9869	0,9851	0,9765	0,9788	0,9815
307	0,9854	0,9859	0,9858	0,9862	0,9858	0,9868	0,991	0,9864	0,9841	0,9847	0,9858	0,988	0,9908	0,9908	0,9919	0,9914	0,9908	0,9899	0,9899	0,9888	0,9869	0,9792	0,981	0,9838
308	0,9854	0,9859	0,9858	0,9862	0,9858	0,9868	0,991	0,9864	0,9841	0,9847	0,9858	0,988	0,9908	0,9908	0,9919	0,9914	0,9908	0,9899	0,9899	0,9888	0,9869	0,9792	0,9809	0,9837
309	0,9778	0,98	0,9796	0,9803	0,9788	0,9809	0,9851	0,9788	0,9782	0,9762	0,98	0,9805	0,9844	0,985	0,9859	0,9866	0,9835	0,9843	0,984	0,9807	0,979	0,9725	0,9738	0,9776
310	0,9834	0,9839	0,9837	0,9842	0,9837	0,9846	0,9893	0,9843	0,982	0,9829	0,9839	0,9868	0,9892	0,9893	0,9906	0,9903	0,9892	0,9889	0,9884	0,9872	0,9858	0,9775	0,9796	0,9814
311	0,9751	0,9757	0,9746	0,9761	0,975	0,9764	0,9792	0,9756	0,973	0,9725	0,9756	0,9761	0,98	0,9763	0,9792	0,9807	0,9796	0,978	0,9783	0,9779	0,9751	0,9682	0,9694	0,9725
312	0,9745	0,975	0,9739	0,9755	0,9743	0,9758	0,9785	0,9749	0,9723	0,9717	0,9749	0,9754	0,9795	0,9757	0,9785	0,9801	0,979	0,9773	0,9777	0,9771	0,9745	0,9675	0,9687	0,9718
313	0,9695	0,9705	0,9688	0,9708	0,9696	0,9708	0,9731	0,9701	0,9672	0,9661	0,9703	0,9699	0,9743	0,9683	0,9725	0,9751	0,9737	0,9718	0,9722	0,9723	0,9687	0,9623	0,9633	0,9668
314	0,9669	0,9678	0,9662	0,9683	0,967	0,9682	0,9703	0,967	0,9642	0,9635	0,9675	0,9661	0,9709	0,9639	0,9686	0,9717	0,9705	0,9688	0,969	0,9693	0,9657	0,9594	0,9602	0,9641
315	0,9632	0,9652	0,9611	0,9649	0,9631	0,9641	0,9657	0,9651	0,9615	0,9572	0,965	0,9659	0,9707	0,9609	0,9682	0,9712	0,9682	0,9651	0,966	0,9675	0,9612	0,956	0,9574	0,9595
316	0,9747	0,9748	0,9751	0,9755	0,975	0,9753	0,984	0,979	0,9753	0,9762	0,9759	0,9803	0,985	0,9834	0,9852	0,985	0,9844	0,983	0,9833	0,9822	0,9793	0,967	0,9693	0,9729
317	0,9744	0,9745	0,9748	0,9752	0,9747	0,975	0,9838	0,9788	0,975	0,9759	0,9755	0,9801	0,9848	0,9832	0,985	0,9848	0,9842	0,9828	0,9831	0,982	0,9791	0,9667	0,969	0,9726
318	0,9715	0,9712	0,9715	0,9723	0,972	0,9718	0,9817	0,9773	0,9732	0,9741	0,9721	0,977	0,9826	0,9805	0,9829	0,982	0,9816	0,9808	0,9809	0,9798	0,9773	0,9633	0,966	0,9692
319	0,9674	0,9678	0,9685	0,9676	0,968	0,9668	0,9791	0,9724	0,9657	0,9677	0,9685	0,9755	0,9822	0,9788	0,9799	0,9825	0,9811	0,9788	0,9796	0,9783	0,9728	0,9579	0,9597	0,9664
320	0,9738	0,974	0,9743	0,9747	0,9742	0,9744	0,9833	0,9783	0,9745	0,9753	0,9751	0,9797	0,9845	0,9828	0,9848	0,9846	0,9838	0,9823	0,9827	0,9816	0,9787	0,9661	0,9686	0,9721
321	0,9734	0,9736	0,9739	0,9743	0,9738	0,974	0,9829	0,9779	0,9742	0,975	0,9747	0,9794	0,9842	0,9824	0,9844	0,9842	0,9835	0,9819	0,9823	0,9812	0,9783	0,9657	0,9682	0,9717
322	0,9732	0,9736	0,9739	0,9743	0,9737	0,9739	0,9829	0,9779	0,9741	0,9748	0,9747	0,9795	0,9843	0,9825	0,9846	0,9843	0,9836	0,9818	0,9823	0,9812	0,9783	0,9656	0,9682	0,9717
323	0,97	0,9697	0,9704	0,9708	0,9699	0,9706	0,9817	0,9761	0,9729	0,9739	0,973	0,9782	0,983	0,9812	0,9832	0,983	0,9823	0,9806	0,9812	0,98	0,9766	0,9624	0,9647	0,9683

Table B.3: Scenario 1, case 1.3: 100% DSR, Utsira bus voltages [p.u.]

Appendix C

Scenario 2: Ferry charging

Bus/hour	1	2	3	4	5	6	7	8	9	9.10-9.30	10	11	12	13	14	15	16	17	17.25-17.45	18	19	20	21	22	23	24
201	1,0018	1,0026	1,003	1,0032	1,0025	1,0038	1,0029	1,0014	0,9998	0,9651	1,0004	1,0012	1,0032	1,0052	1,0056	1,0067	1,005	1,0039	0,9677	1,0029	1,0026	1,0017	0,9969	0,9962	0,9978	1,0006
202	0,9651	0,9659	0,9662	0,9664	0,9657	0,9669	0,9661	0,9646	0,9631	0,9295	0,9636	0,9644	0,9664	0,9684	0,9687	0,9697	0,9681	0,967	0,932	0,9659	0,9657	0,9648	0,9602	0,9596	0,9611	0,9639
203	0,9661	0,9669	0,9673	0,9674	0,9669	0,968	0,9673	0,9658	0,9642	0,9308	0,9649	0,9656	0,9674	0,9694	0,9697	0,9709	0,9693	0,9682	0,9334	0,9673	0,9671	0,9661	0,9616	0,9608	0,9624	0,9649
204	0,9661	0,9669	0,9673	0,9674	0,9669	0,968	0,9673	0,9658	0,9642	0,9308	0,9649	0,9656	0,9674	0,9694	0,9697	0,9709	0,9693	0,9682	0,9334	0,9673	0,9671	0,9661	0,9616	0,9608	0,9624	0,9649
205	0,9666	0,9673	0,9677	0,9679	0,9673	0,9685	0,9677	0,9663	0,9647	0,9313	0,9653	0,9661	0,9678	0,9698	0,9702	0,9713	0,9698	0,9687	0,9339	0,9677	0,9675	0,9666	0,962	0,9613	0,9628	0,9654
206	1,0423	1,0432	1,0436	1,0438	1,0432	1,0444	1,0436	1,042	1,0403	1,0043	1,041	1,0418	1,0437	1,0459	1,0462	1,0475	1,0458	1,0446	1,0071	1,0436	1,0433	1,0424	1,0375	1,0366	1,0383	1,0411
207	0,9657	0,9665	0,9669	0,9671	0,9665	0,9677	0,9669	0,9655	0,9639	0,9301	0,9645	0,9653	0,9671	0,9691	0,9694	0,9706	0,9691	0,9679	0,9327	0,967	0,9668	0,9658	0,9612	0,9604	0,962	0,9646
208	0,9884	0,9892	0,9896	0,9898	0,9893	0,9906	0,9897	0,9881	0,9865	0,9518	0,9872	0,9881	0,9901	0,9921	0,9924	0,9937	0,9918	0,9904	0,9544	0,9897	0,9893	0,9883	0,9836	0,9828	0,9844	0,9871
209	0,9656	0,9664	0,9668	0,9669	0,9664	0,9676	0,9668	0,9654	0,9637	0,9299	0,9644	0,9652	0,967	0,969	0,9693	0,9705	0,9689	0,9678	0,9326	0,9669	0,9666	0,9657	0,9611	0,9603	0,9619	0,9644
210	0,9873	0,988	0,9886	0,9886	0,988	0,9887	0,988	0,9867	0,9852	0,9505	0,986	0,9869	0,9887	0,991	0,9917	0,9923	0,9908	0,9891	0,9529	0,9882	0,9881	0,9872	0,9825	0,9816	0,9832	0,9859
211	0,9656	0,9663	0,9667	0,9669	0,9663	0,9675	0,9668	0,9653	0,9637	0,9299	0,9644	0,9651	0,9669	0,9689	0,9693	0,9704	0,9689	0,9677	0,9325	0,9668	0,9666	0,9657	0,961	0,9603	0,9618	0,9644
212	0,9814	0,9824	0,983	0,9832	0,9826	0,9837	0,9823	0,9802	0,978	0,9438	0,9796	0,9806	0,9829	0,9851	0,9853	0,9867	0,9844	0,983	0,9464	0,982	0,9823	0,9813	0,9765	0,976	0,9775	0,9806
213	0,9656	0,9663	0,9667	0,9669	0,9663	0,9675	0,9667	0,9653	0,9637	0,9299	0,9643	0,9651	0,9669	0,9689	0,9693	0,9704	0,9689	0,9677	0,9325	0,9668	0,9666	0,9656	0,961	0,9602	0,9618	0,9644
214	0,9897	0,9904	0,9908	0,991	0,9904	0,9916	0,9908	0,9892	0,9875	0,9529	0,9883	0,9892	0,991	0,9931	0,9936	0,9948	0,9931	0,9919	0,9557	0,9909	0,9907	0,9898	0,985	0,9841	0,9857	0,9885
215	0,9655	0,9662	0,9666	0,9668	0,9662	0,9674	0,9667	0,9653	0,9637	0,9295	0,9643	0,9651	0,9669	0,9689	0,9693	0,9704	0,9689	0,9677	0,9321	0,9668	0,9666	0,9656	0,961	0,9602	0,9617	0,9643
216	0,9655	0,9662	0,9666	0,9668	0,9662	0,9674	0,9667	0,9653	0,9636	0,9294	0,9643	0,9651	0,9669	0,9689	0,9693	0,9704	0,9689	0,9677	0,9321	0,9668	0,9666	0,9656	0,961	0,9601	0,9617	0,9643
217	0,9881	0,9886	0,9887	0,9888	0,9888	0,9902	0,9894	0,9877	0,9864	0,9513	0,9872	0,9878	0,9892	0,9914	0,9921	0,9936	0,9918	0,9905	0,954	0,9896	0,9892	0,9883	0,9834	0,9827	0,9844	0,9871
218	0,9652	0,966	0,9664	0,9666	0,966	0,9672	0,9665	0,9652	0,9635	0,9289	0,9642	0,965	0,9668	0,9688	0,9691	0,9703	0,9687	0,9676	0,9315	0,9667	0,9664	0,9655	0,9608	0,9599	0,9615	0,9641
219	0,9652	0,9659	0,9663	0,9665	0,966	0,9672	0,9665	0,9651	0,9635	0,9287	0,9642	0,965	0,9667	0,9688	0,9691	0,9703	0,9687	0,9676	0,9313	0,9666	0,9664	0,9655	0,9607	0,9599	0,9615	0,964
220	0,9799	0,9807	0,981	0,9813	0,9807	0,9845	0,9856	0,9857	0,984	0,9243	0,9847	0,9856	0,9874	0,9899	0,9903	0,9918	0,9895	0,9883	0,9271	0,9873	0,9872	0,9852	0,9766	0,9744	0,9761	0,9786
221	0,981	0,9817	0,9821	0,9824	0,9818	0,9824	0,9818	0,9802	0,9781	0,9429	0,9795	0,9805	0,9833	0,9852	0,9849	0,9864	0,9845	0,9831	0,9453	0,9818	0,9814	0,9805	0,9757	0,9749	0,9768	0,9801
222	0,9665	0,9673	0,9677	0,9678	0,9673	0,9684	0,9677	0,9662	0,9646	0,9312	0,9653	0,966	0,9678	0,9698	0,9701	0,9713	0,9697	0,9686	0,9338	0,9677	0,9675	0,9665	0,962	0,9612	0,9628	0,9653
223	1,0631	1,064	1,0644	1,0646	1,064	1,0652	1,0644	1,042	1,0402	1,0243	1,0617	1,0417	1,0645	1,0667	1,0671	1,0684	1,0667	1,0654	1,0272	1,0644	1,0642	1,0631	1,0581	1,0573	1,059	1,0618
301	0,9833	0,9838	0,9836	0,9841	0,9837	0,9848	0,9829	0,9809	0,9785	0,943	0,9792	0,9802	0,9825	0,9858	0,9859	0,9874	0,9859	0,9853	0,9485	0,9844	0,9844	0,9833	0,9783	0,9771	0,9789	0,9816
302	0,9806	0,9811	0,9809	0,9814	0,9811	0,9823	0,9799	0,9777	0,9752	0,9398	0,9761	0,9769	0,9797	0,9833	0,9832	0,9849	0,9832	0,9827	0,946	0,982	0,982	0,9807	0,9757	0,9746	0,9762	0,9789
303	0,9805	0,9811	0,9809	0,9814	0,9811	0,9823	0,9798	0,9776	0,9752	0,9397	0,976	0,9769	0,9797	0,9833	0,9832	0,9849	0,9832	0,9827	0,946	0,982	0,982	0,9807	0,9756	0,9746	0,9762	0,9789
304	0,9804	0,981	0,9808	0,9813	0,981	0,9822	0,9797	0,9775	0,9751	0,9396	0,9759	0,9767	0,9796	0,9832	0,9831	0,9848	0,9831	0,9826	0,9459	0,9819	0,9819	0,9806	0,9755	0,9744	0,9761	0,9788
305	0,9835	0,9839	0,9838	0,9842	0,9838	0,9849	0,9831	0,9811	0,9787	0,9432	0,9793	0,9804	0,9827	0,9859	0,986	0,9875	0,986	0,9855	0,9487	0,9846	0,9845	0,9835	0,9785	0,9773	0,979	0,9818
306	0,9818	0,9813	0,9806	0,9812	0,981	0,9817	0,979	0,9756	0,9725	0,9367	0,9731	0,9751	0,9762	0,9805	0,9808	0,9828	0,982	0,9827	0,9456	0,9816	0,9821	0,9813	0,9765	0,9743	0,9766	0,9793
307	0,9833	0,9837	0,9836	0,9841	0,9837	0,9847	0,9829	0,9809	0,9785	0,9429	0,9791	0,9802	0,9825	0,9858	0,9858	0,9874	0,9859	0,9853	0,9485	0,9844	0,9844	0,9832	0,9783	0,9771	0,9788	0,9816
308	0,9833	0,9837	0,9836	0,9841	0,9836	0,9847	0,9829	0,9809	0,9785	0,9429	0,9791	0,9802	0,9825	0,9858	0,9858	0,9874	0,9859	0,9853	0,9485	0,9844	0,9844	0,9832	0,9783	0,9771	0,9788	0,9816
309	0,9757	0,9779	0,9775	0,9782	0,9767	0,9788	0,9769	0,9732	0,9726	0,9341	0,9706	0,9744	0,9749	0,9794	0,98	0,9814	0,9811	0,978	0,9426	0,9788	0,9784	0,9751	0,9703	0,9703	0,9717	0,9755
310	0,9813	0,9817	0,9815	0,9821	0,9815	0,9825	0,9812	0,9787	0,9764	0,9411	0,9774	0,9784	0,9813	0,9842	0,9844	0,9861	0,9848	0,9837	0,9474	0,9833	0,9828	0,9816	0,9772	0,9753	0,9775	0,9793
311	0,9728	0,9734	0,9723	0,9739	0,9728	0,9742	0,9711	0,97	0,9673	0,9302	0,9668	0,9699	0,9705	0,975	0,9713	0,9746	0,9751	0,974	0,9361	0,9724	0,9727	0,9723	0,9664	0,9659	0,9672	0,9703
312	0,9723	0,9728	0,9717	0,9732	0,972	0,9736	0,9704	0,9693	0,9666	0,9294	0,9661	0,9693	0,9698	0,9744	0,9708	0,9739	0,9745	0,9734	0,9353	0,9717	0,9721	0,9715	0,9657	0,9652	0,9665	0,9696
313	0,9673	0,9682	0,9665	0,9686	0,9673	0,9686	0,9649	0,9644	0,9615	0,9235	0,9605	0,9646	0,9642	0,9692	0,9632	0,968	0,9695	0,968	0,9296	0,9662	0,9666	0,9667	0,9599	0,96	0,9611	0,9645
314	0,9646	0,9655	0,9639	0,966	0,9647	0,966	0,962	0,9614	0,9585	0,9208	0,9578	0,9619	0,9604	0,9657	0,9589	0,964	0,9661	0,9648	0,9264	0,9631	0,9634	0,9636	0,9569	0,9571	0,9579	0,9618
315	0,9609	0,9629	0,9588	0,9626	0,9608	0,9619	0,9574	0,9594	0,9558	0,9142	0,9515	0,9593	0,9602	0,9656	0,9558	0,9636	0,9656	0,9625	0,9225	0,9594	0,9604	0,9618	0,9523	0,9537	0,9551	0,9572
316	0,9774	0,9775	0,9778	0,9781	0,9777	0,978	0,9758	0,9734	0,9697	0,9341	0,9706	0,9702	0,9748	0,98	0,9785	0,9807	0,9795	0,9788	0,9413	0,9775	0,9778	0,9766	0,9706	0,9698	0,9721	0,9756
317	0,9772	0,9773	0,9776	0,978	0,9775	0,9778	0,9756	0,9732	0,9694	0,9338	0,9703	0,9699	0,9745	0,9798	0,9782	0,9805	0,9793	0,9786	0,9411	0,9773	0,9776	0,9764	0,9704	0,9695	0,9719	0,9754
318	0,9757	0,9754	0,9757	0,9765	0,9761	0,976	0,9736	0,9717	0,9676	0,9319	0,9685	0,9665	0,9714	0,9775	0,9755	0,9784	0,9764	0,976	0,939	0,9752	0,9753	0,9742	0,9686	0,9675	0,9702	0,9733
319	0,9739	0,9744	0,9751	0,9742	0,9746	0,9734	0,9709	0,9667	0,96	0,9252	0,962	0,9629	0,9699	0,9772	0,9738	0,9754	0,9769	0,9755	0,9369	0,9732	0,974	0,9727	0,964	0,9646	0,9663	0,973
320	0,9766	0,9768	0,9771	0,9775	0,977	0,9773	0,9751	0,9727	0,9689	0,9332	0,9697	0,9695	0,9742	0,9795	0,9778	0,9802	0,979	0,9783	0,9405	0,9767	0,9771	0,976	0,97	0,969	0,9714	0,9749
321	0,9762	0,9764	0,9767	0,9771	0,9766	0,9769	0,9748	0,9723	0,9685	0,9328	0,9693	0,9691	0,9738	0,9791	0,9775	0,9799	0,9786	0,9779	0,9401	0,9763	0,9768	0,9756	0,9696	0,9686	0,971	0,9745
322	0,976	0,9764	0,9767	0,9771	0,9765	0,9768	0,9747	0,9722	0,9685	0,9326	0,9692	0,9691	0,9739	0,9793	0,9775	0,98	0,9788	0,978	0,94	0,9763	0,9768	0,9756	0,9696	0,9685	0,971	0,9745
323	0,975	0,9747	0,9754	0,9758	0,9749	0,9757	0,9735	0,9704	0,9673	0,9317	0,9683	0,9674	0,9726	0,978	0,9762	0,9786	0,9775	0,9767	0,9388	0,975	0,9756	0,9744	0,9679	0,9674	0,9697	0,9733

Table C.1: Scenario 2, case 2.1: Ferry charged with one battery, Utsira bus voltages [p.u.]

Bus/hour	1	2	3	4	5	6	7	8	9	9.10-9.30	10	11	12	13	14	15	16	17	17.25-17.45	18	19	20	21	22	23	24
201	0,9999	1,0007	1,0011	1,0013	1,0006	1,0019	1,0011	0,9996	0,9979	1,0058	0,9985	0,9994	1,0013	1,009	1,0104	1,01	1,0032	1,002	1,0083	1,001	1,0008	0,9998	0,9951	0,9943	0,9959	0,9987
202	0,9633	0,964	0,9644	0,9646	0,9638	0,9651	0,9643	0,9628	0,9613	0,9688	0,9618	0,9627	0,9647	0,972	0,9733	0,973	0,9663	0,9652	0,9712	0,9642	0,964	0,963	0,9584	0,9577	0,9593	0,9621
203	0,9643	0,9651	0,9655	0,9656	0,9651	0,9663	0,9655	0,9641	0,9624	0,9701	0,9631	0,9639	0,9656	0,973	0,9744	0,9741	0,9676	0,9664	0,9725	0,9655	0,9653	0,9644	0,9598	0,959	0,9606	0,9631
204	0,9643	0,9651	0,9655	0,9656	0,9651	0,9663	0,9655	0,9641	0,9624	0,9701	0,9631	0,9638	0,9656	0,973	0,9744	0,9741	0,9676	0,9664	0,9725	0,9655	0,9653	0,9644	0,9598	0,959	0,9606	0,9631
205	0,9648	0,9655	0,9659	0,9661	0,9655	0,9667	0,966	0,9645	0,9629	0,9705	0,9635	0,9643	0,9661	0,9734	0,9748	0,9745	0,968	0,9669	0,973	0,966	0,9657	0,9648	0,9602	0,9595	0,961	0,9636
206	1,0404	1,0412	1,0416	1,0418	1,0412	1,0425	1,0417	1,0401	1,0383	1,0466	1,0391	1,0399	1,0418	1,0497	1,0512	1,0509	1,0439	1,0427	1,0492	1,0417	1,0414	1,0404	1,0355	1,0347	1,0364	1,0391
207	0,9639	0,9647	0,9651	0,9652	0,9647	0,9659	0,9651	0,9637	0,9621	0,9698	0,9627	0,9635	0,9653	0,9727	0,9741	0,9739	0,9673	0,9661	0,9723	0,9652	0,965	0,964	0,9594	0,9586	0,9602	0,9627
208	0,9865	0,9873	0,9877	0,9879	0,9874	0,9888	0,9878	0,9863	0,9846	0,9927	0,9854	0,9863	0,9882	0,9959	0,9972	0,997	0,99	0,9885	0,9951	0,9879	0,9875	0,9865	0,9817	0,9809	0,9825	0,9852
209	0,9638	0,9646	0,9649	0,9651	0,9646	0,9658	0,965	0,9636	0,9619	0,9697	0,9626	0,9634	0,9652	0,9726	0,974	0,9738	0,9672	0,966	0,9722	0,9651	0,9648	0,9639	0,9593	0,9585	0,96	0,9626
210	0,9854	0,9861	0,9867	0,9867	0,9861	0,9869	0,9861	0,9849	0,9833	0,9915	0,9842	0,985	0,9869	0,9948	0,9965	0,9956	0,9889	0,9872	0,9937	0,9864	0,9862	0,9853	0,9806	0,9797	0,9813	0,984
211	0,9637	0,9645	0,9649	0,9651	0,9645	0,9657	0,965	0,9635	0,9619	0,9697	0,9626	0,9633	0,9651	0,9726	0,974	0,9737	0,9671	0,9659	0,9721	0,965	0,9648	0,9639	0,9592	0,9584	0,96	0,9626
212	0,9795	0,9805	0,9811	0,9813	0,9807	0,9818	0,9805	0,9783	0,9761	0,9851	0,9777	0,9787	0,981	0,9889	0,9901	0,9901	0,9825	0,9812	0,9874	0,9801	0,9805	0,9794	0,9746	0,974	0,9755	0,9787
213	0,9637	0,9645	0,9649	0,965	0,9645	0,9657	0,9649	0,9635	0,9618	0,9697	0,9625	0,9633	0,9651	0,9726	0,974	0,9737	0,9671	0,9659	0,9721	0,965	0,9648	0,9638	0,9592	0,9584	0,96	0,9625
214	0,9878	0,9886	0,9889	0,9891	0,9885	0,9897	0,989	0,9874	0,9857	0,9938	0,9865	0,9873	0,9892	0,9968	0,9984	0,9981	0,9912	0,9901	0,9964	0,9891	0,9888	0,9879	0,9831	0,9822	0,9838	0,9866
215	0,9636	0,9644	0,9648	0,9649	0,9644	0,9656	0,9649	0,9635	0,9618	0,9697	0,9625	0,9633	0,9651	0,9726	0,974	0,9737	0,9671	0,9659	0,9722	0,965	0,9648	0,9638	0,9591	0,9583	0,9599	0,9624
216	0,9636	0,9644	0,9647	0,9649	0,9644	0,9656	0,9649	0,9635	0,9618	0,9697	0,9625	0,9633	0,9651	0,9726	0,974	0,9737	0,9671	0,9659	0,9721	0,965	0,9647	0,9638	0,9591	0,9583	0,9599	0,9624
217	0,9862	0,9867	0,9868	0,9869	0,9869	0,9883	0,9875	0,9858	0,9845	0,9927	0,9853	0,986	0,9874	0,9952	0,997	0,997	0,99	0,9887	0,9951	0,9878	0,9873	0,9864	0,9815	0,9808	0,9825	0,9852
218	0,9634	0,9641	0,9645	0,9647	0,9641	0,9654	0,9647	0,9633	0,9617	0,9696	0,9624	0,9631	0,9649	0,9725	0,9739	0,9737	0,9669	0,9657	0,9721	0,9648	0,9646	0,9636	0,9589	0,958	0,9596	0,9622
219	0,9633	0,9641	0,9644	0,9646	0,9641	0,9653	0,9647	0,9633	0,9616	0,9696	0,9623	0,9631	0,9649	0,9725	0,9739	0,9737	0,9669	0,9657	0,9721	0,9648	0,9646	0,9636	0,9588	0,958	0,9596	0,9621
220	0,9768	0,9775	0,9779	0,9781	0,9776	0,9814	0,9825	0,9827	0,9809	0,9937	0,9817	0,9825	0,9844	0,996	0,9983	0,9973	0,9864	0,9853	0,9962	0,9842	0,9842	0,9821	0,9735	0,9712	0,9729	0,9754
221	0,979	0,9798	0,9802	0,9805	0,9798	0,9805	0,9799	0,9783	0,9761	0,9851	0,9776	0,9786	0,9814	0,989	0,9899	0,9899	0,9826	0,9812	0,9874	0,9799	0,9795	0,9786	0,9737	0,9729	0,9749	0,9781
222	0,9647	0,9655	0,9659	0,966	0,9655	0,9667	0,9659	0,9645	0,9628	0,9705	0,9635	0,9643	0,966	0,9734	0,9748	0,9745	0,968	0,9668	0,9729	0,9659	0,9657	0,9648	0,9602	0,9594	0,961	0,9635
223	1,0403	1,0411	1,0416	1,0417	1,0412	1,0424	1,0416	1,0401	1,0383	1,0466	1,0598	1,0398	1,0626	1,0707	1,0722	1,0719	1,0647	1,0635	1,0702	1,0625	1,0622	1,0612	1,0562	1,0346	1,0363	1,039
301	0,9814	0,9818	0,9817	0,9822	0,9818	0,9829	0,981	0,979	0,9766	0,9847	0,9773	0,9783	0,9806	0,9896	0,9908	0,9908	0,984	0,9835	0,99	0,9826	0,9825	0,9814	0,9764	0,9752	0,9769	0,9797
302	0,9786	0,9792	0,979	0,9795	0,9792	0,9804	0,978	0,9758	0,9733	0,9817	0,9742	0,975	0,9779	0,9871	0,9882	0,9883	0,9814	0,9808	0,9875	0,9801	0,9801	0,9789	0,9737	0,9726	0,9743	0,977
303	0,9786	0,9791	0,979	0,9795	0,9792	0,9804	0,9779	0,9757	0,9733	0,9816	0,9742	0,975	0,9779	0,9871	0,9882	0,9883	0,9814	0,9808	0,9875	0,9801	0,9801	0,9788	0,9737	0,9726	0,9743	0,9769
304	0,9785	0,979	0,9789	0,9794	0,9791	0,9803	0,9778	0,9756	0,9732	0,9815	0,974	0,9748	0,9777	0,987	0,988	0,9882	0,9812	0,9807	0,9874	0,98	0,98	0,9787	0,9736	0,9725	0,9741	0,9769
305	0,9816	0,982	0,9819	0,9823	0,9819	0,983	0,9812	0,9792	0,9768	0,9849	0,9774	0,9785	0,9808	0,9897	0,9909	0,991	0,9842	0,9836	0,9901	0,9827	0,9827	0,9816	0,9766	0,9753	0,9771	0,9799
306	0,9799	0,9794	0,9787	0,9793	0,9791	0,9798	0,9771	0,9737	0,9706	0,9787	0,9712	0,9733	0,9743	0,9843	0,9858	0,9863	0,9801	0,9808	0,9872	0,9797	0,9802	0,9795	0,9746	0,9724	0,9746	0,9774
307	0,9814	0,9818	0,9817	0,9822	0,9817	0,9828	0,981	0,979	0,9766	0,9847	0,9772	0,9784	0,9806	0,9896	0,9908	0,9908	0,984	0,9834	0,9899	0,9825	0,9825	0,9814	0,9764	0,9751	0,9769	0,9797
308	0,9814	0,9818	0,9817	0,9822	0,9817	0,9828	0,981	0,979	0,9766	0,9847	0,9772	0,9783	0,9806	0,9896	0,9908	0,9908	0,984	0,9834	0,9899	0,9825	0,9825	0,9814	0,9764	0,9751	0,9769	0,9797
309	0,9737	0,976	0,9755	0,9763	0,9747	0,9769	0,975	0,9713	0,9707	0,9762	0,9687	0,9725	0,973	0,9832	0,985	0,9848	0,9792	0,9761	0,9843	0,9769	0,9765	0,9732	0,9684	0,9684	0,9697	0,9736
310	0,9794	0,9798	0,9796	0,9802	0,9796	0,9806	0,9793	0,9769	0,9745	0,9829	0,9755	0,9765	0,9794	0,988	0,9893	0,9895	0,983	0,9818	0,9889	0,9815	0,981	0,9797	0,9753	0,9734	0,9755	0,9773
311	0,9709	0,9715	0,9704	0,9719	0,9708	0,9723	0,9691	0,9681	0,9654	0,9725	0,9649	0,968	0,9686	0,9788	0,9763	0,9781	0,9732	0,9721	0,978	0,9705	0,9709	0,9703	0,9644	0,9639	0,9652	0,9683
312	0,9703	0,9708	0,9697	0,9713	0,9701	0,9717	0,9684	0,9674	0,9647	0,9717	0,9642	0,9674	0,9679	0,9783	0,9757	0,9774	0,9726	0,9715	0,9773	0,9698	0,9702	0,9696	0,9638	0,9633	0,9645	0,9676
313	0,9653	0,9663	0,9645	0,9666	0,9653	0,9667	0,963	0,9625	0,9596	0,9661	0,9585	0,9627	0,9623	0,9731	0,9683	0,9714	0,9676	0,9661	0,9718	0,9643	0,9646	0,9647	0,958	0,958	0,9591	0,9625
314	0,9626	0,9636	0,9619	0,964	0,9628	0,9641	0,9601	0,9594	0,9566	0,9635	0,9559	0,9599	0,9585	0,9696	0,9639	0,9674	0,9642	0,9629	0,9688	0,9612	0,9614	0,9617	0,9549	0,9551	0,9559	0,9599
315	0,9589	0,9609	0,9568	0,9606	0,9588	0,9599	0,9555	0,9575	0,9539	0,9572	0,9495	0,9574	0,9583	0,9695	0,9609	0,9671	0,9637	0,9606	0,9651	0,9575	0,9584	0,9599	0,9504	0,9517	0,9531	0,9553
316	0,9754	0,9755	0,9758	0,9762	0,9758	0,9761	0,9739	0,9715	0,9678	0,9762	0,9687	0,9683	0,9729	0,9838	0,9834	0,9841	0,9776	0,9769	0,983	0,9756	0,9759	0,9747	0,9687	0,9678	0,9701	0,9737
317	0,9752	0,9753	0,9757	0,976	0,9756	0,9759	0,9737	0,9713	0,9675	0,9759	0,9684	0,968	0,9726	0,9836	0,9832	0,9839	0,9774	0,9767	0,9828	0,9754	0,9757	0,9745	0,9685	0,9676	0,9699	0,9735
318	0,9738	0,9735	0,9738	0,9745	0,9742	0,9741	0,9716	0,9698	0,9656	0,9741	0,9666	0,9646	0,9695	0,9813	0,9805	0,9818	0,9745	0,9741	0,9808	0,9733	0,9734	0,9723	0,9666	0,9655	0,9683	0,9714
319	0,972	0,9724	0,9732	0,9722	0,9727	0,9715	0,969	0,9648	0,958	0,9677	0,9601	0,9609	0,968	0,981	0,9788	0,9788	0,975	0,9737	0,9788	0,9713	0,9721	0,9708	0,9621	0,9627	0,9644	0,971
320	0,9746	0,9749	0,9752	0,9755	0,975	0,9754	0,9732	0,9708	0,967	0,9753	0,9678	0,9676	0,9723	0,9833	0,9828	0,9837	0,9771	0,9764	0,9823	0,9748	0,9752	0,9741	0,968	0,967	0,9695	0,973
321	0,9742	0,9745	0,9748	0,9752	0,9747	0,975	0,9729	0,9704	0,9666	0,975	0,9674	0,9672	0,9719	0,983	0,9824	0,9833	0,9768	0,976	0,9819	0,9745	0,9749	0,9737	0,9676	0,9666	0,9691	0,9726
322	0,9741	0,9744	0,9748	0,9751	0,9746	0,9749	0,9728	0,9703	0,9666	0,9748	0,9673	0,9672	0,972	0,9831	0,9825	0,9835	0,9769	0,9761	0,9818	0,9744	0,9749	0,9737	0,9677	0,9665	0,9691	0,9726
323	0,9731	0,9728	0,9735	0,9739	0,9729	0,9738	0,9716	0,9685	0,9653	0,9739	0,9664	0,9655	0,9707	0,9818	0,9812	0,9821	0,9756	0,9748	0,9806	0,9731	0,9737	0,9725	0,966	0,9655	0,9678	0,9714

Table C.2: Scenario 2, case 2.2: Ferry charged with two batteries, Utsira bus voltages [p.u.]

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