Master's thesis

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

Magnus Rein Hatletveit

A Case Study on the Impact of Vehicle-to-Grid on Reliability of Supply in a Norwegian Distribution System

Utilization of RELSAD - A Python Package for Reliability Analysis

Master's thesis in Energy and Environmental Engineering
Supervisor: Olav Bjarte Fosso
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Abstract

Reducing emissions to reverse climate change is one of the primary objectives of the sustainability goals set forth by the United Nations [1]. Extensive electrification of the world has been pointed out as the most promising alternative to lower the carbon footprint on Earth. The transport sector alone is assumed to be responsible for approximately 27 % of the world's total emissions [2], which has led to an extensive overhaul of the traditional car fleet from conventional fossil-driven vehicles to electric vehicles. As electric vehicles are becoming the most prominent choice of transportation, the electricity demand is predicted to increase drastically in the years to come [3]. As the power grids could become more congested, services will be needed to aid the grid in critical periods. If the growth of electric vehicles persists, the batteries of electric vehicles will have a significant amount of untapped potential for battery storage that might be used for additional grid services. This is the main purpose of Vehicle-to-Grid (V2G) technology, which provides an opportunity of feeding electricity back into the grid from electric vehicles in times of need. This master's thesis will attempt to answer if the Vehicle-to-Grid technology can impact the reliability of supply of the power grid in Norway. Reliability indices such as Energy Not Delivered (ENS), System Average Interruption Frequency Index (SAIFI) and System Average Interruption Duration Index (SAIDI) will be the main results that will be investigated in relation to the impact of Vehicle-to-Grid technology on grid reliability.

The work of investigating Vehicle-to-Grid impact on reliability factors of the power grid has been conducted using a simulation tool in Python called RELSAD [4], allowing for the usage of Monte Carlo simulation to study a large number of outcomes related to the planning of large-scale, complex systems like the power grid. To represent parts of the Norwegian power grid, a reference grid model created by CINELDI [5] has been used for case experiments. The work in this thesis includes implementing and constructing an existing grid model from Matpower-files to a new grid model in Python using the RELSAD properties. The work done in this thesis may provide a framework for new studies of power grid reliability using RELSAD on the existing reference grid or entirely new grid models. In addition, further work was conducted to create scripts for running the Monte Carlo simulations in RELSAD on the reference grid model. The grid was tested with three case scenarios to determine the Vehicle-to-Grid impact on the reliability of the reference grid. The first case included an EV park in the grid model without V2G services activated. The second case utilized the same EV park as the first case but with activated V2G services. The third case used the same EV park as the first and second cases but with an increased EV charging capacity from 3.7 kW to 7.4 kW.

The main findings from the simulations of the first and second cases were a reduction in ENS from 15.70 MWh to 15.45 MWh, meaning that activating V2G can contribute to reducing approximately 1.6 % of energy which is not being delivered to grid customers. SAIFI and SAIDI were also reduced by 1.22 % and 0.72 % respectively, indicating that the EVs could reduce the ENS with a lower number of expected interruptions and lower interruption duration. The simulation results from the second and third cases indicated a reduction of ENS from 15.45 MWh to 15.36 MWh, with reductions to SAIFI and SAIDI of 0.62 % and 1.1 % respectively. This could indicate that the increased charging capacity of EVs connected by V2G could improve the energy delivered to customers in the grid during a lower number of interruptions and lowered interruption duration. It is noted that the improvements on ENS are relatively small in this case since the experiments are based only on a single EV park of 20 vehicles connected to a large distribution grid. If one were to connect more EV parks, which would be more realistic regarding the number of customers in the grid, the impact on ENS would probably be more significant. As an answer to which extent using EVs through V2G during grid interruptions will improve the amount of Energy Not Supplied, SAIFI and SAIDI in the grid, the answer would be more complex. Energy Not Supplied will probably be reduced as a consequence of using V2G services during interruptions. SAIFI and SAIDI would probably experience a more significant reduction with a greater number of EVs with V2G services in the system. In this way, more interruptions occurring in other parts of the grid probably could have been avoided.

Sammendrag

Reduksjonen av utslipp for å reversere klimaendringene er en av de viktigste punktene fra bærekraftsmålene fremsatt av Forente Nasjoner [1]. Omfattende elektrifisering av verden har blitt pekt på som ett av de mest lovende alternativene for å minske klimaavtrykket på Jorden. Transportsektoren alene er antatt å være ansvarlig for omtrent 27 % av verdens totale utslipp [2], noe som har ført til en stor overhaling av bilparken fra tradisjonelle, fossildrevne kjøretøy til elektriske kjøretøy. Ettersom elektriske kjøretøy er i ferd med å bli det mest populære alternativet, er behovet for elektrisitet spådd til å øke drastisk de neste årene [3]. Siden strømnettet kan komme til å bli mer overbelastet trengs det flere tjenester som kan bistå nettet i kritiske perioder. Dersom veksten av elektriske kjøretøy fortsetter kan batteriene hos elektriske kjøretøy være en uutnyttet kilde til batterilagring som kan brukes i samspill med strømnettet. Dette er hovedformålet til Vehicle-to-Grid teknologi som tilbyr en mulighet for å levere elektrisitet tilbake til strømnettet fra elektriske kjøretøy i perioder med behov for mer elektrisitet. Denne masteroppgaven vil forsøke å besvare spørsmål rundt om Vehicle-to-Grid teknologi vil kunne ha en innvirkning på forsyningssikkerheten til strømnettet i Norge. Pålitelighetsfaktorer slik som Energy Not Delivered (ENS), System Average Interruption Frequency Index (SAIFI) og System Average Interruption Frequency Index (SAIDI) vil være de viktigste fokusområdene som kommer til å bli undersøkt i forbindelse med innvirkningen av Vehicle-to-Grid teknologi på forsyningssikkerheten i strømnettet.

Arbeidet med å undersøke innvirkningen fra Vehicle-to-Grid på pålitelighetsfaktorer for strømnettet har blitt gjort ved å bruke et simuleringsverktøy i Python kalt RELSAD [4], som tilbyr bruken av Monte Carlo simulering for å studere et større antall utfall relatert til planlegging av større, komplekse systemer som strømnettet. Som en representasjon av det norske strømnettet har en CINELDIs referansenett-modell [5] blitt brukt til eksperimenter. Arbeidet som ble gjennomført inkluderer implementasjon og komposisjon av en eksisterende nettmodell fra MATPOWER-filer til en nettmodell på RELSAD-format i Python. Arbeidet som har blitt gjort i denne oppgaven er ment til å fungere som et rammeverk for videre studier på forsyningssikkerheten på det eksisterende referansenettet ved hjelp av RELSAD, eller helt nye nettmodeller i RELSAD. Videre arbeid ble gjennomført for å lage kode for å kjøre Monte Carlo simuleringer i RELSAD for referansenettets modell. Nettet ble testet for tre ulike scenarioer for å avgjøre innvirkningen fra Vehicle-to-Grid på påliteligheten til referansenettet. Det første scenarioet inkluderte en elbilpark i nettmodellen uten V2G-tjenester aktivert. Det andre scenarioet brukte den samme elbilparken som for det første scenarioet, men denne gangen med V2G-tjenester aktivert. Det tredje scenarioet brukte samme elbilpark som det første og det andre scenarioet, men denne gangen med økt ladekapasitet på elbilene fra 3.7 kW til 7.4 kW.

De viktigste funnene fra simuleringene av det første og det andre scenariene var en reduksjon i ENS fra 15.70 MWh til 15.45 MWh, noe som kan bety at aktivering av V2G kan bidra til å redusere 1.6 % ikke-levert energi til nettkundene. SAIFI og SAIDI ble redusert med henholdsvis 1.22 % og 0.72 %, noe som kan indikere at elbilene vil være i stand til å redusere ENS med lavere antall avbrudd og lavere avbruddsvarighet. Resultatene fra simuleringene for det andre og tredje scenarioet indikerte en reduksjon av ENS fra 15.45 MWh til 15.36 MWh, med reduksjon av SAIFI og SAIDI på henholdsvis 0.62 % og 1.1 %. Dette kan indikere at den økte ladekapasiteten til elbilene som er koblet til gjennom V2G kan forbedre mengden energi som leveres til nettkundene under lavere antall avbrudd og lavere varighet på avbruddene. Det er verdt å merke seg at forbedringene i ENS er relativt små i dette tilfellet siden eksperimentene er basert på én enkelt elbilpark med 20 biler som er koblet til et større distribusjonsnett. Hvis man hadde koblet en mer realistisk mengde elbiler i sammenheng med hvor mange elbiler som eksisterer i Norge per sluttbruker, ville antakeligvis innvirkningen på ENS vært betydelig større. Som et svar på spørsmålet om bruken av elbiler gjennom V2G under avbrudd i nettet vil være i stand til å forbedre mengden Ikke-levert Energi (ENS) i nettet, SAIFI og SAIDI, ville svaret vært mer sammensatt. Ikke-levert Energi (ENS) vil trolig bli redusert som en konsekvens av å bruke V2G teknologi under avbrudd. SAIFI og SAIDI ville trolig blitt mer redusert dersom et større antall elbiler med V2G hadde vært koblet til større deler av nettet. På denne måten kunne antakeligvis flere avbrudd som forekommer i andre deler av nettet vært unngått.

Preface

This master's thesis is submitted as the final work of a master's degree at the Norwegian University of Science and Technology (NTNU) in Energy and Environmental Engineering (MTENERG) and is a part of the field of Electric Power and Energy Systems (TET4900). The thesis was finalized in the spring of 2023 and is a continuation of the work conducted in the specialization project of December 2022.

The master's thesis has been written in collaboration with SINTEF Energy and the CINELDI and FuChar workgroups. CINELDI, also known as the Centre for Intelligent Energy Distribution, is a research center designated to working towards digitalizing and modernizing the electricity distribution grid for higher efficiency, flexibility and resilience. FuChar is a project aiming to minimize investment and operating costs related to the grid integration of electric transport, with a focus on high-power charging.

I would like to thank my main supervisor, Professor Olav Bjarte Fosso, for his contributions during the work of this master's thesis. I would also like to thank my co-supervisors; Iver Bakken Sperstad and Aurora Fosli Flataker, for their quality guidance and support during the work on this thesis. I would also like to thank the creator of the RELSAD python package, Stine Fleischer Myhre, for her dedication to aiding me in my work with the usage of RELSAD and helping me to understand the tools and models in a good way.

I would also like to dedicate a special thanks to my friends, my family and my girlfriend for providing motivation and continuous support during my education.

Trondheim, 11.06.2023

Magnus Rein Hatletveit

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Abbreviations

Abbreviation	Description
EV	Electric Vehicle
BEV	Battery Electric Vehicle
HEV	Hybrid Electric Vehicle
PHEV	Plug-in Hybrid Electric Vehicle
H2	Hydrogen
LPG	Liquefied Petroleum Gas
CNG	Compressed Natural Gas
LNG	Liquefied Natural Gas
V2X	Vehicle-to-Everything
V2G	Vehicle-to-Grid
DSO	Distribution System Operator
TSO	Transmission System Operator
SoC	State of Charge
V	Volt
A	Ampére
CRN	Common Random Numbers
RELSAD	RELiability tool for Smart and Active Distribution networks
ENS	Energy Not Supplied
SAIFI	System Average Interruption Frequency Index
SAIDI	System Average Interruption Duration Index

1 Introduction

The global climate change has launched a green transformation of the energy sector. The 17 sustainability goals set forth by the United Nations [1] encourage nations to work towards a brighter and more renewable future. Among these goals set by the UN are statements of affordable and green energy for everybody and the need for climate action. This has provided incentives for communities to reduce their overall carbon footprint. As a result, the electrification of the world has been intensified by the use of renewable energy resources. This has also led to substantial electrification within the transport sector, as traditional vehicles are assumed to be responsible for 27 % of the world's total greenhouse gas emissions [2].

1.1 Motivation

Norway has traditionally been a supplier of affordable and renewable energy through the utilization of hydropower plants. According to estimates, the energy production in Norway related to hydropower plant production is 89 % of the total energy production [6], whereas 99 % of Norway's total energy production is collected using renewable energy sources such as wind power and hydropower [6]. Although the Norwegian energy mix does not account for large emissions, the transport sector does. According to Statistisk Sentralbyrå (SSB), transport account for approximately 30 % of the total greenhouse gas emissions in Norway [7]. When this is added to the fact that Norway is the second highest country for private car driving per kilometer each day [8], one might understand the urgency to reduce transport emissions. As road traffic is responsible for 56 % of the emissions from the transport sector in Norway, the electrification of Electric Vehicles (EVs) has been staked out as one of the most promising renewable reforms for the future of Norway.

The renewable reform of the private car industry in Norway has already been initiated. The Norwegian government has created incentives to encourage Norwegian citizens to acquire non-emission vehicles by cutting taxes and fees on buying and owning EVs [9]. Cutting taxes and fees on EVs has contributed to making EVs a more attractive investment for Norwegian car owners. In addition to the reduction in prices, the government has introduced a number of advantages for EVs such as free parking, lowered tolls and the possibility to travel in public transport lanes. The Norwegian government has also made a national transport plan (Nasjonal Transportplan) for the years between 2018 and 2029, which includes ambitions for electrification of the transport sector [10]. This includes a set of goals to lower the total greenhouse gas emissions from transportation over a given period of time. According to this plan, all new private cars and light vans will be emission-free from the year 2025. The transport plan also states that all public buses will be zero-emission vehicles or fueled by biogas by the year 2025. In addition to this, all new heavy vans, 75 percent of new long-distance buses and 50 percent of new trucks are set to be zero-emission vehicles by 2030. The incentives provided by the Norwegian government are already starting to affect the car fleet in Norway. As of August 2022, the Norwegian car fleet consists of approximately half a million EVs [11]. This accounts for 16 % of the total cars registered in Norway in 2022. This is already a significant step towards a more renewable and electric future of transportation.

As the share of EVs increases, so does the need for a robust vehicle charging infrastructure. This is why the Norwegian government has invested approximately 136 million NOK since 2015 to establish charging stations all across the country [9]. Charging points are an essential part of the green overhaul of the transport sector, but they might come with some challenges for the power grid's performance. As stated in [12], the challenges related to the reliability of supply are expected to increase with the increase of charging capacity for EVs. Some of the challenges the Norwegian power grid might encounter in the future are stated as overloads of grid components such as transformers and lines. Other challenges can be related to maintaining a stable voltage quality in the Norwegian power grid. Since World War II, there has been an extensive restructuring of the Norwegian power grid [13]. After the war, electricity became the main source of energy in private homes after being considered a luxury item for many households in the years prior. During the 1960s, almost every person in Norway had access to electricity in their homes. In recent times, the power grid expansion in Norway has been met with several protests and social resistance within environmental movements [14]. As the need for electricity is increasing rapidly, so will the need for reinforcements in the power grid to cope with the demand. NVE has predicted that the energy balance will have fewer opportunities for slack in the future [3]. The report states that the demand for power will increase by between 2 and 6 GW in the years before 2030. This confirms that there is a significant need for better utilization of the power grid infrastructure.

1.2 Problem Definition

As mentioned in Section 1.1 the expansion of electric vehicles may provide a need for new solutions for the existing grid infrastructure. In the coming years, the Norwegian power grid might be exposed to increased stress on its components, as mentioned in [12]. The induced stress on the grid could increase the risks of failing components such as transformers and power lines. As the electric vehicle car fleet grows larger, so does the increase in charging demand. NVE has predicted a possible scenario of 1.5 million EVs in Norway by 2030 [12]. From today's number of EVs in the Norwegian car fleet of 460 734 [15], this is a significant increase in the share of EVs. The need for electricity could be as much as 4 TWh for EVs in Norway alone, according to [12]. The periods when many users charge their EVs simultaneously could provide challenges for the grid and its components. As there are increasingly more EVs on the roads today and in the future, there exists an untapped potential for battery capacity for the grid. This untapped potential needs to be investigated further, which provides a starting point for the work being conducted in this thesis. There have been a lot of work done previously on the challenges on the power system culminating from an increase in EVs. Therefore, this thesis will attempt to study the opportunities for using EVs as a resource for the power system rather than considering EVs as a challenge for the system.

1.3 Objective and Contribution

As this work will investigate the potential of V2G through EVs for the power grid, a basic objective needs to be established. This thesis will aim to answer the following question:

"To what extent will using EVs through V2G during grid interruptions be able to improve the reliability of supply measured by Energy Not Supplied, SAIFI (System Average Interruption Frequency Index) and SAIDI (System Average Interruption Duration Index)?"

This statement aims to investigate if EVs can contribute through V2G to improve the value of the grid reliability factors such as ENS, SAIFI and SAIDI. The main goal of the thesis is to explore the opportunities for more energy delivered to grid customers and reduce the number of grid interruptions and grid downtime using V2G. In addition, the thesis will also provide a framework for the utilization of the RELSAD python package [4]. The thesis shows how to implement a realistic reference grid model [5] into the existing RELSAD structure. As RELSAD is a relatively new tool for reliability analysis, this thesis hopes to provide an example of how to utilize the RELSAD model, such that others might also make use of RELSAD in the future.

1.4 Outline

The structure of this masters thesis will consist of the following sections:

- **Section 1 - Introduction:** An introduction to the matter at hand and an establishment of objectives, contributions and outline of the master's thesis.
- **Section 2 - Background:** A manifestation of the existing background material on the main topics of the master's thesis, which also contains a literature review on some of the most important discoveries regarding Vehicle-To-Grid technology.
- **Section 3 - Theory:** Presents the most important theoretical aspects of the master's thesis, in addition to providing a supplementary understanding of the methods that are being utilized in the thesis.
- **Section 4 - System Description:** Provides a basic understanding of the reference system being used for investigation. This thesis will be based on the CINELDI reference grid model [5] for further analysis, and the properties of this system will be clarified in this part of the thesis.
- **Section 5 - Methodology:** This section will present the methods being used to obtain the results of this thesis, while also establishing the main foundation for the case analysis.
- **Section 6 - Results:** This section presents the most important discoveries and results that were obtained by the methods described in section 5. Additional results from this part can also be found in the Appendix.
- **Section 7 - Discussion:** This section discusses the results and their significance in answering the main objective of this master's thesis. The accuracy and uncertainty of results will also be discussed in this part.
- **Section 8 - Conclusion:** This section aims to describe the most important results and findings from this master's thesis.
- **Section 9 - Further Work:** This section aims to provide a foundation for further work that was not included in this master's thesis. It will act as a starting point for the continuation of the work conducted.

This master's thesis is built on the foundation of previous work conducted in the specialization project of December 2022 [16]. Parts of the Introduction and Background sections of this thesis have been reformulated, extended and/or constructed using selected parts of the specialization project, the intent being that the master's thesis is a self-supporting piece of work that can be used independently of other projects. Still, it is important to clarify that these specific parts of this thesis will include some similar elements to the specialization project mentioned.

2 Background

Background knowledge is a fundamental part of any scientific study. It provides a foundation for further understanding of the topics being investigated. To get a more nuanced perspective of the research field, one must review a broad perspective of existing literature and research. The knowledge obtained from previous work lays out a benchmark for further studies on the topic. In addition to this, the examination of existing literature is an important process of gaining a thorough understanding of the past and present state of things. In this chapter, the development of EVs both globally and nationally will be investigated further. The progress of battery technology and charging infrastructure will also be explored in this part. Furthermore, the basis of the Norwegian power grid will also be explained. Both the topics of general grid structure, grid planning and the reliability of the power grid will be examined, along with introductions to grid flexibility and grid simulation tools. Henceforth, the existing literature on V2G technology will be investigated.

2.1 Electric Vehicles

In a world where the focus is increasing on cutting greenhouse gas emissions, the share of EVs internationally has multiplied rapidly for the past decade. This is also confirmed by the Global Electric Vehicle Outlook of 2022 produced by the International Energy Agency (IEA) [17]. This section will contain information on the global development of EVs. The section will also cover the situation of EVs in Norway. Furthermore, the section will include the present technology related to EV charging and the battery technology being utilized by EVs today.

2.1.1 The Global Development of Electric Vehicles

Through the Electric Vehicles Initiative of 2010, the Clean Energy Ministerial has gathered many of the world's most influential countries all over the world [17]. The goal is to accelerate the adoption of EVs all over the world by tracking and monitoring the progress of electric mobility worldwide, as well as consulting countries to make the best decisions for EV integration. Since the start of the initiative, the growth of EVs on a worldwide basis has been growing almost exponentially. As stated by [17], the sales of EVs in 2021 doubled from the year before, bringing the total number of electric cars globally to 16.5 million vehicles. This indicates the rapid growth of EVs globally, as the total number of EVs has tripled since 2018.

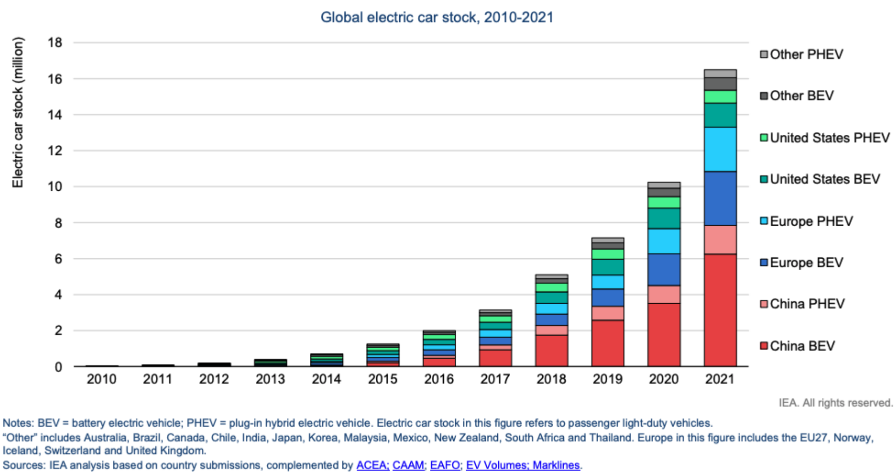


Figure 1: The global electric car stock between the years 2010 and 2021 [17].

Figure 1 depicts the evolution of the global electric car stock from 2010 until 2021. It is observed that larger countries such as China and the US are the leading countries in total BEV and PHEV stocks globally. Europe, while also holding a respectable share of EVs globally, has almost as many plug-in hybrid vehicles (PHEVs) as purely battery-powered vehicles (BEVs). China's largest share of EVs are purely battery powered, and thereby responsible for less greenhouse gas emissions. However, the energy mix in China is largely dependent on coal and oil for power production [18]. In Europe, the energy mix is more differentiated and consists of a larger share of renewable energy sources [19]. To reach the goals of the climate agreement from Paris in 2015 [20], the world needs a combination of both clean transportation and a renewable energy mix.

The projection for EV shares in the years to come implies continuous growth globally. Statistics from [21] show an increase of EV sales globally to increase with 227 % from today until 2027, with BEV sales amounting to 82.3 % of the total sales of EVs. This continuous growth in EVs poses the question of whether the power grid infrastructure can withstand such a demand for electricity. This question will be further investigated in Section 2.2 and Section 2.3.

2.1.2 Electric Vehicles in Norway

The global development of EVs seems also to affect the Norwegian light-vehicle fleet. The EV sales for the first quarter of 2022 are just one of many record-setting sales quarters lately in Norway for light vehicles. By March 2022 the total number of EVs sold in Norway amounted to 83.7 % of all the cars that were sold in total [22]. The goal of the national transport plan created by the Norwegian government is well within reach, being that all cars sold by the year 2025 should be emission-free [10]. The fact that 19 of the 20 most sold car models in Norway are EVs, per January 2022, confirms that the substantial transformation towards an all-electric transportation fleet already is underway [22].

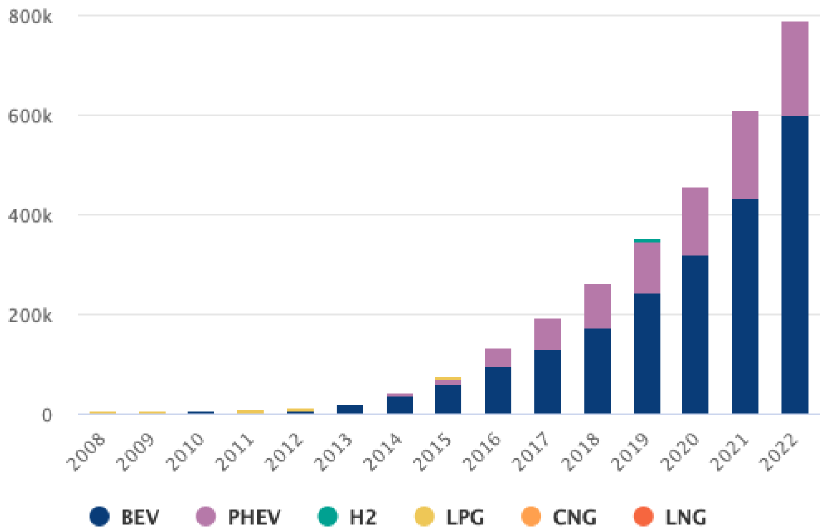


Figure 2: The registered Norwegian alternatively fuelled vehicle stock between the years 2008 and 2022 [23].

It is safe to say that the amount of EVs has been growing a lot in the last few years. As observed in Figure 2, the increase in EVs is almost exponential during the years between 2008 and 2022. It is evident that there is a correlation between the global development of EVs seen in Figure 1 and the national development seen in Figure 2. The development seen in Figure 2 also depicts an exponential increase in both BEVs and PHEVs, although the number of PHEVs are significantly less than BEVs.

2.1.3 Charging Technology

The extensive growth of EVs worldwide has also accelerated the search for new solutions regarding charging technology. Through the development of new charging solutions, a new way of utilizing the potential of EV batteries has been discovered. V2X, also known as Vehicle-to-X or Vehicle-to-anything, provides opportunities for a wider area of application for EV batteries. Applications such as two-way charging with EVs are one of the most prominent applications that this new technology can offer. The V2X technology is based on the functionality of two-way communication between a vehicle and the object it is connected to, and the opportunity for the EV to affect or be affected by other connected components. There are already multiple variants being investigated such as V2I (Vehicle-to-Infrastructure), V2V (Vehicle-to-Vehicle) and V2G (Vehicle-to-Grid) [24]. These new technologies can provide a larger range of benefits such as more road safety, traffic efficiency and energy savings. Studies have also been conducted combining the V2X concept with the new 5G communication technology, where linking enabling technologies for V2G technologies along with 5G have been investigated. As stated in [25], the possibilities for increased use of AI models are also mentioned as a technology that can benefit the development of V2X appliances. The possibilities for smart communication between vehicles and other connected elements will only increase as a result of advancements in communication technology and the progress of artificial intelligence. New applied sciences of intelligent networks and cloud data processing will accelerate these opportunities even further, according to [25].

The charging infrastructure is in constant development. In the dawn of the electric transportation era, the most common alternative in Norway has been to charge personal vehicles through a standard 230-volt outlet. In recent years, the battery capacity of EVs has increased, leading to higher demand in terms of the capacity of electrical sockets found in most houses. This has raised questions about whether standard residential outlets are built to handle such an increase in power demand. The fear of underdeveloped electrical outlets and the dangers of electrical malfunctions and electrical fires has sparked a change to the standards of the Norwegian electrical installation manual. The standard of electrical installations created by the Norwegian Electrotechnical Committee (NEK) was recently updated with changes stating that charging from a common electrical outlet will now be illegal from the end of 2022, although emergency charging will still be accepted [26]. The rules are now providing incentives for people to acquire specially designed charging ports designated for the sole purpose of charging their EVs privately in their homes. This limits the potential dangers of malfunctions of electrical components and the potential dangers of electrical fire. The new charging stations not only offer a safer alternative for EV charging, but they can also reduce the amount of time at which householders charge their EVs.

Vehicle-to-Grid (V2G) is the technology enabling vehicles to receive power themselves and deliver power back to the grid. This technology can be useful to act as a backup power supply during grid interruptions. Other beneficial aspects of V2G technology can be the financial aspect related to charging or the ability to enable fast frequency responses to the grid. As the world grows more dependent on unreliable power sources such as solar- and wind power, the need for fast-frequency response appliances to stabilize the power grid will only increase. This is an area where the V2G technology can be particularly useful. Evaluation of the vehicle-to-grid technology shows that the development and integration of fast-frequency-response solutions so far have been limited. Considering the most common charging points used worldwide, V2G is currently only supported by one charging type [27]. For reference, the most common charging types and their V2G appliances are listed in Table 1. The installation of one-way EV chargers can be done by using existing or new facilities. V2G chargers can be installed similarly, but need a more detailed assessment of existing facilities. However, V2G-chargers may require improved communication or continuous metering if they are used to support grid services such as fast frequency response [27].

Name	Standard	Supports V2G
Type 1	SAE J1772-2009	No
CCS Combo 1	SAE J1772-2009	No
Type 2, Mennekes	IEC 62196/SAE J3068	No
CCS Combo 2	IEC 62196	No - planned
CHAdeMO	C601, IEC 62196	Yes
Guobiao	GB/T 20234	No
Tesla	N/A	No

Table 1: EV charger standards [27]

2.1.4 Battery Technology

The most commonly used battery type for both EVs and PHEVs today is the lithium-ion battery [28]. The lithium-ion battery has a high power-to-weight ratio, which makes it ideal for weight limitation on vehicles. Vehicles with less weight will reduce both their overall wear and tear, as well as their fuel consumption. The lithium-ion battery also contributes to high energy efficiency, which ultimately reduces vehicle costs. The lithium-ion battery also performs well under high-temperature conditions, which is important for a year-round EV. As an added bonus, the lithium-ion battery also has a low self-discharge rate, making it resistant to losses of power when the vehicle is unused.

In addition to the lithium-ion battery, there are also several other types of batteries that are being used in vehicles. The nickel-metal hybrid battery has been widely used in hybrid EVs due to its safety and long life cycle. The main drawbacks of the nickel-metal hybrid battery are its high cost and high self-discharge rate. The overheating at high temperatures and the need to control hydrogen losses are also disadvantages related to this battery type. Another battery type that is commonly used is the lead-acid battery. The lead acid battery is typically of low cost, safe to use and very dependable. The downside of the lead-acid battery is its short life cycle, combined with reduced capabilities in lower temperatures, as well as low energy density. Additionally, one might also mention ultracapacitors as another option for EV batteries. The ultracapacitor uses polarized fluids connected to an electrolyte and an electrode. The ultracapacitor are very energy dense and can provide extra power boosting for acceleration and uphill driving while also being able to restore large parts of braking energy. The ultracapacitors can be very useful as secondary storage in EVs as a provider of energy balance, supplementing the conventional chemical batteries [28].

As the area of use for batteries increases, the development of more efficient and cheaper batteries will accelerate. The economic aspect of the batteries will also probably improve in the future, making EVs a competitive alternative to fossil-fueled vehicles. Looking at the prices of lithium-ion batteries for EVs, it is evident that the prices have already decreased massively. The prices of a lithium-ion battery in 2010 costed 1100 USD, while the price of the same battery was a mere 156 USD in 2019 [27]. This is a reduction of 85.7 %. The most common type of EV battery is the lithium-ion battery today, and the IEA reports that this will probably still be the case in the next decade [17]. The reason for this trust in lithium-ion batteries is due to several factors, such as well-established technology, large investments and low readiness for alternative technologies [27].

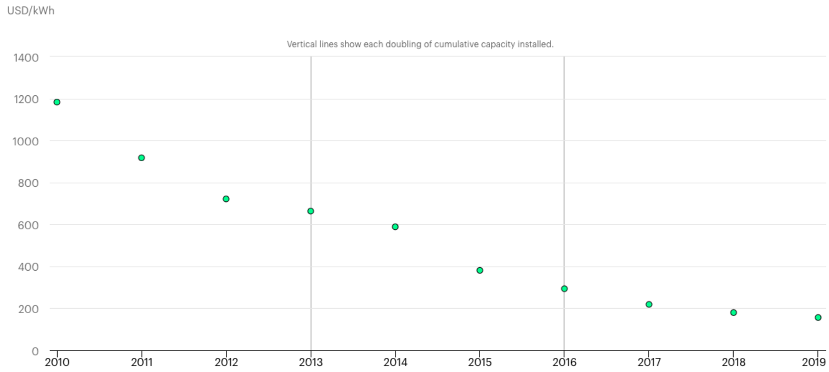


Figure 3: The development of prices regarding lithium-ion batteries for EVs between the years 2010 and 2019 [29].

2.2 The Norwegian Power Grid

The Norwegian power grid is an essential part of the basic infrastructure in Norway. The grid is responsible for the safe and reliable distribution of electricity to all Norwegian households and industries. The growing need for more electricity has been central to the continuous development of the power grid, and the new movement towards more renewable energy resources has provided more incentives for further expansion of the grid. As renewable energy sources such as solar and wind require large areas for production, the production sites have been pushed to more remote locations. Another reason for choosing distant locations for power production has also been due to the increasing resistance among Norwegian inhabitants being situated next to larger production sites [30]. As a consequence of the choice of energy production locations, the power needs to be transported from where it is produced to where it is consumed. This transportation can often be over vast distances, as most of the electricity consumption is needed in the larger cities in Norway. This needs to be done safely and with minimal losses of energy along the way. This is the main purpose of the power grid. Throughout this section, the different characteristics of the Norwegian power grid will be explained, along with the methods of planning for the future of the power grid. Potential challenges and obstacles to the power grid in the future will also be discussed in this part.

2.2.1 Grid Structure

The Norwegian power grid consists of three main grid types: The transmission grid, the regional grid and the distribution grid [31]. The transmission grid is used for the national transportation of power. The transmission grid is called the central grid and is often referred to as the "national freeway" of electricity. It is also used for international transportation of power. The transmission grid is operated with the highest voltage of all the grid types and typically has a voltage of 420 or 300 kV. The distribution grid is responsible for the local transmission of energy before the electricity reaches the customer. The distribution grid is normally operated with the lowest voltage of all the grid types and typically has a nominal voltage between 22 kV and 230 V. The regional grid is often used as the connection between the transmission grid and the distribution grid, and the regional grid is typically operated with voltages between 45 and 132 kV [32].

The power grid is operated with a high voltage level for transmission. This is to minimize the current in transmission, hence also the power losses in the transmission lines. Over long distances, the power losses can be significant. Typically, the power is produced and transformed up to the desired level of transmission voltage. Then, the power is transported through the transmission grid. With the use of transformers between the grids, the voltage is stepped down to a lower level. From the transmission grid to the regional grid to the distribution grid, the voltage is reduced from high voltage to low voltage, leaving the consumers at the end of the distribution grid with appropriate voltage levels for everyday consumption, typically at 230 V. It is worth mentioning that certain industry buildings require larger voltage levels and have a high demand for power to operate their facilities, and can therefore sometimes be connected directly to the regional grid.

2.2.2 Grid Planning

Thorough grid planning is essential for a robust electrical infrastructure. Handling the uncertainty in production and loads while being constrained by transmission line capacities is no simple process. Both technical, economic and social factors need to be considered when planning new grid solutions. SINTEF Energy Research has provided a systematic approach to the planning of grids in [33]. In [33], the first step of the grid planning approach is the establishment of prerequisites for further analysis. At the beginning of the planning process, the motivation for the grid development needs to be clarified, along with a detailed overview of the grid area. Further, an analysis of production and loads in the area needs to be examined. In addition to this, the benefits of the alternative solution must be weighed up against existing infrastructure solutions. From this, a technical analysis must be performed of the alternative solution. This analysis can contain a detailed simulation of aspects such as load flow analysis, reliability analysis and voltage stability analysis, and some of these focus points from grid planning will also be conducted in this thesis. If the new grid solution passes these tests, then the grid project needs to be analyzed in terms of cost. Both operational and construction costs need to be examined in order to conduct a thorough economic examination. Finally, the proposal for the new grid plan needs to be formalized and provided with final documentation.

As a consequence of the Norwegian Energy Law of 1991, the TSO in Norway (Statnett) was granted a greater responsibility for the economy and the efficiency regarding grid planning [33]. Today, grid operators are imposed by the government to follow certain objectives, some of them being:

"***The Act shall ensure that the generation, conversion, transmission, trading, distribution and use of energy are conducted in a way that efficiently promotes the interests of society, which includes taking into consideration any public and private interests that will be affected.*** [33]"

To achieve these goals, it is important for the TSO to invest time and resources into an extensive grid planning process before progressing with new grid solutions. With the electrification of Norway in recent years, the focus on the security of supply has been strengthened. To ensure that the power flowing in the grid arrives at its destination, the TSO must design the grid in a way that can handle everyday operations, as well as handling unforeseen and the most extreme of situations. This is a careful deduction of risk versus efficiency. The TSO must evaluate costs related to investment, operation, losses, interruptions and bottlenecks. Meanwhile, the laws and regulations of the grid also need to be upheld at any given moment.

In grid planning, the focus has been to enhance the cables to endure the so-called "worst-case" scenarios, as described in [34]. These scenarios would often be based on the maximum load demand possible in a certain area. Although sufficient, these planning methods are not very optimized, nor fitting to the actual consumption patterns on a day-to-day basis in reality. The probability of peak consumption is always present, although it is very low. Studies conducted by [35] has shown that there is only about 67 % exploitation of the grid structure about 50 % of the time of the actual grid capacity in Norway. This means that 33 % of the capacity in the grid is left unused 50 % of the time [35].

In the future, the demand for electricity will most likely increase. Concerns of whether the current power grid can handle future electrification have already been raised [36]. New solutions need to be explored for the benefit of the power system and the reliability of supply in the future. The capacity could be exploited more in the future, given new technology such as advanced cable sensors. Other important resources to keep the power grid in balance are spinning reserves. These are stand-by, or "spinning", sources of generation that are able to respond after a short time by signals from the grid for increased production [37]. The continuous expansion in renewable energy sources contributes to more variability in grid operation, thus providing a more urgent need for flexibility. The battery capacity of EVs can play an important role in the future of power system operation, but the consequences of V2G on grid reliability need to be investigated before implementations of

V2G solutions are made.

2.2.3 Reliability of Supply

In this section, the source material has been collected from SINTEF Energy Research's handbook for grid planning [33]. The definitions of terminology have been collected from [38]. Terminologies are mainly given in Norwegian, but this thesis has attempted to make its own interpretation in English of the definitions given. The terminologies in this thesis might be slightly nuanced from the definitions provided in [38] due to translation.

One of the most important aspects of grid planning is to ensure reliability of supply. Reliability of supply is defined as the ability of the power system to provide electrical energy to its end user. The energy law recited by [33] in the chapter on grid planning emphasizes the importance of socioeconomic optimal quality of delivery. The optimal quality of supply is defined by the minimization of total socioeconomic costs such as:

- Investment costs
- Operational- and maintenance costs
- Costs of losses
- Interruption Costs
- Congestion costs

The development of the KILE arrangement of 2001 enhanced the importance of interruption costs with the grid operator. KILE (kvalitetsjusterte inntektsrammer ved ikke levert energi) is defined as quality-adjusted revenue frameworks in the case of non-delivered energy. Non-supplied energy is defined as the calculated amount of energy that would have been delivered to the end user had the interruption not occurred. Interruption is defined as the lack of supply of electrical energy to one or more end users, where all the supplied voltages are below 5% of the agreed voltage level. The interruptions are distinguished between notified and non-notified interruptions. Interruption separates from the term failure, which is defined as a lack of ability to fulfill certain supply demands. Failure and fault are frequently used interchangeably but have different meanings. While failure is defined as a lack of ability to fulfill demands of supply, a fault is a lack of ability to fulfill certain supply standards due to internal conditions. A fault can be the result of a failure, either on the unit itself or due to a latent fault from an earlier point in time. While failure is an event, the fault is a state. These malfunctions in the grid lead to something called repair time, which is the time from the start of repair until the grid elements' function is restored and ready for operation. When talking about interruptions, failures and faults, they all describe a lack of delivering a supply of power according to certain demands. A demand can often be related to the quality of delivery, which is a superior term for several subgroups such as voltage quality, service or information. Voltage quality is defined as the quality of voltage given certain requirements. These requirements can for instance be related to voltage frequency, voltage RMS value or the symmetry of the voltage signal.

2.2.4 Flexibility

Flexibility, in relation to power system operation, is defined as the ability to modify the production, or consumption pattern, often as a response to an external signal, to provide a service for the grid or to ensure the security of supply [39]. This can for instance be dependent on the price signal in the market, indicating the balance of supply and demand. A flexible consumer measure can be to lower or completely cut off consumption in periods of either low production or high demand in the power grid. Flexibility can come with several benefits. One of them is more even distribution of load profiles, avoiding the highest power peaks in the grid. This can contribute to reduced costs for the consumers, as well as reduced losses and better utilization of the grid for the TSO.

There are different forms of flexibility. Some of them are load shifting and valley filling which are applied by shifting the load consumption demand from high-demand periods to low-demand periods. This will often coincide with moving the load to low-price periods of time since this is a signal from the market of low demand in the grid. Another method is peak clipping which is active control of the consumers' load usage to lower the total peak. Strategic conservation can also be used to lower the overall consumption volume of the load demand. Examples of these methods are illustrated in Figure 4.

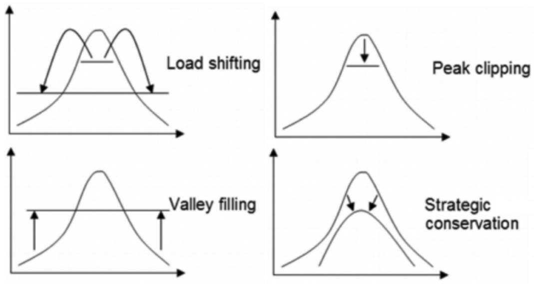


Figure 4: Illustration of the different types of consumer flexibility [40].

A report from Statistisk Sentralbyrå [41] has illustrated the average power consumption curve of a Norwegian household. The proposed load curves for each hour of the day are indicated in Figure 5.

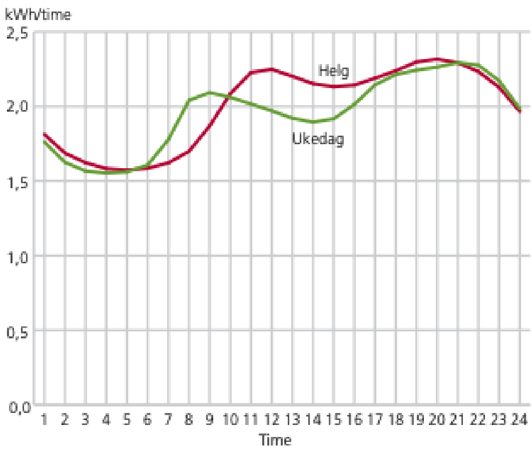


Figure 5: Illustration of average load profile for Norwegian households. The red curve is the load profile for weekends and the green curve is the load curve for weekdays [41].

As seen from Figure 5, there are certain peaks of power consumption during the day in Norwegian households. Especially the periods between 06:00 and 09:00 and between 15:00 and 23:00 for weekdays are peaks during the day in which flexibility methods could be an efficient measure to reduce the highest peaks.

2.2.5 RELSAD

As the power system becomes increasingly more complex, advanced simulation tools are necessary to analyze grid operation properly. One recently developed tool for this is called RELSAD, which is short for RELiability tool for Smart and Active Distribution networks [4]. This is a Python-based reliability assessment tool that seeks to function as a foundation for the reliability calculation of modern distribution networks. RELSAD is designed for open use and can be utilized by scientists, engineers and Distribution System Operators (DSO) for the planning and operation of modern distribution systems. RELSAD facilitates Monte Carlo simulation-based reliability analysis of modern power grids and sequential simulation of the grid behavior. The algorithm allows for user-specified inputs such as attributes for grid topology, load data management and simulation settings. The package supports user-selected time increment steps over a user-defined time period. The tool allows for the integration of active components such as microgrids, distributed generation, batteries and electric vehicles. RELSAD offers many useful features. One of them is a foundation for calculating the reliability of modern, high-complexity distribution networks. Another is the opportunity for extensive reliability analysis to provide a complete picture of the power system and the components in it. The tool also implements the use of active grid appliances and Information and Communication Technology (ICT) systems.

The need for tools like RELSAD in today's power system operation is evident as DSOs are dealing with increasingly more complex networks. With the introduction of more local production of renewable sources such as wind power and solar power, the operation of the grid needs to be analyzed using the appropriate tools. RELSAD also provides modeling of EV charging stations with V2G properties. As more variability from renewable sources enters the energy mix, new situations affecting the power system reliability will occur. Tools that are able to provide thorough reliability analysis of power systems will in the future be absolutely crucial for maintaining the security of supply in power systems. RELSAD is one of these tools and can be used for additional power system analysis as well. Compared to traditional power system analysis methods, RELSAD accounts for the complexity and time dependencies that occur in modern distribution systems.

The RELSAD program allows for the creation of different electrical components to construct a full-size power system model. The components that are used to create the basic power system fundament are the bus and lines. These are basic components of the RELSAD power system object, and allow users to specify the topology of the grid. In addition to the basic components of buses and lines, there are also a set of additional components which can be specified for each bus or line. For bus objects, this pertains to production units, electrical vehicles and batteries. For the line objects, the related components are circuit breakers and disconnectors. These components and the relation between them have been visualized by the illustration in Figure 6.

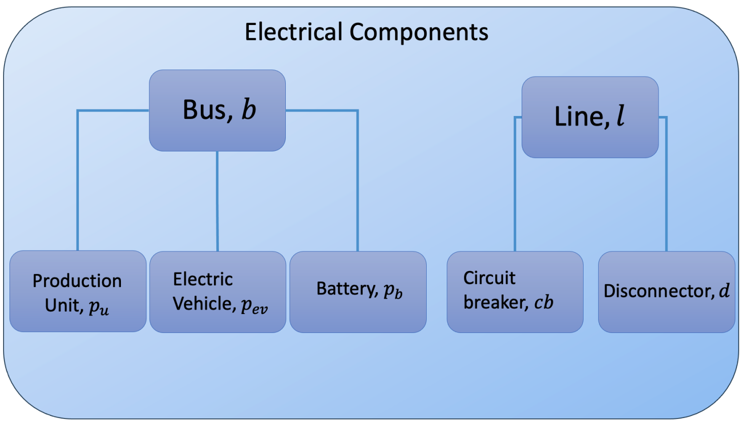


Figure 6: Illustration of electrical power system components in RELSAD. The figure is created based on [42]. Full overview can also be found in the RELSAD documentation [43].

The RELSAD simulation works on certain input values. To successfully run a Monte Carlo simulation of a system, the input values have to be specified. These input values are topology attributes, reliability attributes and component-specific attributes. Followingly, the input values will be considered during the Monte Carlo simulation process. During this process, load flow, minimization of load shedding and gathering of reliability data will be conducted. Finally, the results from the Monte Carlo simulation are collected in reliability index distributions. The process of simulation in RELSAD is also illustrated in Figure 7.

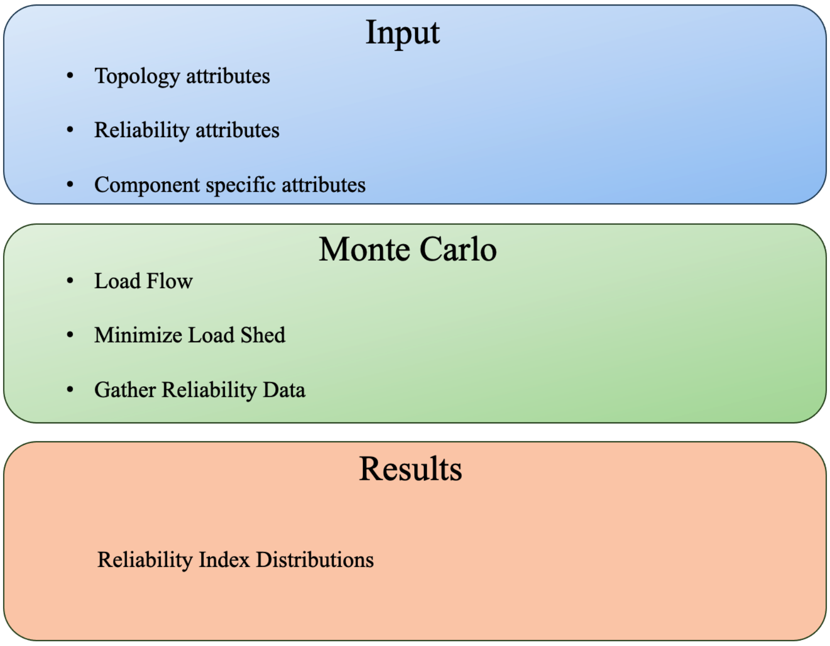


Figure 7: Illustration of the structure of inputs, Monte Carlo simulation and results in RELSAD. The figure is created based on [42]. Full overview can also be found in the RELSAD documentation [43].

2.3 Literature on Vehicle-to-Grid Technology

Vehicle-to-Grid, or V2G, describes a system that utilizes the services an EV can provide to the grid while connected. This can be services such as fast frequency response, flexibility services or demand scheduling. The V2G technology is often implemented using two-way communication technology between the vehicle and the grid operators. Some of the known studies on V2G technology and its implementation will be presented. This section aims to give a perspective of where the V2G technology is today, but also provide a vision of what might be possible as further solutions in the future of V2G.

2.3.1 The Use of V2G for Residential Charging

A review found in [2] discusses the impact of EV integration with the grid system. The integration of electric vehicles in the power grid provides many advantages such as the balancing of load. With the large amount of battery potential in the EVs, the possibilities for flexibility in loads provide many possibilities for load shifting. Another positive aspect of V2G technology is the potential for active power regulation from the battery of the EV. The EVs also bring in more potential spinning reserves along with frequency regulation, benefiting peak demand reduction and utility operating costs for the grid operator.

Although the possibilities for EV flexibility services mostly are positive, there are some challenges. The results found in [2] raise concerns regarding the voltage stability and quality when introducing EV charging. On a distribution level, the challenges related to power quality, harmonic distortion and unbalanced voltages are highlighted in several research studies of today. The load impact of many households charging their EVs simultaneously will bring new challenges related to grid capacity. Environmental changes are also complex challenges requiring thorough investigation before acting. Although the idea of emission-free transport is regarded as sustainable, the expansion of grid infrastructure is currently not an emission-free process. Many large countries such as India are still dependent on fossil resources such as oil, gas and coal to produce a major part of their electricity [44]. This environmental estimation needs to be accounted for in the investment toward an electric future.

Another aspect of the V2G charging technology is the impact on the EV batteries' life span. The main concern regarding V2G technology has been the accelerating degradation of the lithium-ion batteries used in EVs as a result of frequent charging and discharging. This concern is also backed up by literary research conducted in [45] explaining that rapid and ultra-rapid charging of EVs causes more degradation than fast charging, although this degradation is limited to an extent by battery management systems. However, actual studies of V2G operation with EVs conducted in [46] claim that the proposed charging strategies only mitigate the aging process from 7.3 - 26.7 % for the first 100 days and gradually vary to 8.6 - 12.3 % for one-year continual operation, compared to the reference standard charging approach. For the conventional operation of different EVs, the average degradation for a large number of vehicles is expected to be around 2.0 % [47]. The battery degradation is certainly not accelerating over time as fast as first feared, as [46] confirms, but the increased degradation from V2G is a genuine problem.

Although rapid charging seems to be an issue amongst EV users regarding the span of useful battery life, other methods are being tested to exploit the untapped potential of EV batteries. One of which is the electrification of Tiller Videregående Skole in Trondheim. This building is equipped with solar panels on the roof and produces its own energy when the sun is shining [48]. The solar panels are planned to be used in collaboration with the installation of recycled EV batteries. By installing stationary EV batteries in the building, the EV batteries are able to recharge when solar production is high and store energy for later. When the electricity prices are rising, the building can supply itself with stored energy from the EV batteries, thereby reducing the costs of operation. In this way, the problem of battery degradation is less of an issue since the batteries are stationary. In addition to this, the building is also connected to the grid, which provides additional supply when the battery levels are low. Therefore, there is no problem with EVs leaving the building at unfavorable timing since the batteries are installed permanently. The batteries of used EVs provide a much cheaper installation cost compared to using new batteries and are expected to provide a minimum of ten years of efficient energy storage, according to the supplier of the batteries, Eco Stor [49].

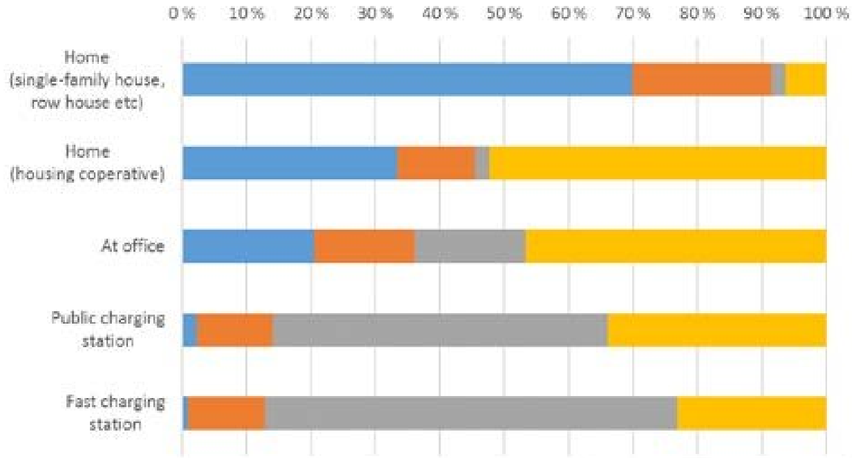
Studies shown in [2] also emphasize the helpful attributes of V2G charging regarding renewable power production. In the development of more sustainable forms of electricity production, power generation will also become more uncertain and oscillatory. Based on the volatility of changing weather, power sources such as wind and solar will require more from the consumer side of the grid, and the V2G integration provides a more flexible and interchangeable load system that benefits renewable production. The discharging of batteries will be able to counter the irregularity of renewable power generation.

A study conducted in [50] utilizes real-world data from a residential neighborhood in Trondheim to investigate the potential for EV flexibility. In this study, the nature of charging patterns and load profiles pertaining to EV charging has been analyzed. Charging habits such as plug-in and plug-out times, power consumption and idle charging were investigated. The study supports the claim that EV charging is a main source of flexible electricity use in apartment buildings. Some of the other conclusions were that idle charging time for cars with private charging was double that of cars with shared charging points. Idle charging when the EV battery is connected to the grid but not charging will provide the optimal potential for EV flexibility. The results of [50] implies that the potential for flexibility will be better for private EV charging compared to shared vehicle charging.

A study in [51] uses RELSAD for analyzing sensitivities of V2G implementation in modern distribution networks. There are several interesting discoveries in this article, one of them being that EVs clearly impact the grid's reliability. However, it is mentioned that the EVs are more suitable for short downtime periods and in combination with other sources, such that they can work as a backup solution for the grid. The studies conducted in [51] provide a good foundation for further investigation of the V2G impact on distribution grids. The study also provides a test of the RELSAD package and confirms that the tool works as intended.

2.3.2 Norwegian Charging Habits

The way that electricity is produced and consumed is changing. Renewable energy sources will become a larger part of the producing side. Traditional consumers are developing into prosumers, a consumer that not only consumes but also produces power. The increase in local production will provide more opportunities for flexibility in the power grid. Resources like energy storage systems, electric vehicles and demand response all provide services that can benefit the reliability of supply, power quality and power capacity in the power system, according to [52]. There are several studies made regarding the potential for using EVs as integrated parts of the power grid. The results presented by [53] are supportive regarding the potential for flexible demand response related to EV charging. Reference [53] states that the non-emission transport scenario of 2030 will be a capacity-related problem rather than an energy-related problem. This is due to the simultaneous EV-charging of households predicted, amounting to high peaks given the predicted growth of the number of electric vehicles in the future.



	Fast charging station	Public charging station	At office	Home (housing coperative)	Home (single-family house, row house etc)
Daily	1 %	2 %	21 %	33 %	70 %
Weekly	12 %	12 %	16 %	12 %	21 %
Monthly or less often	64 %	52 %	17 %	2 %	2 %
Never	23 %	34 %	47 %	52 %	6 %

Figure 8: The charging behavior among Norwegian EV owners in 2018 conducted by Elbilforeningen in collaboration with the ModFlex project [53].

References in [53] recites a survey conducted by the Norwegian Elbilforeningen in collaboration with the ModFlex project asking Norwegian EV owners where they prefer to charge their EVs. Figure 8 illustrates the responses from the survey related to charging behavior. The charging alternative that is most frequent among EV owners is home charging, with 59 % of the group answering that they charge in private houses daily. On the other hand, the EV owners respond that they use public charging stations and fast charging stations monthly or less often 68 % and 51 % of the time, respectively. This can indicate that the potential for EV flexibility is better for home applications rather than at public charging stations.

3 Theory

In this section, the relevant theory to the scientific work is presented. The basics of power flow and power system operation are introduced, as well as the methods for grid planning such as Monte Carlo simulation and grid reliability factors. The methods will only be explained on a basic level, as the understanding of these topics is not a necessity for comprehending further work in this thesis. The theory will rather act as a supplementary overview of the fundamental concepts that are being used later in this thesis.

3.1 Power Flow Analysis

The power flow analysis is the foundation for any study of electrical power grids and their behavior. Through the power flow equations, one is able to understand the cause of power flow and the characteristics of grid behavior. To be able to calculate the power flow, a basic understanding of certain bus types is needed. There are in principle three kinds of bus types when studying a grid using power flow methods. The bus types are defined by their known quantities from a set of four factors. These factors are voltage angle (δ), voltage magnitude (V), active power injection (P) and reactive power injection (Q). The different bus types and their characteristics are presented in Table 2.

Bus Type	**Known quantities**	**Unknown quantities**
Slack Bus (SB)	V, δ	P, Q
Generator Bus (PV)	P, V	Q, δ
Load Bus (PQ)	P, Q	V, δ

Table 2: Bus type characteristics for power flow methods.

The slack bus is the voltage-controlling bus of the network and its known quantities are typically specified to a voltage magnitude of 1 p.u. and voltage angle of zero degrees. The generator buses are typically specified with known quantities for active power injection and voltage magnitude. Load buses have known values pertaining to active power injection and reactive power injection.

For studies of electrical grids, numerical power flow calculations are used. The power flow equations are deducted from the basic laws of physics and electricity. From the voltages V of the grid with associated voltage angles, the admittance matrix Y and the current injections I at each bus i, an expression for the complex power in each bus can be formulated. Using [54] and [55] the procedure of finding the load flow equations will be presented. Starting with the net complex power injected to a bus i being:

$$\overline{S_i} = \overline{V_i} \cdot \overline{I_i^*} \tag{1}$$

where $\overline{V_i}$ is the voltage at bus i, I_i^* is the complex conjugate of the current injection into bus i and $\overline{S_i}$ is the complex power at bus i. Kirchoff's law for current states that the sum of currents into the bus must be equal to the sum of currents out of the bus. Using this law, the following expression can be obtained for the current $\overline{I_i}$:

$$\overline{I_i} = \sum_{k=1}^{n} \overline{V_k} \cdot \overline{Y_{ik}} \tag{2}$$

As Kirchoff's law states, the net sum of currents flowing in and out from a bus must be equal to zero, which is also represented by Equation 2. In Equation 2, $\overline{Y_{ik}}$ is the element from the admittance matrix pertaining to the line between bus i and bus k. Hence, $\overline{V_k}$ is the voltage magnitude at bus k. Inserting Equation 2 into the expression for complex power yields:

$$\overline{S_i} = \overline{V_i} \cdot (\sum_{k=1}^{n} \overline{V_k} \cdot \overline{Y_{ik}}) = \sum_{k=1}^{n} \mid V_i \mid\mid V_k \mid\mid Y_{ik} \mid \angle(\delta_k - \delta_i - \theta_{ik}) \tag{3}$$

where δ_i is the voltage angle at bus i, δ_k is the voltage angle at bus k and θ_{ik} is the angle between buses i and k. The active and reactive power is defined as:

$$P_i =\mid S_i \mid \cos\left(Im(S_i)\right) \tag{4}$$

$$Q_i =\mid S_i \mid \sin\left(Im(S_i)\right) \tag{5}$$

Where P is the active power at bus i and Q is the reactive power at bus i. Separating the complex power expression in Equation 3 into real and imaginary parts using Equation 4 and Equation 5, the result is the power balance equations in Equation 6 and Equation 7.

$$P_i = \sum_{k=1}^{n} \mid V_i \mid\mid V_k \mid\mid Y_{ik} \mid \cos(\delta_i - \delta_k - \theta_{ik}) \tag{6}$$

$$Q_i = \sum_{k=1}^{n} \mid V_i \mid\mid V_k \mid\mid Y_{ik} \mid \sin(\delta_i - \delta_k - \theta_{ik}) \tag{7}$$

where P_i is the net active power injected at bus i and Q_i is the net reactive power injected at bus i, V_i and V_k are the voltages at their respective buses i and k. Y_{ik} is the admittance matrix element in relation to bus i and k, while δ_i and δ_k are the voltage angles at bus i and k and θ_{ik} is the angle element of the admittance matrix pertaining to the angle between bus i and k.

From the power balance equations, a linear system of equations can be expressed as

$$\begin{bmatrix} \Delta P \\ \\ \Delta Q \end{bmatrix} = J^{-1} \begin{bmatrix} \Delta\theta \\ \\ \Delta \mid V \mid \end{bmatrix} \tag{8}$$

where $\Delta\theta$ is the change in voltage angle, $\Delta \mid V \mid$ is the change in voltage magnitude, ΔP is the change in active power and ΔQ is the change in reactive power. J is a matrix of partial derivatives known as the Jacobian:

$$J = \begin{bmatrix} \frac{\partial \Delta P}{\partial \theta} & \frac{\partial \Delta P}{\partial |V|} \\ \\ \frac{\partial \Delta Q}{\partial \theta} & \frac{\partial \Delta Q}{\partial |V|} \end{bmatrix}$$

The system of equations can be solved using different methods. The Newton-Raphson solution methodology is the most commonly used approach, but methods like the Fast-Decoupled-load-flow method and the DC power-flow method are also widely used for power flow calculations [54].

3.2 Monte Carlo simulation

The Monte Carlo method is the general term for stochastic simulation using random numbers [56]. For a complex system like the power system, there are a lot of uncertainty factors to take into account when trying to simulate power system operation. To model the failure rates of lines, transformers and buses, the Monte Carlo method is an effective tool to approach real-life situations. The Monte Carlo method draws random numbers generated either mathematically or physically to represent different outcomes of statistical uncertainty factors. When this process is repeated a sufficient number of times, the average value of the outcomes will converge toward an estimate of real-life events. The mathematical method is most common as it can guarantee reproducibility and can easily be performed on a digital computer.

A random number generated by a mathematical method is strictly speaking not really random and is therefore referred to as a pseudorandom number. The basic requirements for a random number generator are uniformity, independence and long periods. Uniformity pertains to the fact that the random numbers should be uniformly distributed between $[0, 1]$. Independence means that there should be a minimal correlation between random numbers. Long periods ensure that the repeated period is sufficiently long. The Monte Carlo method provides numerical results, and their average values will converge towards more accurate estimates proportionally with the number of samples included [57]. The method is widely used to make an assessment of risk. In this case, the method will mainly be used for grid planning and interruption modeling. By simulating statistically generated interruptions with arbitrary downtime, one can study the potential for EVs as V2G resources in the grid during failure.

3.3 Statistics and Methods

This section presents the most important statistical measures and methods which will be used to analyze the results of this thesis.

3.3.1 Standard Deviation

The standard deviation is a measure of the spread or variability for a set of data. If X is a stochastic variable taking values from a finite data set $x_1, x_2, ..., x_N$, the standard deviation can be written as:

$$\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i - \mu)^2} \tag{9}$$

where μ is the mean value of X.

Standard deviation can be used as a measure of dispersion and is often used to determine the statistical significance of a data set. The lower the number of standard deviation, the closer the values are to their mean value [58].

3.3.2 Variance

In statistics, variance is the squared deviation from the mean of a random variable. The variance is defined as:

$$Var = E[(X - \mu)^2] \tag{10}$$

The variance is also known as the square of the standard deviation. It describes the dispersion of the data from its average value [59].

3.3.3 Standard Error

Considering a statistically independent sample of n observations $x_1, x_2, ..., x_N$ is taken from a statistical population with a standard deviation of σ. The standard error of an average value, $\overline{x}$, can then be described as:

$$\sigma_{\overline{x}} = \frac{\sigma}{\sqrt{n}} \tag{11}$$

The standard error can indicate how much error is made when trying to estimate the mean value of a data set. Lower standard error means a closer approximation of the estimated average [60].

3.3.4 Variability of results from Monte Carlo with Common Random Numbers

The Common Random Numbers (CRN) method is a statistical approach for variance reduction. The purpose is to compare two or more alternative configurations of the same situation. The method can be used when there are multiple outcomes of the same statistical draw from an equal seed, where modifications have been made to the system configuration.

Suppose X_{1j} and X_{2j} are observation results from two different configurations of the same j-th statistical situation of independent replication. The goal is to estimate the difference between two expected values, being:

$$\zeta = E[X_1] - E[X_2] = \mu_1 - \mu_2 \tag{12}$$

By performing n replications of each configuration and letting

$$Z_j = X_{1j} - X_{2j}, j = 1, 2, ..., n, \tag{13}$$

then $E[Z_j] = \zeta$ and $Z(n) = \frac{\sum_{j=1,...,n} Z_j}{n}$ is an unbiased estimator of ζ.

Because the $Z_j's$ are random variables that are identically and independently distributed, the variance (Var) of Z can be written as

$$Var[Z(n)] = \frac{Var[Z_j]}{n} = \frac{Var[X_{1j}] + Var[X_{2j}] - 2Cov[X_{1j}, X_{2j}]}{n} \tag{14}$$

where $Cov[X_{1j}, X_{2j}]$ is the covariance of X_{1j} and X_{2j} [61], [62].

The reduction in variance will be evident when looking at Z, which is the variance of the difference between two estimates rather than looking at the variance of two estimates separately.

3.4 Power Grid Reliability Indices

To analyze any given power grid, one must have a set of specified reliability factors that can determine the reliability of the grid. The reliability factors that will be introduced in this part are crucial for the understanding of the effects of new implementation in the grid and will be used for further analysis in the results part. To present the given reliability factors, one must first specify a set of fundamental reliability parameters. The parameters are as follows:

- The average failure rate for the system, λ_s
- The annual average outage time for the system, U_s
- The average outage time for the system, r_s

Firstly, one needs to be able to determine the amount of energy that is not supplied to the customer during a period of time due to failures and interruptions. This is also known as Energy Not Supplied, or ENS [63], and is defined by Equation 15.

$$ENS_s = U_s P_s \tag{15}$$

where P_s is defined as the interrupted power for the system s over a year.

Another useful index in terms of grid reliability is the SAIFI, meaning the System Average Interruption Frequency Index. This factor says something about the average interruption frequency of a system over a given period of time and can be used to determine if the total number of interruptions is increasing or decreasing. SAIFI is defined as

$$SAIFI = \frac{\sum \lambda_i N_i}{\sum N_i} \tag{16}$$

where N_i is the total number of customers at bus i, and $\sum \lambda_i N_i$ is the total number of customer interruptions over all buses in the system.

When grid planning, one might also want to know something about the average duration of the interruptions experienced by the customers. This is referred to as the System Average Interruption Duration Index, often referred to as SAIDI. It is defined as

$$SAIDI = \frac{\sum U_i N_i}{\sum N_i} \tag{17}$$

where $\sum U_i N_i$ is the total number of customer interruption duration. SAIDI is often used to say something about the expected duration of interruptions each customer is most likely to experience over a given time period [63].

4 System Description

This section will present the reference system used in the scientific work. Topology and attributes will be introduced to provide a more complete understanding of the reference system that is utilized. The choice of designated nodes for V2G implementation will also be justified in this part.

4.1 Grid topology

The CINELDI reference grid has been used for further work in this study [5]. The grid is based on a radial, Norwegian, medium voltage electric power distribution system operated at 22 kV. For anonymity purposes, the real grid that was used to create the reference grid will remain undisclosed. However, the reference grid is based on a real-world grid, and can therefore be considered representative of a realistic distribution system in Norway. Data from a real Norwegian distribution grid company has been used to develop fitting load profiles for the grid. The grid consists of 124 nodes and 123 distribution lines. The grid contains 54 load buses with connected load profiles. The rest of the buses are connecting buses, cable joints, branch points and so on. The distribution lines are a mix of underground cables and overhead lines. A diagram of the reference system can be seen in Figure 9.

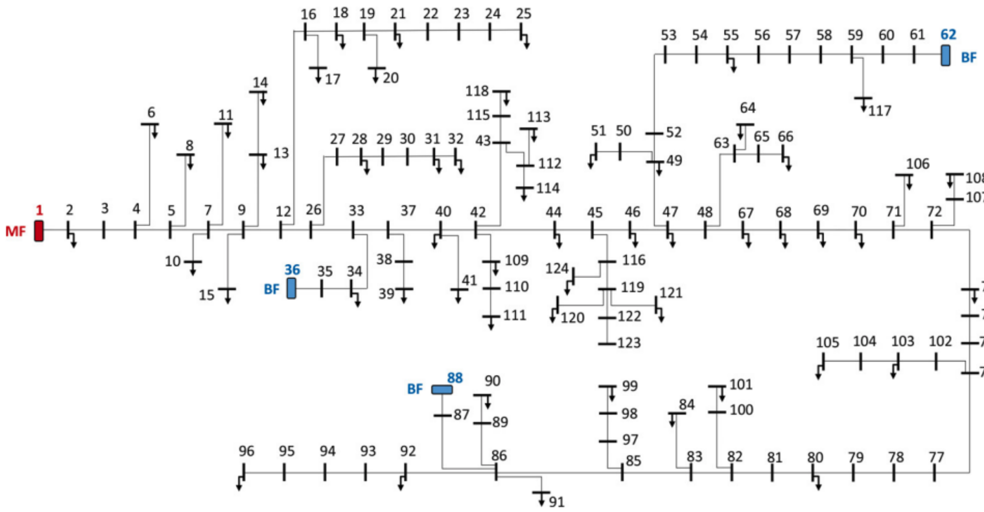


Figure 9: Diagram showing the reference system from CINELDI [5].

As observed in Figure 9, the main feeder (MF) is located at node 1, and three backup feeders (BF) are located at nodes 36, 62 and 88. The main feeder is connected to a high-voltage (HV) regional distribution grid. For the purpose of the studies conducted in this case, the backup feeders have been removed from the grid model and replaced with EV charging stations supporting V2G services. The reason for removing the backup connection to external grids was with the purpose to analyze the grid in a more isolated matter, seeing how the grid responds to only being able to receive additional power injection from the V2G nodes. In addition, the backup feeders connected to external grids were removed to minimize the amount of disturbance of results looking at the EV impact on the grid only.

The nodes that were chosen as candidates for V2G nodes are the same as the backup feeder nodes previously for the purpose of being able to investigate if the EVs could work as a form of backup supply during grid faults and interruptions. The nodes 36, 62 and 88 in Figure 9 all seem to be vulnerable points in the grid during a potential grid failure since they are located far from the main source of power. It is also important to choose nodes that are adequately apart from each other to minimize the risk of failure on all three backup generators. For Case 1, 2 and 3 in Section 5, only node 117 was tested with V2G. As RELSAD does not allow for V2G activation on buses without loads, the nearest load point of bus 62 was used for further experiments. For further work, other nodes might be interesting to investigate with V2G.

5 Methodology

This part will include the method used to obtain the results of the study. This contains the working phase of the project and the limitations to which the work has been restricted to. The details of the modeling setup will also be presented, and the features of the RELSAD implementation will be described. Further, the reasoning behind the choice of case studies and their limitations will be explained. An illustration has been made to present the most important work conducted in this master's thesis. This illustration can be found in Figure 10.

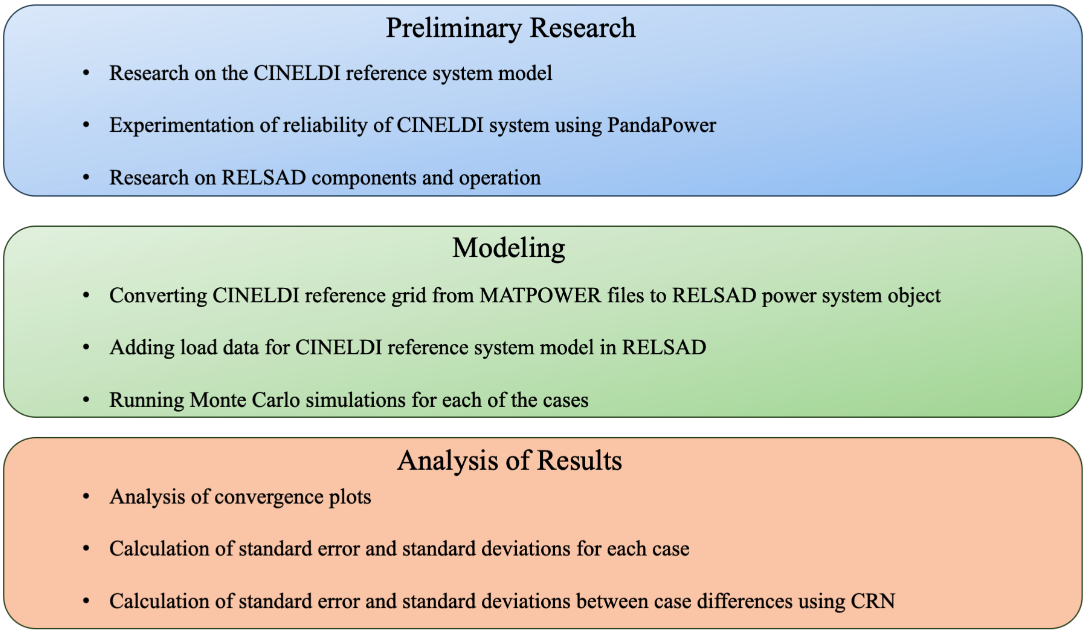


Figure 10: An illustration showing the most important parts of the work that has been conducted in this thesis.

5.1 Preliminary Research

One of the most important parts when analyzing the impact of V2G charging during grid failure is to have a realistic model of a real-world power system. For this purpose, the CINELDI reference system [5] was chosen as the benchmark grid for further studies. As the system is based on a Norwegian distribution grid, this will increase the realism of results when simulating. The system is big enough to look at the larger consequences of different situations when simulating failures and interruptions. The system is sufficiently complicated to replicate realistic operation, but not overly so that one fails to understand how the components will affect each other during simulation. In the early stages of the study process, a Python package called Pandapower [64] was used to get familiarized with the system behavior. The Pandapower package allowed for load flow simulation and provided an overview of the characteristics of the system. Several failure and interruption simulations were conducted by removing lines and buses to get a look at the system during failure. The load flow analysis also provided a clear perception of where the power was flowing and which areas of the system which are especially vulnerable during faults. The reasoning from these simulations laid the foundation for the choice of which buses to equip with V2G services later on in the study. Although the Pandapower package proved useful for familiarization with the reference system's properties, there was evidently a need for more detailed analysis software when simulating grid faults and interruptions.

The studies on the V2G impact on grid reliability during system failure could not be conducted without the appropriate tools. Therefore, the RELSAD package [4] was recognized as the most promising option when looking at the effect of two-way charging EVs on the power grid. The creator of the RELSAD package was contacted through a meeting to learn more about the details of the tools' properties and methods. During the meeting, it was established that the RELSAD package was a good fit for the work that was planned. After the meeting, the plan for the implementation of the CINELDI reference grid [5] in a RELSAD model was established. A significant amount of time was put into reading into and understanding how the RELSAD package should be used [43]. The implementation of a new grid model in the RELSAD program would not only be of great use for analyzing the reference system but also work as a framework for future RELSAD implementation of other systems. The work that was planned intended to make an example for others to be able to make use of, as well as also test the existing RELSAD software for improvements. The points mentioned were highlighted as the most important contributions of this project.

5.2 Modeling of the CINELDI reference grid in RELSAD

As the data for the reference system from CINELDI [5] was only given as CSV files in MATPOWER format, the data needed to be converted from data files into RELSAD grid models. The work of transferring all the data from the original system into RELSAD attributes and objects proved to be an extensive process. All buses, lines and other power system components had to be read from the CSV files and into RELSAD components. The reading of data into a RELSAD power system object was created as a function, where buses and lines were read from CSV files through a for-loop. In this for-loop, the values from CSV files for buses and lines were initiated into RELSAD bus objects and line objects. When all buses and lines had been created as RELSAD objects, the slack bus was set to bus 1, equally as in [5]. This was done by creating a transmission system and connecting it to bus 1. Further, the main system controller for the RELSAD grid model was implemented. From this, the power system object could be created. After the power system object was created, all the buses and lines were added to the power system object, creating a full-scale RELSAD model of the CINELDI reference grid. The grid model was plotted and examined to validate that the system was the same as the original reference system. The function ultimately returns the power system object that is created, facilitating further use of the power system object. The RELSAD power system was initialized using the function created in the appendix Section A. To fully understand the objects and classes in the RELSAD model that is being referred to here, documentation for the RELSAD package can be found in [43]

After the power system object had been created containing all buses and lines of the original reference grid, the load data from the original system needed to be added to the RELSAD power system model. Further, to extract the load data time series from the CSV files and map them to the correct buses, a function from the work of SINTEF was used [65]. This created a data frame of each bus and their respective load data for each hour through an entire year. From this data frame, the values were extracted and added to arrays for load data. These arrays of load data were then added to each of the corresponding RELSAD load bus objects.

After the load data had been mapped to each individual bus object in RELSAD for an entire year, the simulation of the RELSAD model could begin. Here, the time period for the Monte Carlo simulation was set to one year from 2018 to 2019 to match the load data period of the reference system. The time step interval was set to hourly intervals. The number of iterations was tested to be able to reach a sufficient accuracy in results. The number of iterations also had to be weighed up against the total run time of the program, as the program uses increasingly more time to simulate with a higher number of iterations. Ultimately, 3000 iterations were decided to be the best trade-off between accuracy in results and the run-time of the program. The program was run on a MacBook Air 2017 model with a run-time of approximately 25 hours for each case of 3000 iterations. The Monte Carlo simulation was run for each of the individual cases presented in Section 5.4. The code script for the Monte Carlo simulation conducted using the RELSAD python package can be found in the appendix Section A. The process of the Monte Carlo simulation in RELSAD has been illustrated in Figure 11.

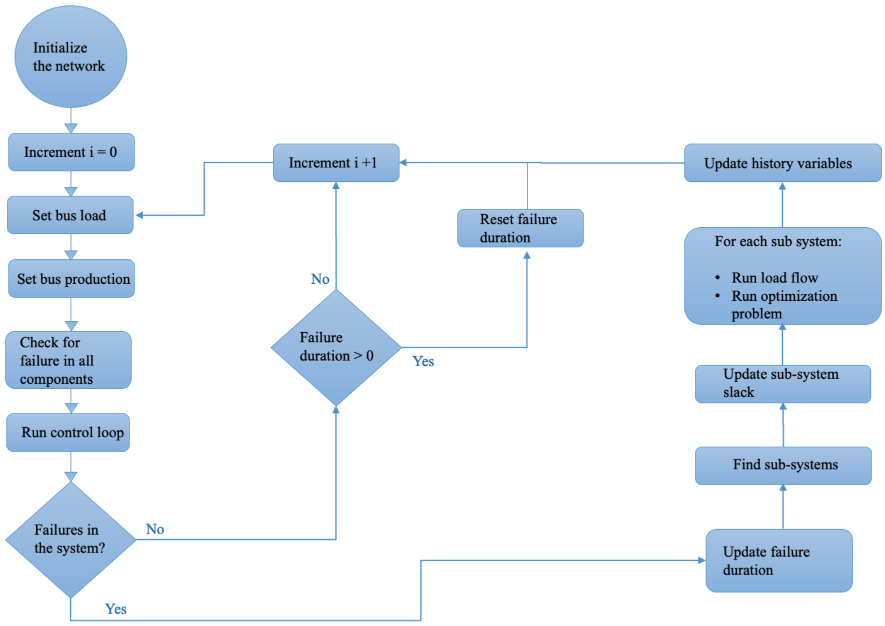


Figure 11: Flow chart showing the RELSAD iteration method. Illustration has been based on work from [42].

5.3 Statistical Analysis of Results

After the results were obtained from the Monte Carlo simulation in RELSAD, the results were analyzed using statistics. The results were compared to the interruption statistics in Norway from 2021 to determine whether the results were within realistic boundaries. Further, convergence plots were created and analyzed to determine whether the Monte Carlo simulation had obtained an estimate with sufficient convergence and a limited amount of fluctuations.

Standard error and standard deviation were calculated for each of the case results to determine the uncertainty of the results. In addition to this, the method of Common Random Numbers (Section 3.3.4) was used to calculate the standard deviation, variance and standard error between case differences to investigate if the differences in case results were a product of case modifications or coincidences.

5.4 Case study

5.4.1 Case 1: Monte Carlo simulation with charging station without V2G

For the first case situation, the grid was simulated without any services supporting V2G. However, an EV charging station was connected to bus number 117, pertaining to the grid model shown in Figure 9. This was to emulate the effect of a backup feeder connected externally to the grid. The charging station was placed in the outskirts of the grid further away from the main feeder, in order to maximize the coverage of sources in case of grid failure. The bus for the charging station was largely chosen with the idea of comparing with the methodology of case 2 in mind. Therefore, the charging station had to be connected to a load bus, since the RELSAD model currently only activates V2G for a station that is connected to a load bus. The charging station that was connected was equipped with the parameters described in Table 3.

Parameter	**Value**
Bus number	117
Number of Vehicles	20
Charging capacity EVs [kW]	3.7
Minimum SoC	0.2
Maximum SoC	0.9
Efficiency	0.95
V2G activated	No

Table 3: Characteristics for the EV charging station in case 1

Table 3 presents the characteristics for the simulation of case number one. For the number of vehicles, 20 EVs were placed at bus number 117, which was consisting of a load demand equivalent to 28 households. The number of EVs per household was chosen optimistically to get a significant impact from the vehicles onto the grid. The charging capacity for each EV was set to 3.7 kW to emulate the standard EV charging capacity of Norwegian households. A common choice for charging equipment in Norwegian households is a charging cable capacity of 16 A, which amounts to a total of approximately 3.7 kW of charging capacity when using a standard 230 V IT grid. The choice of 3.7 kW charging capacity was also made to be able to compare to an increase of charging capacity in case number three. The EVs in the RELSAD model were connected to a class object called EVPark, which simulates the EVs as a part of a bigger EV charging station. This station was modeled in the same way as a battery, and the number of EVs available at any time was summed to provide a total demand for the system. The total demand of this EVPark was the sum of 20 EVs with 3.7 kW charging capacity each, amounting to a total of 0.074 MW. The total demand from the grid was somewhere between 3 and 5 MW at any given time, which implies that the total load demand from the EVs was between 1.48-2.46 percent of the entire grid's load demand. For bus 117 with 28 households, the total load demand for the bus was somewhere between 0.5-0.8 MW during the year. This means that the EVs would be responsible for approximately 9.25-14.8 % of the total load demand at bus 117. In RELSAD, the SoC and the availability of the EVs associated with the EVPark-object were drawn from a uniform distribution model. The input variables chosen for lower and upper bounds were chosen as 20 % and 90 % respectively. This is referred to as minimum and maximum SoC in Table 3. The total efficiency of the EVPark-object was chosen to be 95 %. In this case, the V2G is not activated, and the EVs will only work as an extra load for the system.

5.4.2 Case 2: Monte Carlo simulation with charging station with V2G

For the method of case two, the V2G services for the EV charging station from case one were activated. The idea of this case is to analyze the effects of V2G on the same reference scenario as case number one. All other parameters between case one and case two remained the same in order to eliminate any disturbance factors for further comparison of results. The simulation of case two was conducted using the same random seed sampling as in case number one. This means that the Monte Carlo simulation draws the exact same fault incidents as before, but now with V2G capabilities activated. This approach allows for a more precise comparison between cases one and two, knowing that the only thing that has changed between the two scenarios is the activation of V2G services. This allows the results to be of more value since the difference between the two cases will represent the actual impact of the V2G for that specific system topology. The parameters pertaining to case two can be observed in Table 4.

Parameter	**Value**
Bus number	117
Number of Vehicles	20
Charging capacity EVs [kW]	3.7
Minimum SoC	0.2
Maximum SoC	0.9
Efficiency	0.95
V2G activated	Yes

Table 4: Characteristics for the EV charging station in case 2

5.4.3 Case 3: Monte Carlo simulation with V2G activated and increased EV charging capacity

For case three, the V2G parameters were still activated from case number two. An important aspect of V2G is how much the vehicles are able to charge and discharge in relation to the grid at any given time. As a fault occurs in the system, the loads will need an instant flow of supply from backup services until the system fault is fixed. Although the batteries of the EVs can provide significant amounts of power, the power flow is restricted by the charging facilities such as charging ports or charging cables. In this scenario, the idea is to get a grasp of the importance of charging capacity for the EVs when operating as V2G components. Therefore, the charging capacity of the EVs were increased from 3.7 kW to 7.4 kW. When using the same reference scenario as case two, but with increased charging capacity, one might be able to say something about the restrictions that the charging capacity brings when using V2G. Further details of case number three can be found in Table 5.

Parameter	**Value**
Bus number	117
Number of Vehicles	20
Charging capacity EVs [kW]	7.4
Minimum SoC	0.2
Maximum SoC	0.9
Efficiency	0.95
V2G activated	Yes

Table 5: Characteristics for the EV charging station in case 3

5.5 Assumptions

In order to simulate real-life scenarios with Monte Carlo methods, some assumptions and simplifications had to be made. Using the RELSAD package, some modifications had to be made to fit into the models. As for the modeling of the reference grid [5], the lines were modeled with failure rates of 0.07 and repair times drawn from a normal distribution from the RELSAD program. The minimum and maximum values for repair time draws were set to 0.5 hours and 2.0 hours respectively.

The backup feeders and the external grid connections at buses 36, 62 and 88 were removed from the reference grid to eliminate any disturbances from external grids into the main results and to keep the system isolated to case changes only. Also, the grid load data that was used for the grid model in RELSAD pertains to today's load demand situation, with the system having a maximum load demand of 6.407 MW. The load data that was used was a set of normalized load data that would work as a representative model for grid operation.

As for the EV-park modeling in RELSAD, the individual EVs in the EV-park were assumed to be identical. This is of course not very realistic, as real-life charging points will receive all kinds of different EVs every day. This is currently still the only way to model EVs in RELSAD. The EV-park objects were also modeled with charging capacities of 3.7 kW and 7.4 kW in each of the cases respectively. This was done to emulate the real-life restrictions of charging equipment for EVs. The size of the charging capacities was chosen to represent the most typical private charging limitations.

The limits for SoC were set to a minimum of 0.2 and a maximum of 0.9 times the full battery capacity respectively. This was done to prevent situations of maximum depletion and augmentation of the EV batteries to prolong battery life and prevent unwanted battery states for the customers. The EV batteries were also modeled with an efficiency of 0.95 to replicate realistic battery behavior.

6 Results

In this part, the results obtained from the study will be presented. The section will provide the results of the Monte Carlo simulation for the three reliability indices: ENS, SAIFI and SAIDI. The results presented will follow the same structure as the cases presented in Section 5.

6.1 Results for Energy Not Supplied (ENS)

ENS is short for Energy Not Supplied and says something about the amount of energy that is not supplied in the grid during grid failure periods. The convergence plot in Figure 12 shows the value of ENS for all three cases. The plot is based on calculations of the expected value of ENS for every iteration. The expected value for ENS was calculated using the mean value for the dataset at every given iteration. As explained earlier, RELSAD was triggered using the same seed for all the cases. This is also observed in Figure 12, where the course of the three graphs is identical. The only difference between ENS in the three cases is that the values for each iteration have been shifted. The ENS values in Figure 12 are evidently more unstable in the first iterations, but seem to converge well after approximately 1500 iterations. It is observed a larger reduction in ENS between cases one and two compared to the reduction between cases two and three.

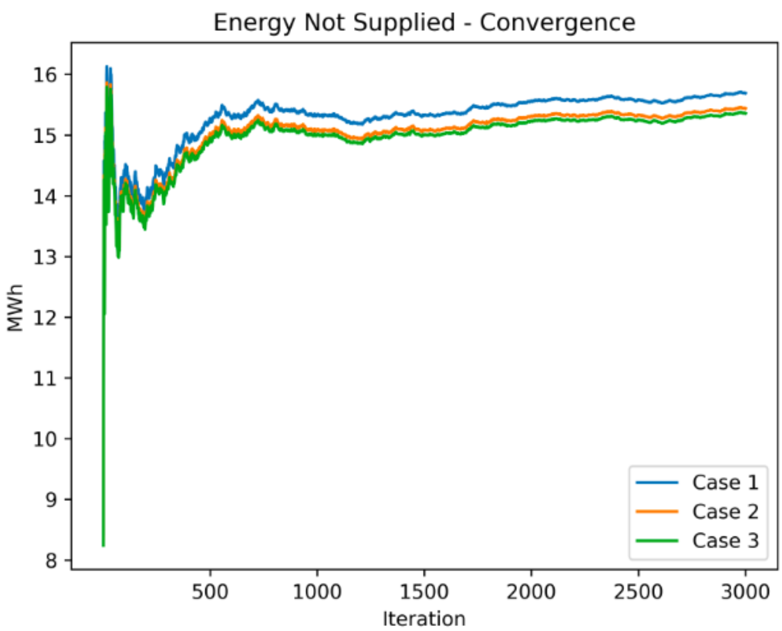


Figure 12: Mean ENS convergence of all cases. Zoomed plots to get a better view of case differences can be found in Section B.

The main characteristics of the data from Figure 12 is presented in Table 6. It is observed from Table 6 that the difference in ENS between cases one and two is the mean ENS value of case two subtracted from the mean ENS value of case one. Subtracting 15.45 MWh from 15.70 MWh, the change is found to be 0.25 MWh. The mean ENS value has evidently been reduced by approximately 1.6 %. Similarly, the mean ENS values are observed to be 15.45 MWh for case two and 15.36 MWh for case three. Further, the difference in mean ENS between cases two and three is found to be 0.09 MWh, a reduction of approximately 0.6 %.

Statistic	Case 1	Case 2	Case 3
Minimum [MWh]	0.00	0.00	0.00
Maximum [MWh]	70.67	69.71	69.15
Mean Value [MWh]	15.70	15.45	15.36
Standard Deviation [MWh]	9.09	8.95	8.89
Standard Error [MWh]	0.1659	0.1634	0.1623

Table 6: ENS characteristics for all cases.

The comparison of case data was analyzed using the Common Random Numbers method Section 3.3.4 leading to a reduction in variance between the cases. Here, the variance, standard deviation and standard error were calculated from the difference between case values for each of the case permutations. It is observed that between cases one and two there is a standard deviation of 0.1369 MWh. The reduction of 0.25 MWh is significantly larger than the standard deviation of 0.1369 MWh between them calculated in Table 7. The reduction between cases two and three of 0.09 is observed to be significantly larger than the standard error calculated between them, which is 0.0013 (Table 7).

Cases	Variance [MWh]	Standard Deviation [MWh]	Standard Error [MWh]
1 & 2	0.0187	0.1369	0.0025
2 & 3	0.0054	0.0734	0.0013
1 & 3	0.0371	0.1927	0.0035

Table 7: Table of statistic results pertaining to the uncertainty between ENS case results using the Common Random Numbers method (Section 3.3.4).

Individual plots of each case and additional zoomed plots can be found in the Appendix Section B.

6.2 Results for System Average Interruption Frequency Index (SAIFI)

SAIFI is short for System Average Interruption Frequency Index and describes the frequency of interruptions that can be expected to be experienced by each grid customer during a year. Figure 13 shows the mean value of SAIFI for each iteration for all three cases. Similarly to ENS, SAIFI oscillates in the beginning, only to stabilize somewhere between 1000 and 1500 iterations. It is observed that the SAIFI seems to converge faster than the mean ENS values. In addition to this, it is also observed that the reduction in SAIFI is significantly larger between cases one and two than between cases two and three.

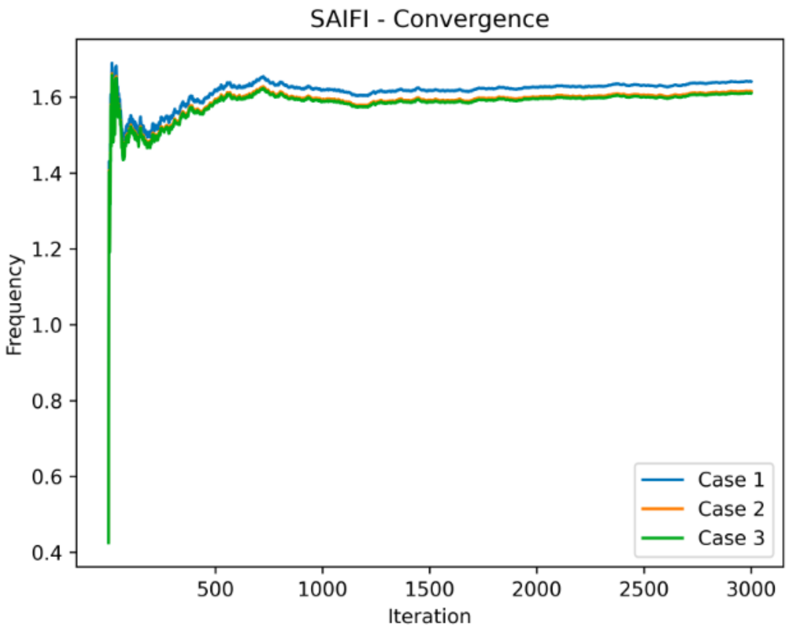


Figure 13: Mean SAIFI convergence of all cases. Zoomed plots to get a better view of case differences can be found in Section B.

Additional characteristics for the data in Figure 13 is presented in Table 8. It is observed that the mean value for SAIFI is found to be 1.64 for case one, 1.62 for case two and 1.61 for case three. A reduction of 0.02 is found between cases one and two, while the reduction between cases two and three is found to be 0.01. The mean SAIFI value has been reduced by 1.22 % between cases one and two and the reduction between cases two and three amounts to 0.62 %.

Statistic	Case 1	Case 2	Case 3
Minimum	0.00	0.00	0.00
Maximum	5.60	5.52	5.49
Mean Value	1.64	1.62	1.61
Standard Deviation	0.84	0.83	0.82
Standard Error	0.0153	0.0152	0.0150

Table 8: SAIFI characteristics for all cases.

Variance, standard deviation and standard error are presented in Table 9. The values in this table was calculated using the Common Random Numbers method described in Section 3.3.4. It is observed that the reduction of 0.02 between mean SAIFI from cases one and two is larger than the calculated standard error of Table 9 which was found to be $2.50 \cdot 10^{-4}$. The same applies between cases two and three, which experienced a reduction of 0.01, but a calculated standard error of $7.12 \cdot 10^{-5}$.

Cases	**Variance**	**Standard Deviation**	**Standard Error**
1 & 2	0.0002	0.0137	$2.50 \cdot 10^{-4}$
2 & 3	$1.56 \cdot 10^{-5}$	0.0039	$7.12 \cdot 10^{-5}$
1 & 3	0.0003	0.0157	$2.87 \cdot 10^{-4}$

Table 9: Table of statistic results pertaining to the uncertainty between SAIFI case results using the Common Random Numbers method (Section 3.3.4).

Individual plots of each case and additional zoomed plots can be found in the Appendix Section B.

6.3 Results for System Average Interruption Duration Index (SAIDI)

As mentioned, the SAIDI, or System Average Interruption Duration Index, says something about the expected interruption duration each grid customer will experience during a year. Figure 14 shows the mean SAIDI calculated for every iteration for all three cases. It is observed a similar convergence as for SAIFI, with stabilization of mean SAIDI values occurring between 1000 and 1500 iterations. It is also worth noting that there is a reduction in mean values between cases one, two and three.

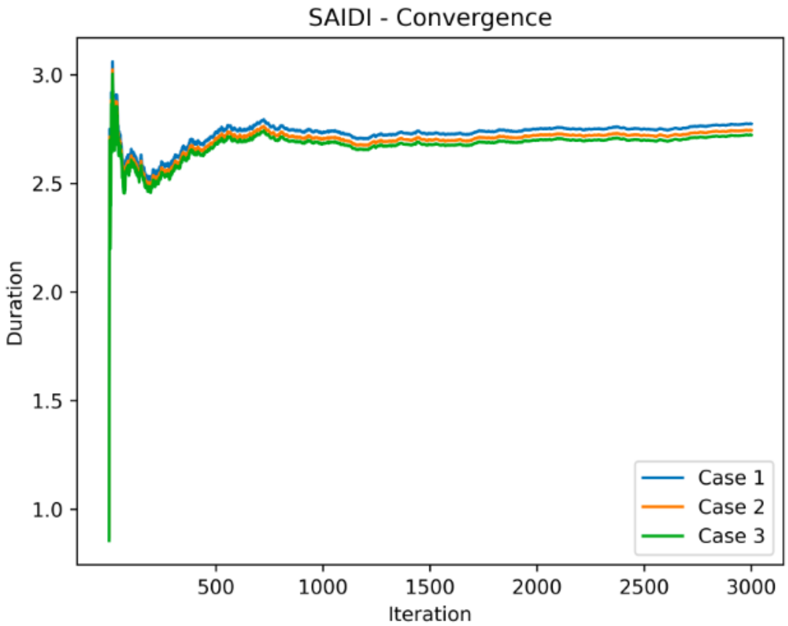


Figure 14: Mean SAIDI convergence of all cases. Zoomed plots to get a better view of case differences can be found in Section B.

The main characteristics of the data used in Figure 14 is presented in Table 11. It is observed a mean SAIDI value of 2.77 hours for case one, 2.75 hours for case two and 2.72 hours for case three. A reduction of 0.02 hours (0.72 %) between cases one and two and 0.03 (1.1 %) hours between cases two and three can be found from the results.

Statistic	**Case 1**	**Case 2**	**Case 3**
Minimum [h]	0.00	0.00	0.00
Maximum [h]	9.99	9.93	9.81
Mean Value [h]	2.77	2.75	2.72
Standard Deviation [h]	1.46	1.45	1.43
Standard Error [h]	0.0267	0.0265	0.0261

Table 10: SAIDI characteristics for all cases.

Calculated results between the cases for variance, standard deviation and standard error can be found in Table 11 using the Common Random Numbers method from Section 3.3.4. Here, the standard error between cases one and two is observed to be $3.74 \cdot 10^{-4}$ hours, which is significantly less than the calculated reduction of 0.02 hours. The standard error between cases two and three was $3.16 \cdot 10^{-4}$ hours, significantly less than the calculated reduction of 0.03 hours.

Cases	**Variance [h]**	**Standard Deviation [h]**	**Standard Error [h]**
1 & 2	0.0004	0.0205	$3.74 \cdot 10^{-4}$
2 & 3	0.0003	0.0173	$3.16 \cdot 10^{-4}$
1 & 3	0.0007	0.0272	$4.97 \cdot 10^{-4}$

Table 11: Table of statistic results pertaining to the uncertainty between SAIDI case results using the Common Random Numbers method (Section 3.3.4).

Individual plots of each case and additional zoomed plots can be found in the Appendix Section B.

7 Discussion

This section will present the most important results of the thesis and discuss the validity of the findings. The uncertainty of the Monte Carlo simulation in relation to result accuracy will be discussed, as well as the effects of simplifications and assumptions for the RELSAD modeling. Sources of error and uncertainty will also be discussed in relation to the results.

7.1 Realism of Results

Looking at the results from the "base case", or case number one with only loads connected, the mean values of ENS stabilize around a mean value of 15.70 MWh (Table 6). Compared to the Norwegian grid interruption statistics of NVE for the year 2021 [66], the total ENS for the whole of Norway was 16.51 GWh, meaning that the reference system might be of a significantly smaller scale than the entire grid in Norway. Looking at the statistics of the county of Trøndelag, the annual ENS of 2021 was at 982.61 MWh, meaning that the reference system represents approximately 1.6 % of the size of the regional grid of Trøndelag, at least in terms of ENS. As the ENS comparisons might be inaccurate given that the CINELDI system might have a higher or lower rate of ENS compared to the Norwegian grid, one might have a look at SAIFI and SAIDI, as these indices are based on an average.

For the entirety of the Norwegian grid, the SAIFI of 2021 was at 3.09. NVE categorizes the total SAIFI on short interruptions of less than 3 minutes (1.44) and long-term interruptions of more than 3 minutes (1.65) [66]. The CINELDI system seems to have a lower total of SAIFI, as the mean value stabilizes around 1.64 (Table 8). It is observed that the overall SAIFI is lower for the CINELDI reference system compared to the Norwegian grid, which might be caused by an optimistic assumption in terms of grid failure rates that are fed into the model. As the RELSAD model does not distinguish between short and long interruptions in its calculations of SAIFI, it might be difficult to say something about the accuracy of the grid model in comparison to the statistics. Still, it is worth noting that the SAIFI numbers for the reference grid are within acceptable and realistic ranges for further analysis.

As for SAIDI, NVE [66] reports a SAIDI of 1.07 minutes per customer for short interruptions (less than 3 minutes) and a SAIDI of 128.5 minutes per customer for long interruptions (more than 3 minutes). The SAIDI for the CINELDI reference system is found to be approximately 2.77 hours per customer (Table 10). This is within realistic boundaries, as the SAIDI from NVE for longer interruptions also amounts to approximately 2.14 hours per customer.

7.2 Impact of V2G

To see if there are any significant effects of installing V2G in the reference system, the purpose is now to compare the results of the different case scenarios. The difference between cases one and two will be investigated first, as this will probably indicate how significant the impact of V2G is. For recapitulation, case number one was a simulation of the reference grid with an EV park object connected without V2G properties activated. Case number two was exactly the same scenario as case number one but with V2G facilities activated for the EVs. Looking at the values of ENS for both cases, the mean ENS for case number one was found to be 15.70 MWh and the mean ENS for case number two was found to be 15.45 MWh (Table 6). It is observed that the ENS value has decreased significantly when activating V2G for the EVs, as these results show a reduction of approximately 1.6 %. This reduction might be due to the EVs' ability to provide extra battery services for the grid during interruptions, providing energy for loads that would not be supplied during the first case. Looking at mean SAIFI values for cases one and two, case one had a SAIFI of 1.64, while case two had a SAIFI of 1.62 (Table 8). It is observed that the SAIFI also decreases between cases one and two. The decrease of SAIFI seems to match the decrease in ENS between cases one and two. The reduction of mean ENS was found to be 1.6 % and the mean SAIFI reduction was

1.22 %. This can indicate that the EVs might be able to reduce the number of interruptions using V2G technology, in addition to reducing the amount of energy not being delivered. Looking at SAIDI results, SAIDI for case one was 2.77 h, and SAIDI for case two was 2.75 h (Table 10). SAIDI results indicate that there are differences between the durations of grid interruptions between the two cases. This leads to the same conclusion as for SAIFI, being that the interruptions seem to change between the two cases. This makes sense, as the EVs can contribute to reduce the amount of downtime for the customers close to the EV charging station. This also justifies the statement that the EVs are in fact able to reduce ENS, SAIFI and SAIDI when V2G is activated. This can be stated on the background of a reduction in ENS, SAIFI and SAIDI. However, the change of ENS, SAIFI and SAIDI is not very large. This might be explained by the number of vehicles being tested in these cases. A number of 20 vehicles on one bus was tested for these cases, which realistically is not very accurate given the size of the distribution system and the number of customers. Although these statements are made, the actual validity of these results will be discussed later in this section.

As for cases two and three, their differences will now be discussed. Case number two was a simulation with an EV park connected to the grid with V2G services activated. Case number three is the same as case number two, except that the charging capacity of the EVs has been increased from 3.7 kW to 7.4 kW from case two to case three, respectively. The ENS values for cases two and three were found to be 15.45 MWh and 15.36 MWh (Table 6), respectively. A decrease of average ENS of 0.6 % can be seen between cases two and three, similar to cases one and two. This makes sense, as the EVs can now provide instant power demand faster than before during grid interruptions. SAIFI for cases two and three are found to be 1.62 and 1.61 respectively (Table 8). SAIDI is found to be 2.75 for case two and 2.72 for case three (Table 10). This also provides the same conclusion as for the comparison between cases one and two. ENS, SAIFI and SAIDI is significantly reduced in both cases. This makes sense, as the only thing that has been changed between cases two and three is the increased charging capacity of the EVs. As the charging capacity is now increased for the EVs, they are able to provide extra power more rapidly than before. This can be observed in the results for SAIFI and SAIDI. The increase in charging capacity can be observed to have a minimal impact on SAIFI in Figure 13, but a larger impact on ENS and SAIDI. The explanation of this might be that the same number of interruptions will still occur in the system even though the charging capacity has been increased. However, the EVs are now more capable of reducing downtime as the reserve power can react more quickly to interruptions. This is what can be observed as significant change in SAIDI.

It is also observed that the standard deviation and the standard error are significantly higher for ENS than for SAIFI and SAIDI. This might occur due to a fluctuating convergence for mean ENS compared to SAIFI and SAIDI, which can be observed more closely in zoomed versions of the plots from the results. These figures can be found in the Appendix Section B and show more clear images of the fluctuations of mean values for ENS, SAIFI and SAIDI. The standard deviation and standard error values do not seem to change significantly between the different cases, though. The reliability indices' accuracy will be discussed later in this section.

7.3 Accuracy of Results

The basic principles of a Monte Carlo simulation are based on the fact that if one makes a sufficient number of draws from a statistical distribution of uncertainty factors, the averages of the values will converge toward an estimate of the actual value. Therefore, the Monte Carlo simulation strongly depends on many draws to make the approximation as good as possible. For complex systems like the power grid, the Monte Carlo simulation can be a good way to approximate the many uncertainties of real-life operations. When many uncertainty factors come together to form a system, these systems can be rather unpredictable. Nowadays, these operations can be performed on computers that run thousands of redraws of the same scenarios. Although a computer can perform this much faster than any human, the simulation of a power grid of the given complexity and uncertainty as real-life is computationally very expensive. There will always be a trade-off between sufficient iterations and simulation time. As the number of iterations increases, the time of simulation increases.

When using the Monte Carlo method as an approximation, there will always be differences in the convergence of different factors. Using case one as an example, the values for SAIFI and SAIDI in Figure 13 and Figure 14, respectively, show that these values seem to be converging well. There are some fluctuations at the beginning of the first 500 iterations, but around 1500 iterations the values seem to converge towards a stable solution. This is also represented in the standard deviation and standard error results for SAIFI and SAIDI, which is within acceptable limits of convergence. The values indicate that the amount of variance around the average value is low enough to say that the values are converging sufficiently close to the estimate. As for the ENS values found in Figure 24, they seem to fluctuate a bit more towards the end compared to SAIFI and SAIDI. This is also evident in the standard deviation and standard error for ENS presented in Table 6. This might have been avoided with more iterations being run of the Monte Carlo simulation, as this would provide the results with more draws, which again would provide a stronger basis for convergence and approximation of the ENS estimate. This could have been done using more time on simulations or gaining access to a more powerful computer to conduct these simulations more quickly. Unfortunately, the computer on which this was simulated was a private computer with limited computational power. Alas, the lack of computational power for simulations will indeed affect the accuracy of results.

7.4 Validity of Results

As the Monte Carlo method is largely dependent on the generation of larger numbers, it is important to question the significance of the results obtained. Since the events that occur during the simulations will be based on random draws, one might not be sure whether the results obtained will come as a result of V2G impact or pure coincidence. To eliminate the randomness of the simulations, the same random seed was used for all three investigated cases. This means the three cases will all experience the same events during the simulation period. As an example, an interruption of 20 minutes on the 1st of January 2018 for case one without V2G will also occur in exactly the same manner for case two with V2G activated. In this way, the RELSAD simulation can replicate a series of events with large precision, making it easier for the user to compare two simulations to each other. As two cases are the same series of events with different modifications to system properties, the comparison between them can eliminate the differences due to chance and random numbers.

As a part of verifying the results, the variance, standard deviation and standard error have been calculated between all cases for ENS (Table 7), SAIFI (Table 9) and SAIDI (Table 11). A major part of the Monte Carlo simulation is to verify if the alterations in system properties cause the results of the three simulation cases or if these changes in results can be related to the standard deviation between random sampling. To calculate the results of variance, standard deviation and standard error between the cases, the Common Random Numbers method has been used. The method is explained in more detail in Section 3.3.4. The focus in this section will mostly be on ENS, as this is the only value with a large uncertainty related to standard error. Both SAIFI and SAIDI results have already been established as within acceptable limits for standard error. For ENS, the standard deviation in Table 7 is found to be 0.1369 MWh between cases one and two. This means that a difference of ± 0.1369 in ENS between cases one and two can be explained by differences in randomness. Using the standard deviation, one can establish that the values of mean ENS most likely will find themselves in an interval of $[ENS - 0.1369, ENS + 0.1369]$. As observed earlier, the difference in ENS between cases one and two was found to be 0.25 MWh (15.70 MWh for case one and 15.45 MWh for case two). Therefore, it is logical to assume that these differences in ENS between cases one and two are most likely caused by the modifications in system properties and not a coincidence. This can therefore justify the claim that the V2G technology actually can contribute to a reduction in ENS for the CINELDI reference power grid [5]. Similarly, for cases two and three, the ENS standard deviation is 0.0734 MWh between them, as presented in Table 7. Going back to previous findings, the difference in ENS values between cases two and three was found to be 0.09 MWh (15.45 MWh for case two and 15.36 MWh for case three). This also confirms that the increase in charging capacity for EVs can be a contributing factor in reducing ENS, SAIFI and SAIDI values for the CINELDI reference power grid [5]. It will also be natural to assume that since the reference grid from CINELDI can be considered as a representative model for Norwegian grids, these conclusions for V2G facilities and the charging capacity for EVs connected through V2G would be applicable for other Norwegian grid systems as well.

7.5 Evaluation of the Monte Carlo method

Although the Monte Carlo method has been chosen as the tool to investigate the impacts of V2G technology on the power grid in this case, this does not mean that the method is the correct approach for all investigative studies on this matter. Monte Carlo has its benefits with a good estimation of systems with many uncertainty factors. As there is a lot of randomness in grid operation, the Monte Carlo method allows for a deeper understanding of many of the possible outcomes of the given system. It is not possible to investigate all possibilities, but by estimating enough samples, there will be a more solid foundation for saying something about what is most likely to happen. Another advantage of the Monte Carlo approach is its simplicity and easily graspable concept. The Monte Carlo method is also very accurate when given the correct sample space and boundaries for a problem.

The Monte Carlo method also has its disadvantages, the most prominent one being its demand for computational power. Including many uncertainty factors also increases the number of calculations that need to be made to cover all possible scenarios. This will be very demanding for a normal computer, which was also experienced when conducting the experiments presented in this master's thesis. In this case, one Monte Carlo iteration for an entire year of data used approximately 30 seconds. Running the chosen set of 3000 iterations led to a computational run time of approximately 25 hours. Increasing this to for instance 5000 iterations would result in a run time of approximately 42 hours. The main takeaway is that the Monte Carlo method is a trade-off between the accuracy of results and computational run time, making the method unavailable for some experiments demanding faster computations. In addition to being computationally expensive, the Monte Carlo method cannot represent all possible outcomes. In terms of real life, one cannot possibly model all the possible events that might occur in reality, and this provides uncertainty to the legitimacy of Monte Carlo results. There might be events or scenarios of real life that no person can foresee, and can therefore be a source of inaccuracy in outcome simulations.

7.6 Sources of Error

As results are obtained and discussed, there will always exist sources of errors related to results. Inaccuracy and errors are a natural part of experiments when trying to model real-life scenarios. Some results might be affected by a lack of precision, as the Monte Carlo simulation requires numerous iterations to converge toward an accurate estimate. With the chosen amount of 3000 iterations, the results will converge to a certain degree. It is difficult to say categorically that the convergence could have been better with more iterations, although it is very likely.

Another factor affecting the accuracy of results is that the reference system [5] is based on a system model, which is not a real-life, existing grid itself. Buses, lines and loads are all based on real-world power grids in Norway, but the system itself cannot be identified as a direct replication of reality. The failure rates of buses and lines can not be guaranteed to represent real-life system operation either. This implies that some of the results might have been different with more realistic power system models such as more accurate load data and a more representative mix of system components. However, the reference system provides an example of a possible scenario for grid operation and provides important insight into the trends and patterns of different system modifications. It works as an important tool for exemplifying the most important aspects of power system operation.

In addition to the arguments above, the Monte Carlo method contributes to a certain degree of error in the results. As the method is based on randomly generated numbers, it is often difficult to distinguish between the impact of system modifications and pure randomness. The results can be analyzed statistically, and one might be able to establish an interval of possible outcomes for certain parameters. Still, it is not possible to say with complete certainty that the results obtained will be the actual outcome of a real-life operation. This is the problem when trying to predict the future. The future holds many outcomes, and a mean value will only bring the average of all previous outcomes, even though there could exist outcomes that are not even factored into the model in the first place. Despite this, the Monte Carlo simulations still provide an important understanding of trends and tendencies of the system being analyzed, which in many cases can be sufficient to make qualified decisions.

8 Conclusion

The purpose of this experiment was to investigate the question: "To what extent will using EVs through V2G during grid interruptions be able to improve the reliability of supply measured by Energy Not Supplied, SAIFI and SAIDI?" This section will investigate the most important results and findings of the previous parts of this thesis and attempt to provide an answer to the question stated earlier in the thesis.

Comparing the results to the interruption statistics in Norway for 2021 provided by NVE [66], the results obtained in this thesis could be deemed realistic in terms of real grid properties. The mean ENS would suggest that the reference grid could represent a smaller part of a larger distribution system. SAIFI and SAIDI seem to fit well with reported numbers for the Norwegian grids on a national basis and could therefore be considered as a realistic approximation of the experienced interruptions for grid customers in Norway.

When comparing cases one and two, one case being without V2G facilities and one case having V2G facilities activated, their mean ENS values after 3000 iterations were found to be 15.70 MWh and 15.45 MWh, respectively. This represents a decrease in mean ENS of 0.25 MWh, or 1.6 %. SAIFI mean values were found to be reduced by 1.22 % and SAIDI mean values were reduced by 0.72 %. This could imply that the V2G technology can contribute to improving ENS, SAIFI and SAIDI for the distribution system. When comparing scenarios with V2G facilities activated, but one having an increased charging capacity of 3.7 kW for the EVs, the reduction of ENS was found to be 0.09 MWh, or 0.58 %. For these two cases, SAIFI was reduced by 0.62 % and SAIDI was reduced by 1.1 %. This would also suggest that the increase in the charging capacity of EVs could contribute to improve the reliability indices such as ENS, SAIFI and SAIDI given the use of V2G technology.

When utilizing the Monte Carlo method for simulations, the goal is to approximate certain parameters and results by drawing randomly from statistical distributions until all outcomes have been investigated. For this study, a number of 3000 iterations was found to be the point of sufficient accuracy and tolerable run time. It was observed that the mean values of SAIFI and SAIDI were converging well around 1500 iterations approximately, but the mean values of ENS seemed to fluctuate more in the later stages of the iterations. A higher standard deviation and standard error for ENS also indicated this. When investigating the values of ENS further in comparison to the other cases, the goal was to learn if the changes in ENS values were caused by system modifications or by the randomness of the Monte Carlo simulation. The standard deviation between cases one and two was calculated by the Random Numbers Method Section 3.3.4 to be 0.1369 MWh, which means that changes within the range of $[ENS - 0.1369, ENS + 0.1369]$ can be considered as a result of chance. However, the changes in ENS between cases one and two showed a decrease of 0.25 MWh, which implies that some of the reduced ENS come as a result of the alteration of V2G properties between cases and not pure coincidence. The same could be concluded between cases two and three, where the standard deviation between the cases was found to be 0.0734 MWh, while the reduction of the mean value for ENS was found to be 0.09 MWh, indicating a change that probably was caused by system modifications.

As the results imply, using V2G technology could improve the amount of energy being delivered to grid customers for a somewhat lowered frequency of interruptions and interruption duration. The question stated earlier in this thesis was: "To what extent will using EVs through V2G during grid interruptions be able to improve the reliability of supply measured by Energy Not Supplied, SAIFI and SAIDI?". The answer to this statement is that there is possible to improve reliability indices such as ENS, SAIFI and SAIFI in this reference system using V2G. Although the changes in reliability indices might appear small, the experiments conducted in this thesis were based on a singular EV park of 20 cars for a large distribution grid. The effects of V2G reduction in ENS would most likely be much more significant if one were to install a more realistic number of EVs pertaining to the size and number of customers in the distribution system. In this way, the reduction of SAIFI and SAIDI also could have been more significant, as the EVs could have been able to prevent more interruptions in more parts of the grid. As stated earlier, the world will experience an increasing demand for electricity in the years to come, which most likely will lead to more grid failures and interruptions without sufficient grid infrastructure development. The growing share of EVs provides an opportunity for utilizing an untapped potential of battery storage to feed back into the grid during periods of high load demand. Another benefit of V2G, in addition to less energy not being supplied, is the frequency stabilization of power grids with EV batteries providing fast frequency reserves (spinning reserves) for the power grid. This will also become more vital in the coming years, as renewable power source integration of solar power and wind power will provide more volatility in predicted power generation.

9 Further Work

The study conducted in this thesis has provided a foundation for further work on this topic. The following areas of research are suggestions for a continuation of the work that has been presented.

One of the topics available for further research is investigating the impact of EV park objects connected to different bus configurations on the CINELDI reference grid using RELSAD. By doing this, one might be able to discover areas of the reference grid that are more profitable for V2G services in terms of reducing the amount of energy not supplied.

It would be interesting to analyze not only the impacts of an EV charging station in the outer rims of the reference grid, but also in the very center of the grid to see if this makes a significant impact on grid reliability. Also, a more realistic number of EVs can be studied to investigate if the ENS, SAIFI and SAIDI will be reduced additionally using more EVs and charging stations in the reference system.

Further, investigating the impact of V2G on future load demand scenarios would be a vital part of understanding the future of grid reliability planning. Here, one might also be able to look at the impact of V2G on grid frequency stabilization. As the grid frequency will become more unpredictable as a result of renewable energy sources, the EVs could work as spinning reserves in the power grid to provide an increase or a decrease in grid frequency.

Another exciting prospect for further investigation is to study the costs related to a reduction in ENS values for grid operators using V2G technology. As the EVs can work as extra battery storage, this could contribute to lowering grid operator costs significantly. In addition to this, the prospects of a market for V2G also need to be investigated, as EV users will not be willing to make their EVs available for V2G services unless there are substantial financial incentives for them to do so. This would be interesting to analyze further.

Finally, the improvement and expansion of the CINELDI reference grid model in RELSAD will be a main area for further work. The most important aspects here will be the implementation of more advanced grid components and an increase in customer types. In addition to this, the statistical distribution models for EV parks which are based on driving habits and statistics could also be improved. In this way, the Monte Carlo simulation will be able to base its statistical events on more realistic scenarios from real-life driving and charging behavior related to EVs.

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Appendix

A Additional Code

A.1 Function creating RELSAD power system object from Matpower CSV-files

Listing 1: Function for transferring Matpower data into a RELSAD power system model

```
import pandas as pd
import numpy as np
import os
import math

from relsad.network.components import (
    Bus,
    Line,
    Disconnector,
    CircuitBreaker,
    ManualMainController,
)

from relsad.network.components import (
    Production,
    Battery,
    EVPark,
)
from relsad.Table import Table

from relsad.network.systems import (
    PowerSystem,
    Transmission,
    Distribution,
)

from relsad.Time import (
    Time,
    TimeUnit,
    TimeStamp,
)

from relsad.StatDist import (
    StatDist,
    StatDistType,
    NormalParameters,
)

from relsad.load.bus import CostFunction
from relsad.visualization.plotting import plot_topology
from relsad.simulation import Simulation
```

```python
def read_net_from_csv_to_RELSAD(folder, baseMVA=10, DiB_version = True):

    ps = 0

    # Importing files
    if DiB_version:
        filename_bus = 'CINELDI_MV_reference_grid_base_bus.csv'
        filename_branch = 'CINELDI_MV_reference_grid_base_branch.csv'
        filename_branch_extra = 'CINELDI_MV_reference_grid_base_branch_extra.csv'
        filename_bus_extra = 'CINELDI_MV_reference_grid_base_bus_extra.csv'
    else:
        filename_bus = 'Cineldi124Bus_Busdata.csv'
        filename_branch = 'Cineldi124Bus_Branch.csv'
        filename_branch_extra = 'Cineldi124Bus_Branch_extra.csv'

    # Read files from .csv files
    filename_bus_fullpath = os.path.join(folder, filename_bus)
    filename_branch_fullpath = os.path.join(folder, filename_branch)
    bus = pd.read_csv(filename_bus_fullpath,sep=';')
    branch = pd.read_csv(filename_branch_fullpath,sep=';')

    # Only try to read extra branch data if input file exists
    filename_branch_extra_fullpath = os.path.join(folder, filename_branch_extra)
    branch_extra_exists = os.path.isfile(filename_branch_extra_fullpath)
    if branch_extra_exists:
        branch_extra = pd.read_csv(filename_branch_extra_fullpath,sep=';')

    # Print bus-dataframe and branch-dataframe from matpower csv-files
    # print(bus)
    # print(branch)

    # Assuming the grid to be operated at frequency 50 Hz
    f_hz = 50.0


    if 'baseKV' in bus.columns:
        s_base_kV = bus['baseKV']
    else:
        s_base_kV = bus['base_kV']

    # Creating a bus list to hold all buses
    BusList = []
    # Creating list to hold all P_max values
    P_max = []

    # Create coordinates for plotting buses
    x = np.linspace(-100,100,200)
    y = np.linspace(-5,5,200)

    for i_bus in bus.index:

        BusCounter = 0

        # Extracting busID
        if 'ID' in bus.columns:
            bus_ID = bus.loc[i_bus,'ID']
        else:
            bus_ID = bus.loc[i_bus,'bus_i']
```

```
if not pd.isna(bus_ID):

    # Extracting variables from bus dataframe
    bus_name = int(bus_ID)
    vn_kv = s_base_kV[i_bus]
    bus_type = 'b'
    zone = bus.loc[i_bus,'zone']
    in_service = True
    if 'Va - degr' in bus.columns:
        Va_degrees = bus.loc[i_bus,'Va - degr']
    else:
        Va_degrees = bus.loc[i_bus,'Va']
    Vm = bus.loc[i_bus,'Vm']
    if 'max_Vm' in bus.columns:
        max_vm_pu = bus.loc[i_bus,'max_Vm']
    else:
        max_vm_pu = bus.loc[i_bus,'Vmax']
    if 'max_Vm' in bus.columns:
        min_vm_pu = bus.loc[i_bus,'min_Vm']
    else:
        min_vm_pu = bus.loc[i_bus,'Vmin']
    Pd = bus.loc[i_bus,'Pd']
    Qd = bus.loc[i_bus,'Qd']
    Va = bus.loc[i_bus, 'Va']


    # Fix problem with decimal operators ',' used in the .csv file
    if type(vn_kv) == str:
        vn_kv = float(vn_kv.replace(',','.'))
    if type(zone) == str:
        zone = float(zone.replace(',','.'))
    if type(max_vm_pu) == str:
        max_vm_pu = float(max_vm_pu.replace(',','.'))
    if type(min_vm_pu) == str:
        min_vm_pu = float(min_vm_pu.replace(',','.'))
    if type(Va_degrees) == str:
        Va_degrees = float(Va_degrees.replace(',','.'))
    if type(Vm) == str:
        Vm = float(Vm.replace(',','.'))
    if type(Pd) == str:
        Pd = float(Pd.replace(',','.'))
    if type(Qd) == str:
        Qd = float(Qd.replace(',','.'))



    # Constructing the RELSAD bus objects

    BUS = Bus(name=('B' + str(i_bus+1)), n_customers=1, coordinate=[x[
        ↪ i_bus]%10, y[i_bus]], is_slack = False)

    # Adding the buses to the bus list
    BusList.append(BUS)

    # Adding each of the maximum power values to the list
    P_max.append(Pd)
```

```
        # Counting number of buses being iterated
        BusCounter = BusCounter + 1



# Declaring line failure rates and repair time
line_stat_repair_time_dist = StatDist(stat_dist_type=StatDistType.TRUNCNORMAL
    ↪ ,parameters=NormalParameters(loc=1.25,scale=1,min_val=0.5,max_val=2,)
    ↪ ,)
fail_rate_line = 0.07

# Creating a list to hold all lines
LineList = []

# Iterating through line objects from Matpower-file

for i_branch in branch.index:

    LineCounter = 0

    # Extracting variables from branch dataframe
    f_bus = branch.loc[i_branch,'f_bus']
    t_bus = branch.loc[i_branch,'t_bus']
    if 'r' in branch.columns:
        r = branch.loc[i_branch,'r']
    else:
        r = branch.loc[i_branch,'br_r']
    if 'x' in branch.columns:
        x = branch.loc[i_branch,'x']
    else:
        x = branch.loc[i_branch,'br_x']
    if 'b' in branch.columns:
        b = branch.loc[i_branch,'b']
    else:
        b = branch.loc[i_branch,'br_b']
    if 'rateA' in branch.columns:
        rateA = branch.loc[i_branch,'rateA']
    else:
        rateA = branch.loc[i_branch,'rate_A']
    if 'rateB' in branch.columns:
        rateB = branch.loc[i_branch,'rateB']
    else:
        rateB = branch.loc[i_branch,'rate_B']
    if 'rateC' in branch.columns:
        rateC = branch.loc[i_branch,'rateC']
    else:
        rateC = branch.loc[i_branch,'rate_C']
    shift = branch.loc[i_branch,'shift']
    br_status = branch.loc[i_branch,'br_status']

    # Fix problem with decimal operators ',' used in the .csv file
    if type(r) == str:
        r = float(r.replace(',','.'))
    if type(x) == str:
        x = float(x.replace(',','.'))
    if type(b) == str:
        b = float(b.replace(',','.'))
    if type(rateA) == str:
```

```
        rateA = float(rateA.replace(',','.'))
    if type(rateB) == str:
        rateB = float(rateB.replace(',','.'))
    if type(rateC) == str:
        rateC = float(rateC.replace(',','.'))
    if type(shift) == str:
        shift = float(shift.replace(',','.'))
    if type(br_status) == str:
        br_status = float(br_status.replace(',','.'))

    # Converting line rating to units kA from units MVA
    base_kV = s_base_kV[f_bus]
    max_i_ka = rateA / base_kV / math.sqrt(3)

    # Base impedance value (ohm)
    Zni = base_kV**2/baseMVA

    # we give impedances in ohm and set the length to 1
    length_km = 1

    # Converting from p.u. to ohm
    r_ohm = r * Zni
    x_ohm = x * Zni

    # Converting charging susceptance from p.u. to ohm
    omega = math.pi * f_hz # 1/s
    c_nf_per_km = b/Zni/omega*1e9/2

    # Constructing the RELSAD line objects
    LINE = Line(name = ('L' + str(i_branch)), fbus = BusList[f_bus-1], tbus =
        ↪ BusList[t_bus-1], r = r_ohm, x = x_ohm, fail_rate_density_per_year
        ↪ = fail_rate_line, repair_time_dist = line_stat_repair_time_dist)

    # Adding RELSAD line to list
    LineList.append(LINE)

    # Update line counter
    LineCounter = LineCounter + 1

# Adding EVPark of 20 EVs to the power system (NB! EVPark must be added to
    ↪ bus with load for V2G to be activated)
num_ev_table = Table(x=np.arange(0,24), y=np.ones(24)*20)
EVPark(name='EV1', bus=BusList[116], num_ev_dist=num_ev_table, v2g_flag=True,
    ↪  inj_p_max=0.0074, inj_q_max=0.0074)


# Creating circuit breaker
E1 = CircuitBreaker(name='E1', line=LineList[0])

# Creating power system controller

C1 = ManualMainController(name='C1', sectioning_time=Time(0))

# Creating power system
ps = PowerSystem(controller=C1)

# Creating transmission system
tn = Transmission(parent_network=ps, trafo_bus=BusList[0])
```

```
    # Creating distribution system
    dn = Distribution(parent_network=tn, connected_line=LineList[0])

    # Need to remove the trafo bus and the distribution line from the bus- and
        ↪ line list
    NewBusList = BusList[1:len(BusList)]
    NewLineList = LineList[1:len(LineList)]

    # We add the buses and lines to the existing distribution system
    dn.add_buses(NewBusList)
    dn.add_lines(NewLineList)

    # We plot the network topology to validate the results
    fig = plot_topology(buses=ps.buses,lines=ps.lines,bus_text=True,line_text=
        ↪ True,)
    fig.savefig("CINELDI_MV_reference_grid.png",dpi=600)


    return ps
```

A.2 Script for running Monte Carlo simulation (Excluding plotting of results)

Listing 2: Script for running Monte Carlo simulation using RELSAD models.

```
import pandas as pd
import numpy as np
import os
import math
import matplotlib.pyplot as plt

from relsad.network.components import (
    Bus,
    Line,
    Disconnector,
    CircuitBreaker,
    ManualMainController,
)

from relsad.network.systems import (
    PowerSystem,
    Transmission,
    Distribution,
)

from relsad.network.components import (
    Production,
    Battery,
    EVPark,
)
from relsad.Table import Table

from relsad.Time import (
    Time,
    TimeUnit,
    TimeStamp,
)

from relsad.StatDist import (
    StatDist,
    StatDistType,
    NormalParameters,
)

from relsad.load.bus import CostFunction
from relsad.visualization.plotting import plot_topology
from relsad.simulation import Simulation

import load_profiles as lp

import read_net_from_csv_to_RELSAD as readRELSAD
```

```
# Reading files for grid data from SINTEF Energy
path_data_set = '/Users/magnushatletveit/Documents/PYTHON/Masteroppgave/RELSAD/
    ↪ relsad-main/Magnus/Data/'

filename_scenario = 'scenario_LEC_only.csv'

filename_residential_fullpath = os.path.join(path_data_set,'
    ↪ time_series_IDs_primarily_residential.csv')
filename_irregular_fullpath = os.path.join(path_data_set,'
    ↪ time_series_IDs_irregular.csv')
filename_load_data_fullpath = os.path.join(path_data_set,'
    ↪ load_data_CINELDI_MV_reference_system.csv')
filename_load_mapping_fullpath = os.path.join(path_data_set,'
    ↪ mapping_loads_to_CINELDI_MV_reference_grid.csv')
filename_scenario_fullpath = os.path.join(path_data_set,filename_scenario)

# Create PowerSystem object in RELSAD using the read-function
ps = readRELSAD.read_net_from_csv_to_RELSAD(path_data_set, baseMVA=10)

# Creating load profiles for the buses (using function created by SINTEF Energy
    ↪ for reference grid load data handling)
load_profiles = lp.load_profiles(filename_load_data_fullpath)

# Mapping load profile to each bus in the grid from one day of load
#profiles_mapped = load_profiles.map_rel_load_profiles(
    ↪ filename_load_data_fullpath,filename_scenario_fullpath,
    ↪ filename_load_mapping_fullpath)

# Creating number of days for each load profile over a year
Days = []
DaysInYear = 365
for i in range (DaysInYear):
     Days.append(i)

# Creating mapped load data for each bus for one whole year (using function
    ↪ created by SINTEF Energy for reference grid load data handling)
profiles_mapped = load_profiles.map_rel_load_profiles(filename_load_data_fullpath
    ↪ ,filename_scenario_fullpath,filename_load_mapping_fullpath, repr_days=Days
    ↪ )

# Power Factor
PF = 0.95

# Adding mapped load data to RELSAD bus objects for an entire year

for i_bus in range(0, len(ps.buses)):
    busname = str(ps.buses[i_bus].name.replace('B', ''))
    busnumber = int(busname)
    Pload_array = np.zeros(len(profiles_mapped)-1)
    Qload_array = np.zeros(len(profiles_mapped)-1)

    if busnumber in profiles_mapped.columns:
            for i_hour in range(0,len(profiles_mapped)-1):
                Pload_array[i_hour] = profiles_mapped[i_bus+1][i_hour]*P_max[i_bus
                    ↪ ]
                Qload_array[i_hour] = profiles_mapped[i_bus+1][i_hour]*P_max[i_bus
                    ↪ ] * math.tan(math.acos(PF))
```

```
            ps.buses[i_bus].add_load_data(pload_data=Pload_array, qload_data=
                ↪ Qload_array)

    else:
        continue


# Creating path for saving simulation results
save_path = os.path.join("Masteroppgave", "RELSAD", "relsad-main", "Magnus", "
    ↪ Results")

# Creating simulation instance
sim = Simulation(power_system=ps, random_seed=1)

# Running load flow
sim.run_load_flow(ps)

# Setting number of iterations for Monte Carlo simulation
Iteration_number = 3000
Iteration_vec = []
for i in range(Iteration_number):
    Iteration_vec.append(i+1)


# Running Monte Carlo simulation and saving results
sim.run_monte_carlo(iterations=Iteration_number,
                    start_time=TimeStamp(year=2018, month=0, day=0, hour=0, minute
                        ↪ =0, second=0),
                    stop_time=TimeStamp(year=2019, month=0, day=0, hour=0, minute
                        ↪ =0, second=0), time_step=Time(1, TimeUnit.HOUR),
                    time_unit=TimeUnit.HOUR, callback=None, save_iterations=
                        ↪ Iteration_vec, save_dir=save_path, n_procs=1, debug=True
                    )
```

B Additional Results

C Case 1: Monte Carlo simulation of CINELDI reference grid without V2G

C.1 ENS

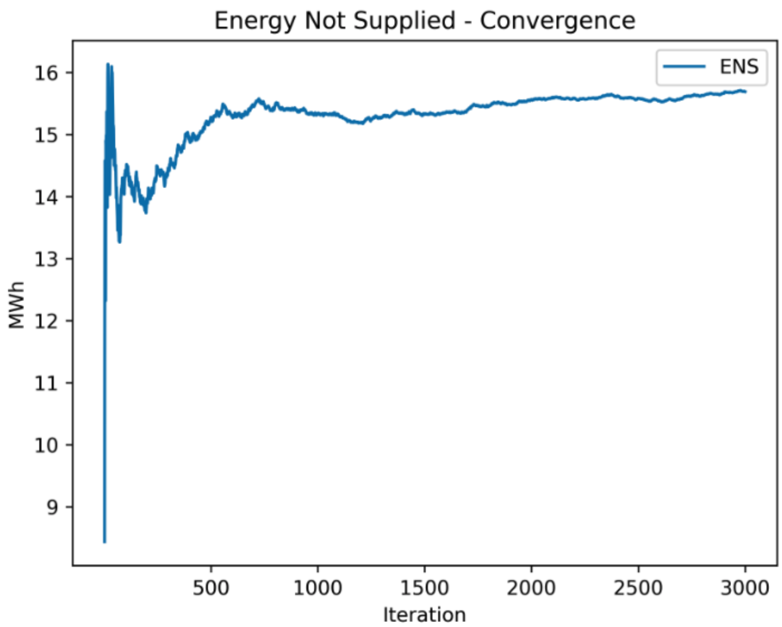

Figure 15: ENS convergence for 3000 iterations.

C.2 SAIFI

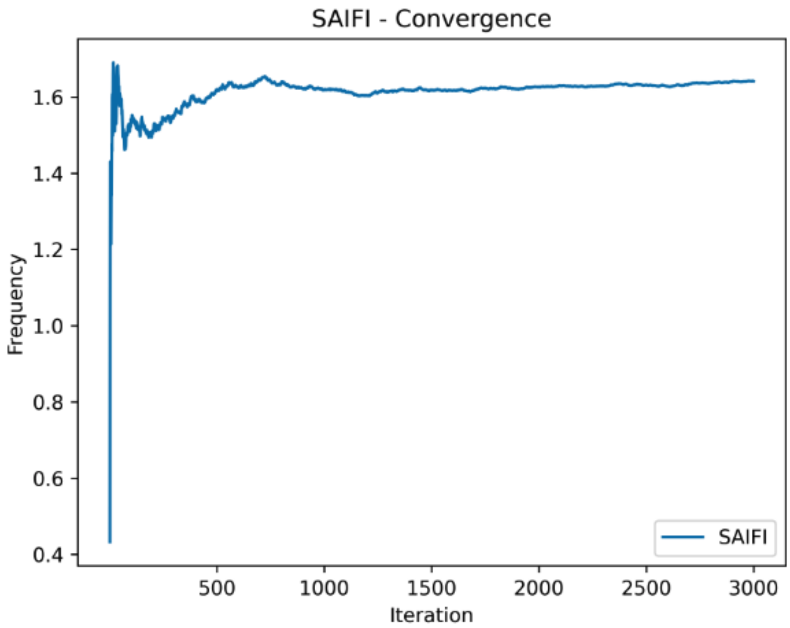

Figure 16: SAIFI convergence for 3000 iterations.

C.3 SAIDI

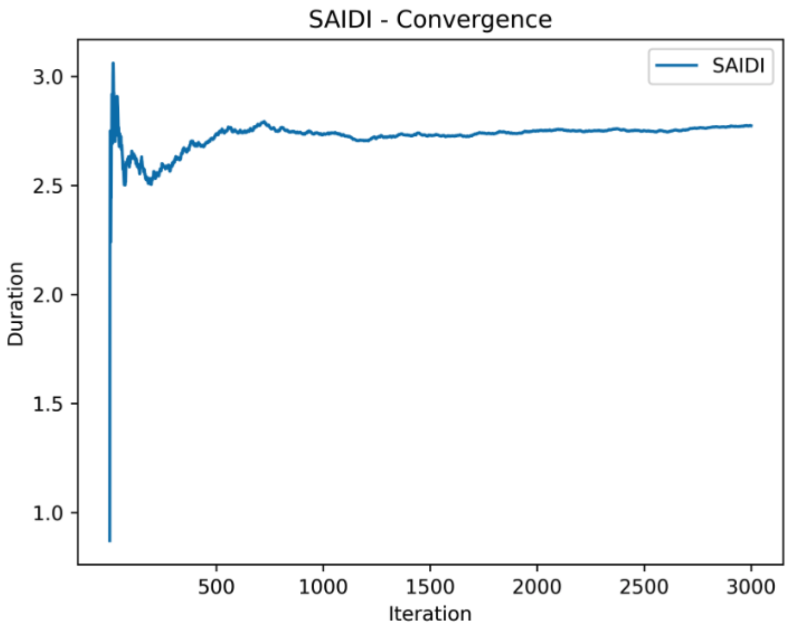

Figure 17: SAIDI convergence for 3000 iterations.

D Case 2: Monte Carlo simulation of CINELDI reference grid with V2G

D.1 ENS

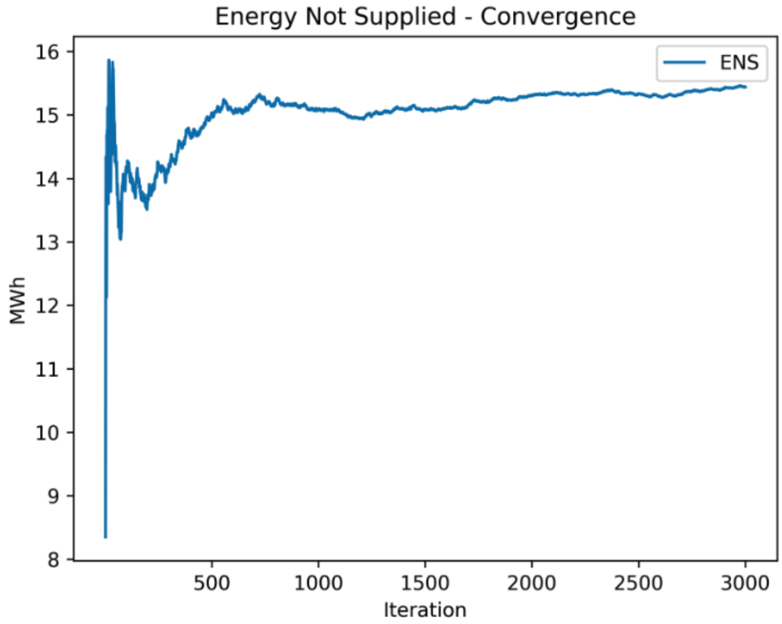

Figure 18: ENS convergence for 3000 iterations.

D.2 SAIFI

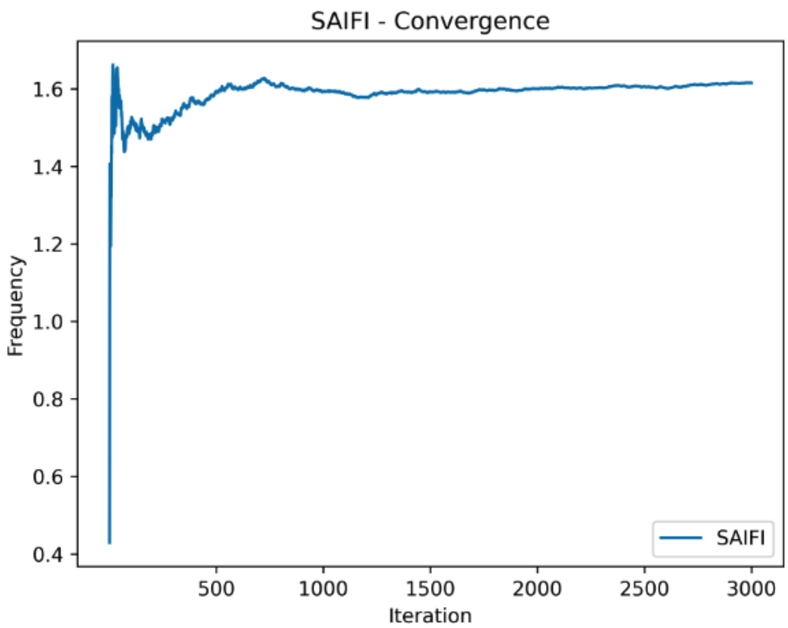

Figure 19: SAIFI convergence for 3000 iterations

D.3 SAIDI

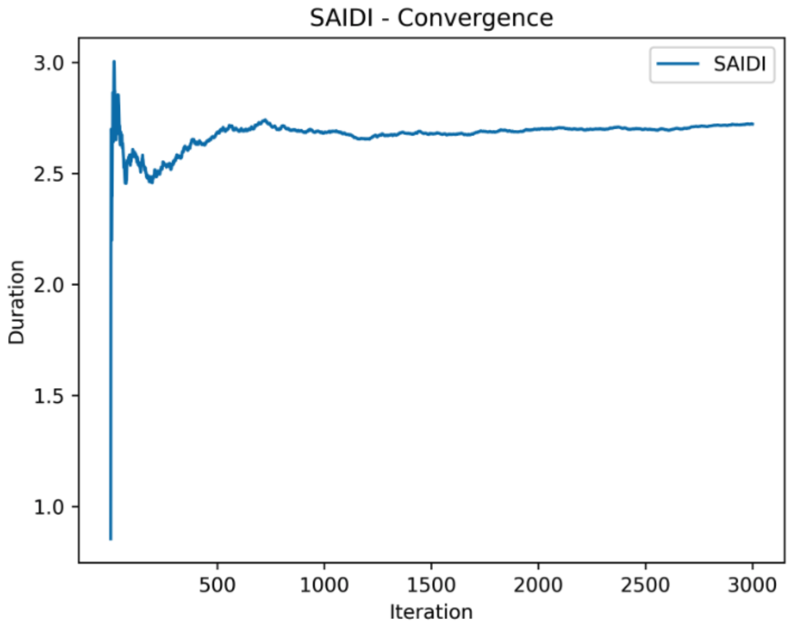

Figure 20: SAIDI convergence for 3000 iterations.

E Case 3: Monte Carlo simulation of CINELDI reference grid with improved EV charging capacity

E.1 ENS

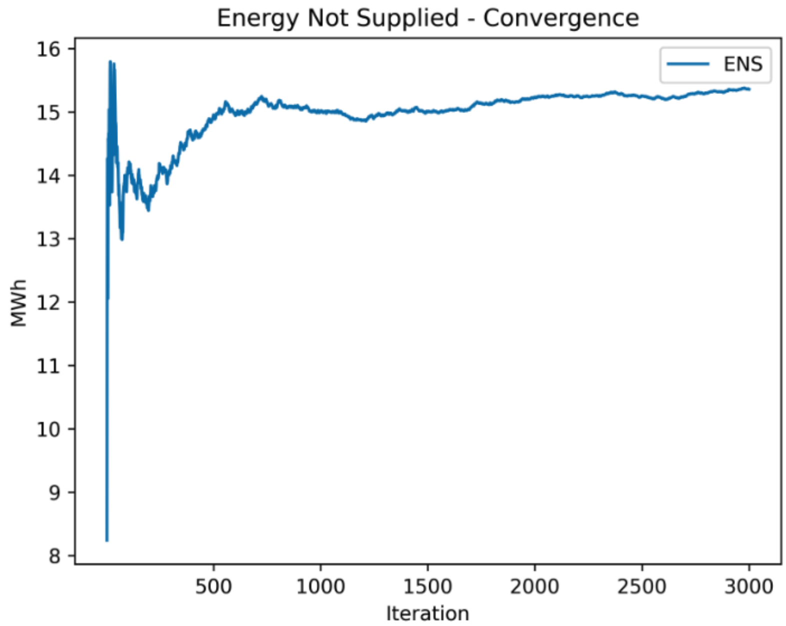

Figure 21: ENS convergence for 3000 iterations.

E.2 SAIFI

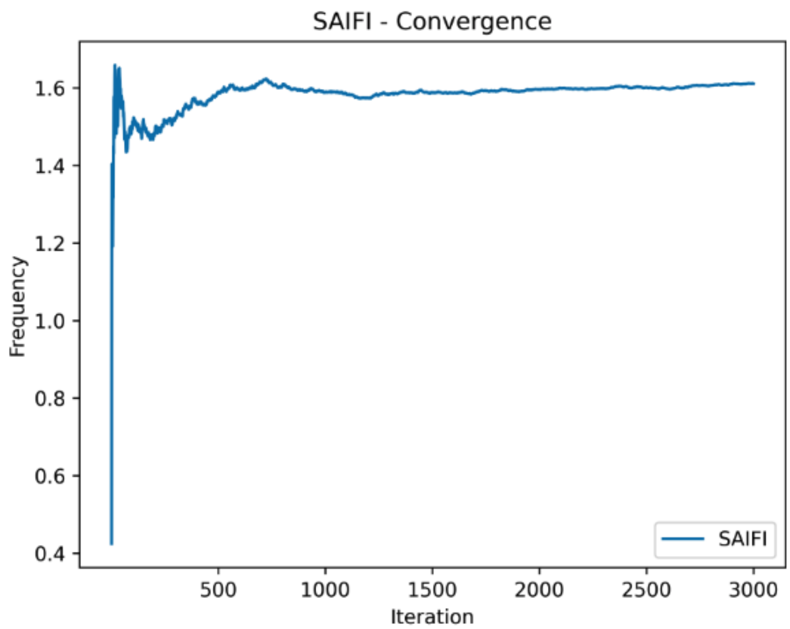

Figure 22: SAIFI convergence for 3000 iterations.

E.3 SAIDI

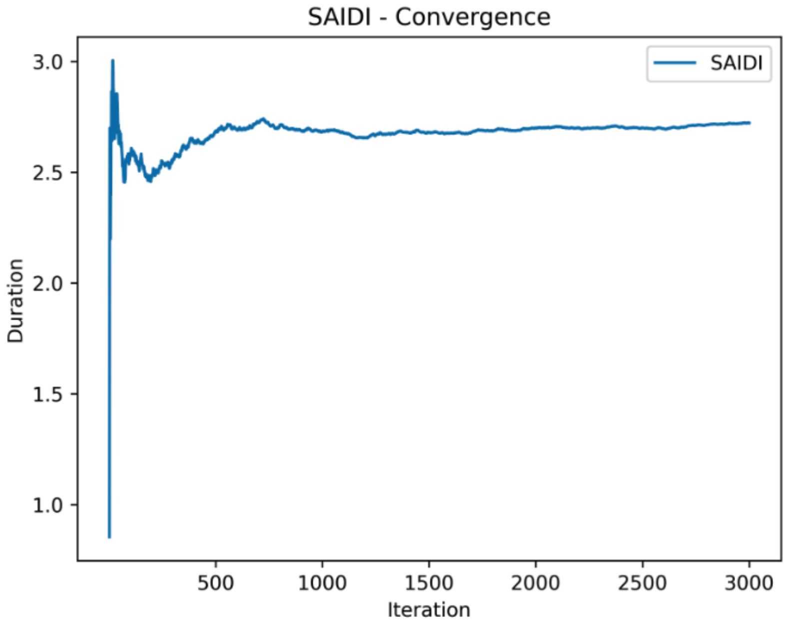

Figure 23: SAIDI convergence for 3000 iterations

F Zoomed Plots

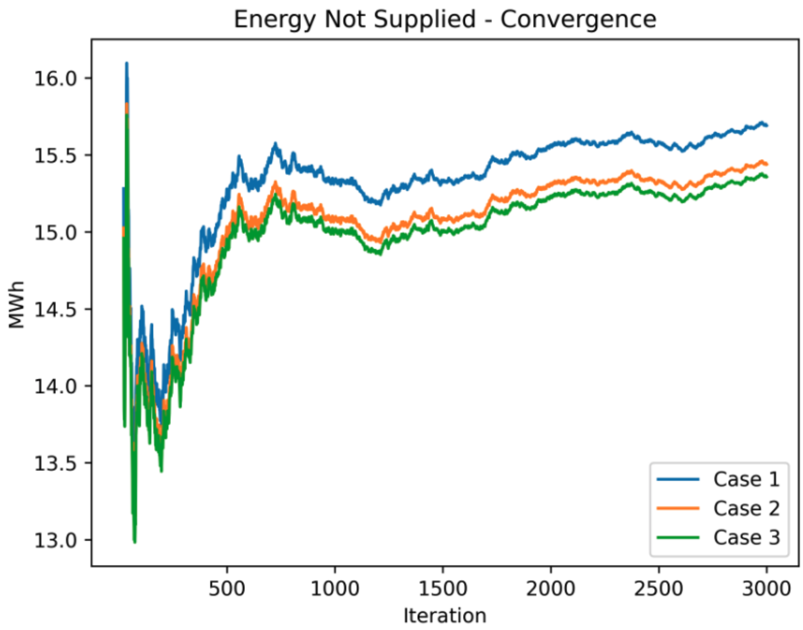

Figure 24: Same plot as Figure 12, but this figure neglects the first 20 iterations to eliminate extreme values and get a clearer view of the case differences.

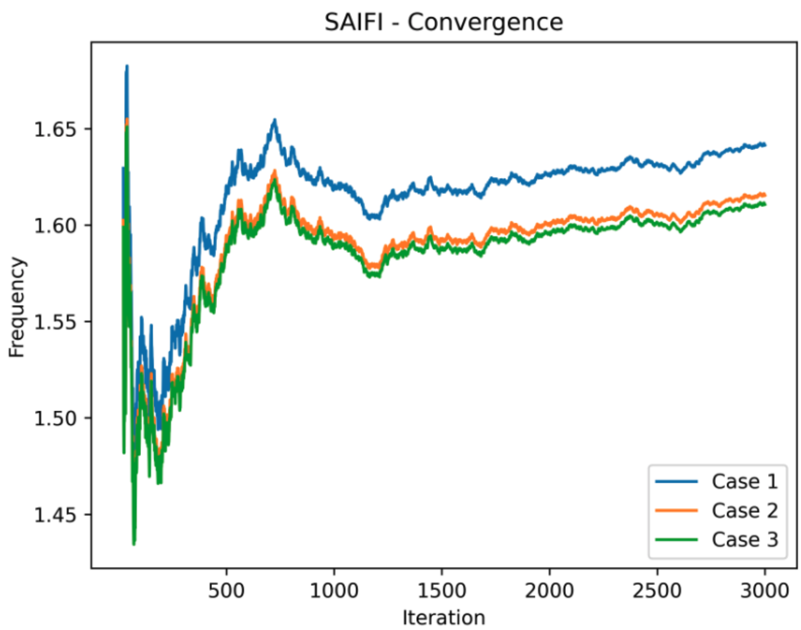

Figure 25: Same plot as Figure 13, but this figure neglects the first 20 iterations to eliminate extreme values and get a clearer view of the case differences.

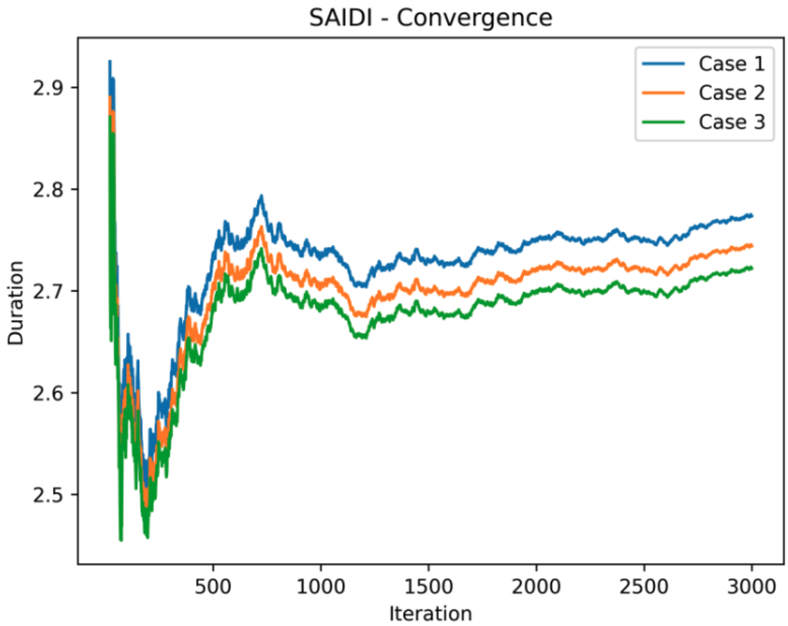

Figure 26: Same plot as Figure 14, but this figure neglects the first 20 iterations to eliminate extreme values and get a clearer view of the case differences.

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