Master's thesis

NTNU
Norwegian University of Science and Technology
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Department of Electric Power Engineering

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Potential of Hydrogen Technology for Coastal Electrification: Minimizing Distribution Grid Impacts through Flexibility

Master's thesis in Energy and Environmental Engineering
Supervisor: Irina Oleinikova, NTNU
Co-supervisor: Basanta Raj Pokhrel, NTNU
Andrei Morch, SINTEF Energi

June 2023

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ZEROKYST

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Preface

This master's thesis represents the finalization of a five-year study program in Energy and Environmental Engineering at the Department of Electric Energy at the Norwegian University of Science and Technology (NTNU). The research started in January 2023 and concluded in June 2023, accounting for 30 ECTS credits.

Given the urgent global need for decisive action in combating climate change, it is the author's sense of responsibility to develop sustainable, technical solutions that can address the challenges posed by the transition to a greener future. Consequently, the chosen topic of this thesis has been both captivating and meaningful. Moreover, considering the immense potential of green hydrogen in the forthcoming energy system and the ongoing progression of electrification, the work conducted in this study is highly relevant and forward-looking.

This master's thesis has greatly benefited from the invaluable contributions of numerous individuals, encompassing both academic and practical expertise. We would like to express our sincere gratitude to our supervisors, Irina Oleinikova and Basanta Raj Pokhrel, for their invaluable guidance and support throughout the duration of this thesis. Additionally, we extend our thanks to them for their supervision during the writing of the research paper [1], which was successfully published at The International Conference on European Energy Markets (EEM) held from 6 to 8 June 2023. Furthermore, we would like to acknowledge the contributions of Andrei Morch from SINTEF Energi, who provided us with the necessary background information regarding the ZeroKyst project.

We are also grateful to Egil Arne Østingsen and Thom Roger Pedersen from Elmea for generously providing us with the relevant data to build a realistic network model. The inclusion of this data significantly enhanced the value of this thesis. Although they were not directly involved in the master thesis, their contribution was a kind gesture.

Additionally, we would like to express our gratitude to the Department of Electric Energy at NTNU for generously sponsoring the travel expenses associated with our participation in the European Hydrogen Week 2022 held in Brussels, Belgium. This week-long conference, organized by the European Commission, Hydrogen Europe, and Clean Hydrogen Partnership, provided a remarkable opportunity to stay abreast of the latest advancements, both in terms of the advantages and challenges linked to clean hydrogen. Participating in this prominent annual event dedicated to hydrogen was not only highly informative but also offered us valuable insights. We would like to express our gratitude to NTNU for providing us with five remarkable and fulfilling years.

Lastly, we would like to express our sincere gratitude to our families and friends who have been supporting us throughout our five-year academic journey. We also extend our heartfelt appreciation to one another for making a strong collaborative environment and consistently dedicating the necessary hours towards our work.

Sofie Lorentzen
Sofie Lorentzen

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Abstract

The electrical power system is currently undergoing a significant transformation in response to the global challenge of climate change. This transformation involves the integration of an increasing number of renewable energy sources (RESs) and distributed generation (DG) at the distribution level. These technologies present challenges for system operators in terms of system stability. In order to effectively manage this transition and ensure the efficient operation of the evolving power system, the implementation of flexibility solutions is crucial. Norway, with its extensive coastline and abundant resources, holds a prominent position as a seafood exporter. To address the pressing need to reduce emissions, it is essential for the maritime sector in Norway to contribute to sustainable solutions. The electrification of the coastal fishing fleet in Lofoten represents an opportunity to achieve emission reduction goals and integrate a zero-emission driveline into the fleet. However, this transition poses challenges to the capacity and operation of the local power system.

This master's thesis aims to address the extent to which the electrification of the coastal fishing fleet in Lofoten affects the local distribution network. Additionally, it will demonstrate how the flexible operation of a water electrolyser can be utilized to minimize the impacts of electrification. Real network data obtained from the local distribution grid operator, Elmea, has been utilized to create a realistic network model in the simulation tool DIgSILENT Power Factory. Real load data from 2022 has been implemented in the software to enable simulations based on daily, weekly, and yearly cases, forming the basis for scenario creation. Furthermore, an electrolyser model has been developed to represent its characteristics and has been implemented at the end of the radial on the network section being analyzed.

The analysis of the present network, considering 2022 loads, indicates that the electrification of the coastal fishing fleet in Lofoten has a relatively low impact on the local distribution network. However, when examining future scenarios, it becomes evident that the lines and cables operate close to their rated values, resulting in a more significant impact from electrification. The flexible operation of the electrolyser is demonstrated for these scenarios, proving not only its feasibility but also its necessity in the worst-case scenario. Based on the results, the water electrolyser offers flexibility solutions such as voltage control to minimize voltage drops and load shifting to avoid network peaks. Additionally, the planned utilization of flexibility through hydrogen production and storage during periods of lower energy consumption is highlighted. The results confirm that the electrolyser is an effective resource for flexible operation, capable of rapid ramping up and down, thereby supporting stable network operation. The economic advantages of flexible electrolyser operation compared to grid reinforcement are yet to be explored in future research. Overall, this thesis not only provides evidence of the electrolyser's potential for flexible operation but also examines the impacts of electrification on the distribution grid.

Sammendrag

Det elektriske kraftsystemet gjennomgår for tiden en betydelig transformasjon som respons på den globale utfordringen med klimaendringer. Denne transformasjonen innebærer integrasjon av en økende mengde fornybar energi og kraftproduksjon på distribusjonsnivå. Disse teknologiene gir utfordringer for systemoperatører når det gjelder systemstabilitet. For å effektivt håndtere denne overgangen og sikre effektiv drift av det utviklende kraftsystemet, er implementering av fleksible løsninger avgjørende. Norge, med sin omfattende kystlinje og rikelige ressurser, har en fremtredende posisjon som sjømateksportør. For å møte det presserende behovet for å redusere utslipp, er det essensielt at den maritime sektoren i Norge bidrar til bærekraftige løsninger. Elektrifiseringen av fiskebåtene i Lofoten representerer en mulighet for å oppnå målene for utslippsreduksjon og integrere en nullutslippsdrivlinje. Imidlertid skaper denne overgangen utfordringer for kapasiteten og driften av det lokale kraftsystemet.

Denne masteroppgaven har som mål å undersøke i hvilken grad elektrifiseringen av fiskeflåten i Lofoten påvirker det lokale distribusjonsnettet. I tillegg vil den demonstrere hvordan den fleksible driften av en et vann-elektrolyseanlegg kan opereres for å minimere konsekvensene av elektrifiseringen. Nettverksdata er innhentet fra den lokale distribusjonsnett-operatøren Elmea, og har blitt brukt til å lage en realistisk nettverksmodell i simuleringsverktøyet DIgSILENT Power Factory. Lastdata fra 2022 er implementert i programvaren for å muliggjøre simuleringer basert på daglige, ukentlige og årlige scenarier, som danner grunnlaget for scenariooppbyggingen. Videre er det utviklet en modell for elektrolyseanlegget for å representere dets egenskaper. Elektrolyseanlegget er implementert i enden av radialen på den delen av distributsjonsnetttet som blir analysert.

Analysen av dagens nettverk, med lastdata fra 2022, indikerer at elektrifiseringen av fiskeflåten i Lofoten har relativt liten innvirkning på det lokale distribusjonsnettet. Imidlertid blir det tydelig når man undersøker fremtidige scenarier at linjer og kabler opererer nær sine nominelle verdier, noe som resulterer i en mer betydelig innvirkning fra elektrifiseringen. Fleksibel drift av elektrolyseanlegget blir demonstrert i de ulike scenarioer, og viser at fleksibel drift ikke bare er gjennomførbart, men dessuten nødvendig når man ser på de verste scenarioene. Basert på resultatene, kan elektrolyseanlegget tilby fleksible løsninger som spenningskontroll for å minimere spenningsfall og lastflytning for å unngå effekttopper. I tillegg fremheves planlagt fleksibilitet gjennom produksjon og lagring av hydrogen i perioder med lavere energiforbruk. Resultatene bekrefter at elektrolyseanlegget er en effektiv ressurs for fleksibel drift, i stand til rask opp- og nedjustering, og støtter dermed stabil nettverksdrift. De økonomiske fordelene ved fleksibel drift av elektrolyseanlegget sammenlignet med nettforsterkning gjenstår for fremtidig arbeid å bli utforsket. Alt i alt, presenterer denne avhandlingen ikke bare bevis på elektrolyseanleggets potensial for fleksibel drift, men undersøker også virkningene av elektrifisering på distribusjonsnettet.

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Acronyms

AC Alternating Current.
AEM Anion Exchange Membrane.

BoP Balance of Plant.

CAPEX Capital Expenditure.

DC Direct Current.
DER Distributed Energy Resources.
DG Distributed Generation.
DNV Det Norske Veritas.
DSL DIgSILENT Simulation Language.
DSO Distribution System Operator.

EEM The International Conference on European Energy Markets.

FCH 2 JU Fuel Cells and Hydrogen 2 Joint Undertaking.
FCP Ferry Charging Point.

GFF Garantikassen For Fiskere.
GHG Greenhouse Gas.

IEA International Energy Agency.

LCV Low Calorific Value.
LNG Liquefied Natural Gas.
LV Low Voltage.

MV Medium Voltage.

NR Newton-Raphson.
NTNU Norwegian University of Science and Technology.
NVE Norges Vassdrags- og Energidirektora.

PEM Proton Exchange Membrane.

RES Renewable Energy Source.

SOEC Solid Oxide Electrolyser Cell.

TSO Transmission System Operator.

VRE Variable Renewable Energy.

Chapter 1

Introduction

1.1 Backround and Motivation

In the past decade, the importance of combating climate change has grown significantly. To limit global temperature rise to 1.5 degrees and address the climate crisis, it is crucial to reduce greenhouse gas (GHG) emissions. One industry that contributes significantly to GHG emissions worldwide is the maritime industry. Norway, known for its vast coastline and abundant fishing resources, is a major seafood exporter and heavily reliant on the oceans for economic development. Therefore, Norway has a pressing responsibility to address emissions reduction in its maritime sector.

Currently, diesel propulsion systems are still widely used in the majority of fishing vessels in Norway, leading to substantial emissions. In fact, fishing vessels in Norway alone accounted for approximately 2% of the country's annual emissions in 2020, equivalent to 878,000 tons of CO_2 [2].

To reduce emissions in Norway's coastal areas, electrification and green energy technologies are essential. However, electrifying sectors that previously relied on fossil fuels will increase the load on the electrical power system, potentially necessitating expensive grid reinforcements to enhance capacity. Oversizing the grid based on peak power consumption may result in underutilization during normal operations. Therefore, flexible operation is necessary to fully utilize the grid's capacity and avoid unnecessary grid developments.

One technology that exhibits great potential for flexible operation is the water electrolysis system for hydrogen production and storage. Hydrogen, produced through water electrolysis, is expected to play a vital role in the future energy system as a green energy carrier. Furthermore, its production relies only on water and energy, making it easily accessible even in remote locations like small places such as Lofoten.

Considering the limited research available on how the operation of electrolysers can benefit the distribution grid through flexibility, this thesis focuses on evaluating electrolysers from a power system perspective. Furthermore, this thesis aims to evaluate the viability of electrifying a fishing fleet in Lofoten, providing valuable insights for future studies within the ZeroKyst project. This master's thesis is conducted in collaboration with the ZeroKyst project, coordinated by SINTEF Energi.

1.1.1 ZeroKyst

ZeroKyst is a partnership between research, interest groups, industry and municipalities, with Selfa Arctic AS serving as the project manager [2]. ZeroKyst project is a part of The Green Platform Initiative, which was launched by the Norwegian Government in May 2020. The initiative provides funding for enterprises and research institutes engaged in green growth and restructuring driven by research and innovation. ZeroKyst aims to reduce emissions by 50% from fishing and aquaculture vessels in the Lofoten area by 2030 [3]. The major objectives are to demonstrate options for mobile energy supply in Lofoten and to decarbonize the seafood industry by switching to hydrogen-electric propulsion [2]. ZeroKyst aims to initiate a technological transformation across various vessel categories within the fisheries and aquaculture sector. This initiative will involve the creation and exhibition of an innovative powertrain system known as Siemens Blue Drive and HybridZ, along with the development of a zero-emission vessel [3].

The ZeroKyst project intends to retrofit ten existing vessels to operate emission-free, while also offering comprehensive services for retrofitting and sustaining such vessels. Additionally, ZeroKyst will provide a comprehensive solution for a versatile supply of electricity and green hydrogen as sustainable maritime fuel [3]. Local hydrogen production is being planned by Lofotkraft Muligheter AS to provide predictable access for the zero emission vessels. It is also intended to create a circular solution system for the utilization of heat and oxygen in hatchery fish production from hydrogen generation [2]. A mobile energy supply unit is also considered, and it will provide a flexible supply of electricity and hydrogen. The many subprojects of the Zerokyst project are depicted in Figure 1.1 [3].

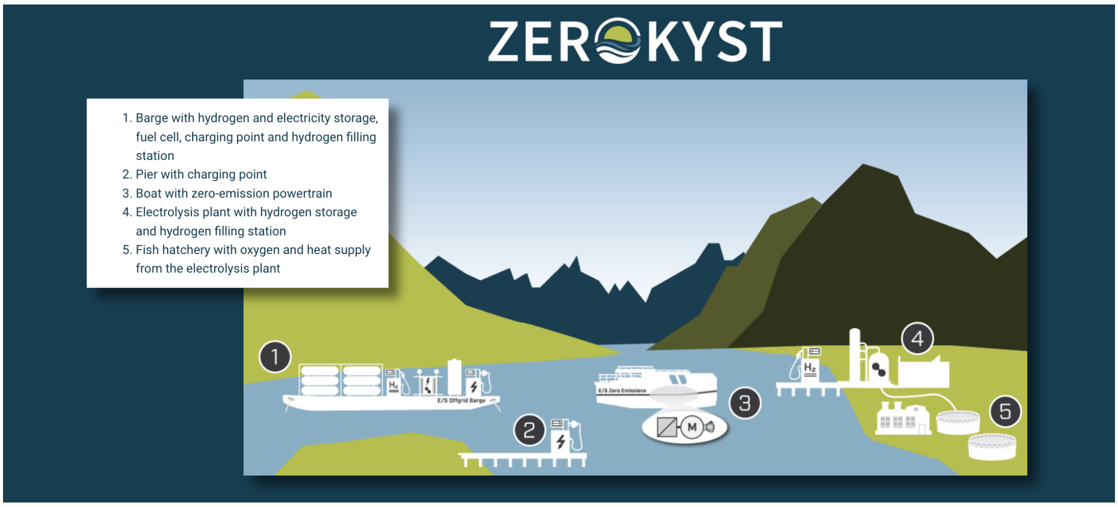

Figure 1.1: ZeroKyst concept sketch with solutions for hydrogen-electric boats, portable energy sources and infrastructure.

Source: [3]

1.2 Objective

This thesis aims to investigate the impact electrifying coastal fishing fleets in Loftoen has on the local distribution network. Additionally, it explores potential flexibility solutions through the implementation of a water electrolysis system. The main objective is to analyze the feasibility of supplying hydrogen to the electrified fishing fleets while utilizing the electrolyser as a flexibility solution to ensure stable operation of the distribution network. To achieve this, a realistic model of the distribution network in Lofoten is developed, allowing for simulation of various scenarios to analyze network effects and flexibility solutions.

The research question for this master thesis is:

To what extent does the electrification of a coastal fishing fleet in Lofoten affect the local distribution network, and how can the flexible operation of a water electrolyser be utilized to minimize these impacts efficiently?

1.3 Scope of Work

The methodology employed in this thesis comprises these main components: a literature review, a modeling phase, and a simulation scenario and results analysis. Each part contributes to the overall research objectives in a systematic manner.

The literature review serves as the foundation for the study, drawing upon relevant academic sources and previous research to establish a comprehensive understanding of the subject matter. Both authors of this master's thesis conducted comprehensive literature reviews on relevant topics. The literature reviews are available in the specialization projects *"How electrification of coastal fishing fleet at Lofoten will influence operation of the distribution network"* by Lorentzen, Sofie cited [4] and *"Electrolysers as a new variable load, optimal operation and consequences for the distribution network"* by Rasmussen, Marius cited [5]. This thesis incorporates insights from these specialization projects in Chapters 2, 3, and 4 in this thesis, thereby enriching the theoretical framework. The theoretical part serves as the foundation for the subsequent modeling phase and the simulation scenario. It establishes the necessary groundwork for analyzing and discussing the results obtained from the simulation. Additionally, a research paper [1] has been published that employs the same methodology as described in this thesis. The recent paper's content has received recognition from the scientific community, validating the efficacy of the methodology proposed in this thesis. The published research paper can be found in Appendix B.

This master thesis has the following structure:

Chapter 2, Change in the Power System: provide a concise overview of the traditional power system, highlighting the challenges introduced by renewable energy techniques and increased integration of DERs. Additionally, the chapter introduces flexibility and its function for the modern power grid.

Chapter 3, Hydrogen Technology in Power System Perspective: provides insights into the current status of the hydrogen industry and the level of technological development. It presents a comprehensive overview of various electrolyser technologies, allowing for a comparative analysis of their potential for flexible operation. Furthermore, it examines different performance factors and parameters crucial for modeling electrolysis within a power system perspective. The knowledge gained from this analysis serves as a foundation for developing an electrolyser model in Chapter 5.

Chapter 4, Electrification of the Coastal Fishing Industry: serves as an introduction to the Lofoten area, which is important for developing a realistic network model of the area. A comprehensive overview of the current situation along the Norwegian coastline is made, emphasizing the urgency for implementing greener and more sustainable solutions. Furthermore, an analysis of the energy consumption patterns of fishing fleets in the Lofoten region is conducted. This is to investigate if the capacity of the distribution grid can accommodate for coastal electrification, which will be simulated in various scenarios outlined in Chapter 6.

Chapter 5, Simulation Model: explains the process of power system analysis and a suitable methodology is selected, which is then thoroughly discussed. To develop accurate network models, collaboration with DSO Elmea is established. Through this collaboration, relevant parameters such as lines/cables parameters and load data is obtained and utilized to construct a realistic network model in DIgSILENT PowerFactory. Furthermore, leveraging the analysis of relevant parameters discussed in Chapter 3, an electrolyser model is being developed in PowerFactory.

Chapter 6: Simulation Scenarios and Results: develops three scenarios and analyzes the potential current and future states of the distribution network. These scenarios were simulated using DIgSILENT PowerFactory to assess the feasibility of electrification and demonstrate the flexible operation of the electrolyser to minimize associated impacts. The results obtained from the simulations are presented and discussed.

Chapter 7: Conclusion and Further Work: summarize the key findings derived from the analysis and discussion, providing a concise and comprehensive conclusion. Additionally, the "Further Work" section suggests potential research topics that warrant investigation but could not be accommodated within the scope of this thesis due to limitations.

1.4 Assumptions

In order to maintain focus on the objectives of this thesis, assumption needs to be considered. Firstly, only a portion of the distribution network is modeled, specifically one radial of the grid. This assumptions arises from various factors. As the grid operators are not officially collaborators in this master's thesis, obtaining actual data for the model is made possible through the kind cooperation of the distribution system operator (DSO) Elmea. However, insights into critical infrastructure are limited.

Secondly, the thesis does not specifically concentrate on the modeling of the hydrogen storage or the dimensioning of a hydrogen storage facility. It is assumed that the storage of hydrogen necessary for the different scenarios is feasible without explicitly examining the storage aspect.

Thirdly, real-time control of the water electrolyser is not modeled as it falls outside the scope of this master's thesis, which primarily focuses on the power system perspective.

Lastly, the investments and costs associated with implementing an electrolyser of the chosen size will not be considered due to the same reason stated above.

Chapter 2

Change in the Power System

The network of connected parts that together make up the electrical power grid includes power producers, power consumers, and several other electrical parts. Power generation, power transmission, and power distribution are the three components that makes up the power system [6]. These components are depicted in Figure 2.1 using distinct colors. Large-scale centralized power plants have typically produced the energy. These large-scale power plants have produced electricity using energy sources like thermal, nuclear, hydro, and fossil fuels. Through the transmission and distribution networks, the centrally located power plants deliver electricity to the end users. The distribution network is a local network that distributes power from the transmission system to the end customers while the transmission network transfers power over great distances. The grid would easily have stability most of the time because the generation from conventional, centralized power facilities is done in accordance with a schedule. Synchronous generators are installed at the producers in a traditional power grid to help maintain stability. The conventional power grid likewise made the assumption that energy only moves in one direction, from centralized producers to the rest of the system [6].

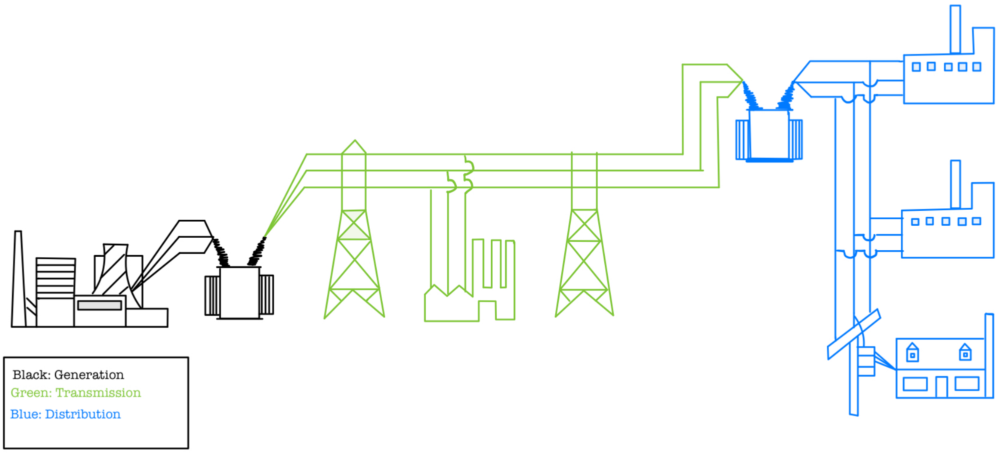

Figure 2.1: Representation of a traditional Power System

Source: [6, 4]

The world is battling the climate crisis, causing a shift in the electric grid. To prevent global temperatures from surpassing 1.5 degrees and remaining under 2 degrees, action is required from relevant parties. Since electricity generation from fossil fuels contributes significantly to global emissions, greener solutions should replace these technologies [7]. The electric grid shift incorporates the integration of renewable resources and DERs. DERs, such as decentralized power sources, can generate excess energy, which can be fed back into the grid. However, this can cause voltage issues for the distribution system due to reverse flows [8].

2.1 Future Power System

Renewable energy sources are progressively being incorporated into the power grid to replace conventional fossil fuel-based power generation as the globe goes through an energy transition. Due to the need for decarbonization and electrification in areas including industrial, transportation, and maritime, there is an increasing need for clean electric power [9]. To transition from fossil fuel-based power generation to sustainable technologies while maintaining operational quality and service capabilities, it is imperative to integrate a substantial amount of renewable generation technologies with limited inertia, expand distribution and transmission networks, and incorporate energy storage systems [9].

To achieve a 100% renewable power grid, large-scale renewable power plants and primary renewable energy sources, such as small-scale distributed generation, need to be implemented [6]. However, integrating DERs that enable bidirectional power flows poses a challenge for traditional power systems, which are designed for unidirectional power flows. This complication may have an impact on the design elements required to maintain the power network's safety and dependability. [7].

2.1.1 Distributed Energy Resources

If energy production is brought closer to where its intended used, there is potential for increased efficiency by avoiding long-distance transmission, transmission losses, and bottlenecks caused by optimal power plant locations. Electrolysers, micro wind turbines and other small-scale producers that generate electricity closer to the end-user are referred to as DG [4]. The integration of RES can increase the volume of DG, which encompasses other forms of DERs such as plug-in electric vehicles [6]. Implementing DER at the customer end of the grid increases consumer involvement and leads to a more complex distribution system with various components that affect operations. Figure 2.2 depicts power systems of the future with greater consumer involvement and DER integration. The DSO should be an active system operator, utilizing DERs connected to the distribution system to increase flexibility. The DSO can provide price signals to consumers and DER owners who do not have direct access to all DERs [6].

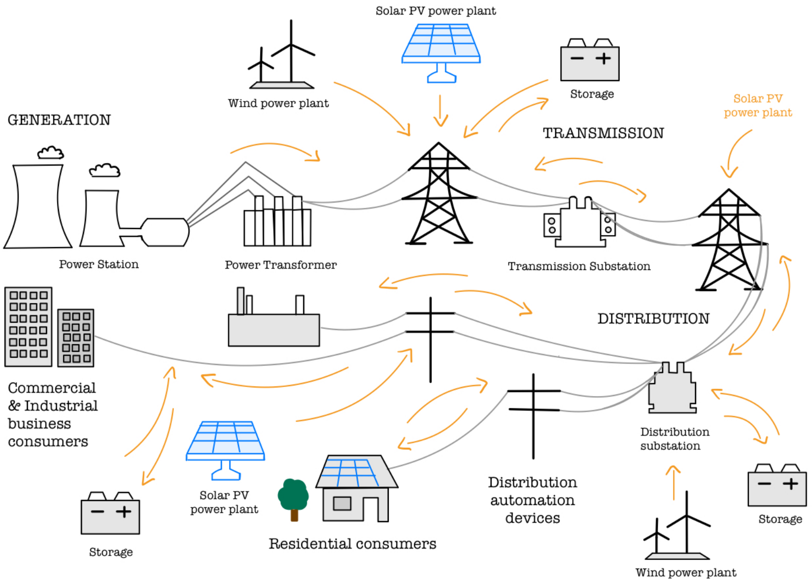

Figure 2.2: Representation of a future power system with DGs and bidrectional power flows.

Source: [4]

2.1.2 Variable Loads in the Distribution Network

The growing trend of RES presents difficulties to the existing electricity system due to its innate time-varying character. VRE loads, such as wind and solar power, introduce difficulties like variability, uncertainty, non-synchronous connection, and location restrictions [6]. Since VRE relies on natural resources that fluctuate over time, it's impossible to have complete control over their power production [10]. Unlike conventional power grids, it's not possible to adjust the power flow to VRE plants to control their output [10].

Forecasting the effects of VRE loads based on natural conditions, such as weather, is not easy for variable loads in the distribution network. This makes it more complicated to generate entirely reliable power plans and forecasts for wind and solar power production [6]. Due to the usage of resource reserves for generation, non-VRE power output can be scheduled in advance to meet anticipated demand [6]. Therefore, the stability of the power systems may be impacted by excessive VRE integration. In the context of the power grid, the presence of inertia is crucial to ensure reliable operation and maintain system stability.

VRE are not directly connected to the grid; instead, they employ power electronics to connect to it. This non-synchronous connection means that VREs do not provide any system inertia. Inertia in power systems refers to the energy stored in large rotating generators that gives them the momentum to keep rotating [11].

2.1.3 Future Power Consumption

In Norway

A report conducted by Statnett, entitled ”Consumption Trends in Norway 2022-2050,” provides estimates of energy consumption increases under different scenarios, as illustrated in Figure 2.3. The scenarios range from *low* (in green) to *extra high* (in dark blue), with *basis* (in black) and *high* (in light blue) in between. The x-axis represents the years in chronological order, while the y-axis represents the electric energy consumption in TWh. Energy assessments regulations require power system investigations to have a minimum 20-year planning horizon [12], making it reasonable to compare current consumption to 2040 or later. In the basis scenario, consumption is projected to increase by 50%, from 140 TWh in 2022 to 210 TWh in 2040 [13]. Comparing the 2022 consumption to the extra high scenario in 2050, where consumption is estimated to reach 300 TWh, the result is a 114% increase in consumption.

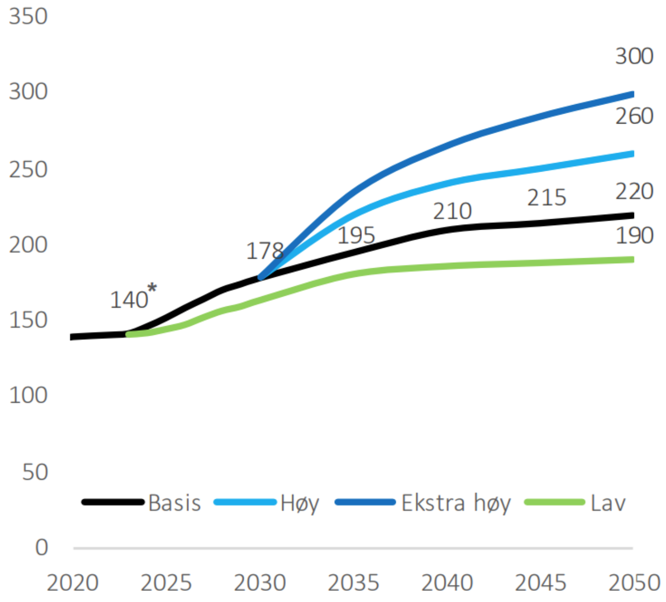

Figure 2.3: The graph displays four different scenarios for annual electric energy consumption [TWh] in Norway, as projected by transmission system operator (TSO) Statnett.

Source: [13]

In Lofoten area

The degree to which electric energy consumption will increase in the Lofoten area compared to in Norway is uncertain, as the scenarios presented in Statnett's report [13] do not provide information on how consumption growth is distributed across the country. To simplify the analysis, the same percentage increases as those presented in that report will be assumed for the Lofoten area in Section 6, Simulation Scenarios and Results.

2.2 Distribution Network in the Lofoten Area

Lofotkraft Produksjon generates around 49 GWh annually, which is roughly 10% of the Lofoten area's total electricity consumption [14]. While most of the electricity is sourced from inland power producers, the power plants in Lofoten hold significant strategic importance. In the event of a disruption in the primary supply line to Lofoten, these power plants can help sustain the power supply in certain parts of the region [14].

Norges vassdrags- og energidirektorat (NVE) has created a map displaying network facilities in Norway. In particular, Figure 2.4 highlights the Lofoten area, where Elmea AS, a network owner and DSO, holds an area concession. Røst and Værøy, two islands which can be seen in the bottom left of Figure 2.4, are linked to Å on the mainland by a 22 kV submarine cable. The regional network in the region comprises 145 kV cables running from Mølnarodden to Kvitfossen in Vågan, where it connects to the "Lofotringen" [15], which is a ring-shaped power supply line for Lofoten. The distribution network connects the various urban areas in Lofoten to the regional network through 22 kV cables. Although the Lofoten Ring is not part of the central grid, it is controlled by Statnett as part of the central grid [14]. The power companies in Lofoten and Vesterålen operate several small power plants, but not enough to meet the region's electricity demands, making the district reliant on electricity from other areas. In the event that one of the two lines develops a fault, the ring connection enables uninterrupted power delivery. However, the district is susceptible if both lines malfunction, as has happened on numerous times [14].

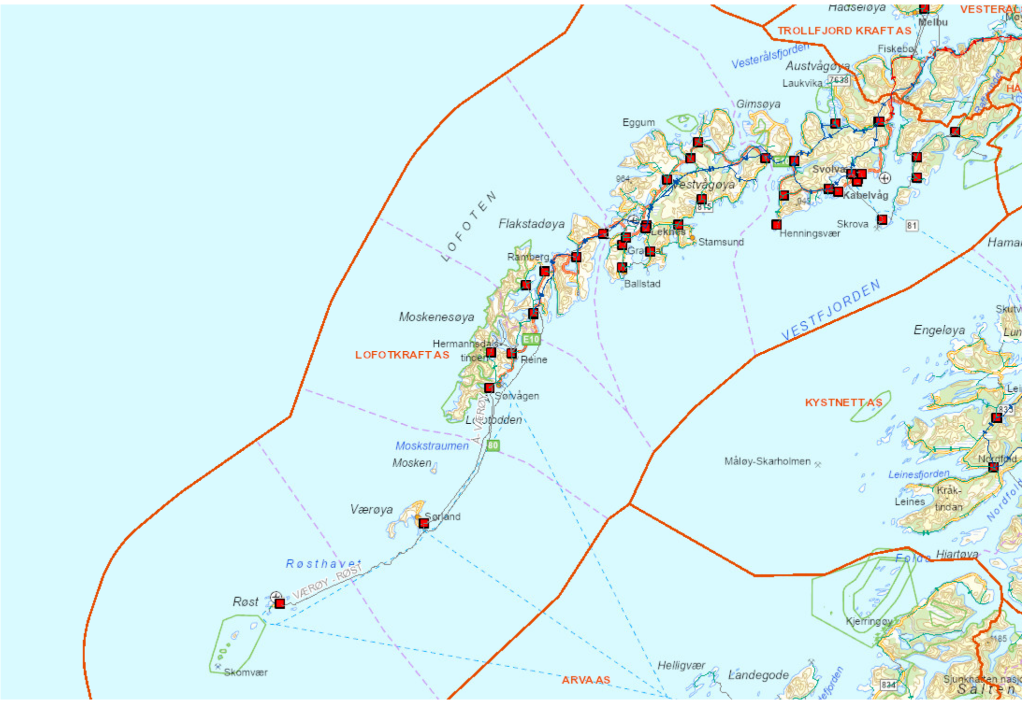

Figure 2.4: An overview of the distribution network in Lofoten taken from NVE temakart [15].

Source: [4]

The distribution network in is undergoing a significant transition as more and more industries are being electrified. This will be the case for the distribution network in Lofoten if there is to be implemented a zero-emission driveline with electrified industries. From electric vehicles to smart homes, the demand for electricity is set to increase significantly in the coming years. However, this transition to electrification also presents a challenge for the distribution network system, as it will require greater flexibility to maintain grid stability. As more devices and appliances are connected to the grid, the demand for electricity will become more variable and dynamic. This can create challenges for grid operators who must ensure that supply and demand are balanced at all times to maintain grid stability. Hydrogen is a promising flexibility solution for the electricity grid as it can be stored and transposed for use as a flexible energy carrier.

2.3 Flexibility Possibilities in Lofoten

As the power system is going through a transition, as mentioned in the previous sections, there is a growing need for flexibility to ensure stable and reliable power system operation. This flexibility is particularly crucial for small-scale technologies, like battery energy storage and controllable loads (or DERs), which generate electricity close to the end-user. The International Energy Agency (IEA) defines power system flexibility as the ability to modify electricity production or consumption in response to variability, whether expected or not. A utility that offers this flexibility is considered a flexible resource, capable of providing voltage and frequency regulation, resolving distribution grid bottlenecks, and acting as a balancing service [6].

2.3.1 Categorisation of Flexibility

Depending on the specific requirements, flexibility resources can be identified either at the local level or throughout the entire power system [9]. Flexibility plays a crucial role in maintaining balance, maintaining voltage levels, securing transfer capacities and ensuring supply. Four categories of flexibility needs can be explored [9]: *Flexibility for Power, Flexibility for Energy, Flexibility for Voltage and Flexibility for Transfer Capacity* [4]. Figure 2.5 depicts the interactions among these four categories in terms of both time and space, while Figure 2.6 provides several examples of flexibility solutions for each category. Given the impact of electrifying the fishing fleet in Lofoten on distribution network operations, this study will further investigate distribution-level flexibility resources to address issues related to high power demand, voltage stability and transfer capacity.

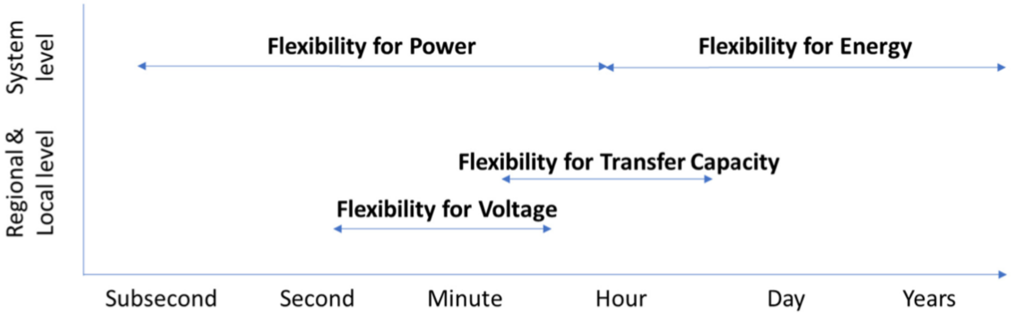

Figure 2.5: Flexibility requirements from a temporal and spatial perspective.

Source: [9]

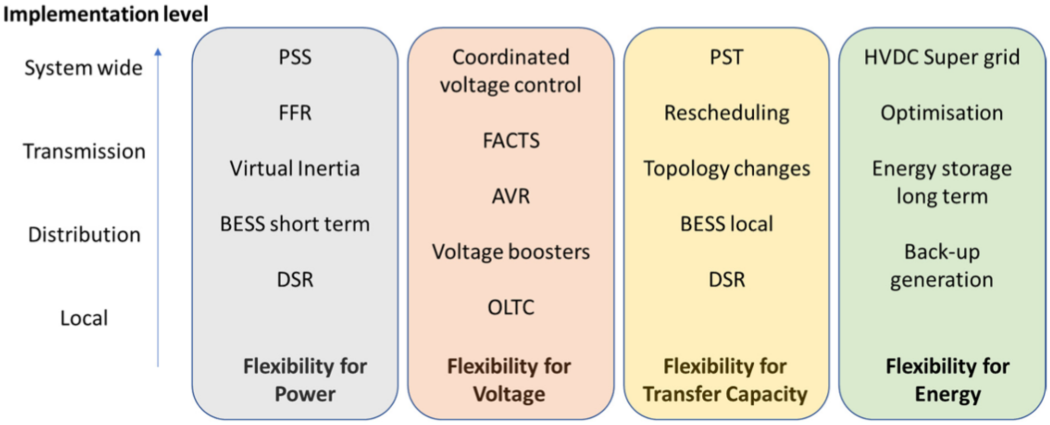

Figure 2.6: Implementation levels for flexibility categories.

Source: [9]

2.3.2 Flexibility at Distribution Level

Utilizing flexibility on distribution level can be a cost-effective and quick solution to handle unpredictable load patterns and integrate distributed generation and new consumption [16]. As demand forecasting becomes more uncertain and peak loads occur less frequently but with greater intensity, the business case for investing in grid capacity weakens [16]. Moreover, grid expansion takes time and money, so having access to flexibility might allow for the early connection of new generation and loads instead of having to wait for capacity expansion.

Throughout the history of distribution grids, the power infrastructure has evolved in parallel with economic expansion. To satisfy demand, distribution companies have concentrated on expanding grid capacity. The vast capacity of the distribution grids and the plentiful flexible generation available in the central system have allowed the system operator to maintain balance [16]. Several ongoing trends pose a threat to this strategy:

- *Expansion of grid capacity has become less cost-effective:* Due to the faster rise of peak load compared to energy demand, caused by advancements in technology and energy efficiency. This results in lower utilization rates of existing and new grid capacity, leading to an increase in unit prices. The trend of demanding underground cables instead of overhead lines, particularly in urban areas, also contributes to the rising unit costs of grid capacity augmentation [16].
- *Leveraging loads for system balancing:* New technology allows for the exploitation of customer flexibility at a lower cost. Single and small loads can be controlled automatically, providing alternatives to rationing and ample capacity margins for managing maximum peaks [16].
- *Increased distributed generation connection:* Introduces new flow patterns and operational challenges to distribution grids, which are closely associated with distributed generation [16].

Three common uses for flexibility at distribution level can be categorized [17]. *Voltage control* which involves using demand-side flexibility to address ower quality issues by adjusting voltage levels. *Congestion management* where momentary network problems that may be expected or unexpected can be handled using demand-side flexibility. *Grid capacity management* which explicitly considers demand-side flexibility as a regular part of network planning and operation.

Voltage control

Ensuring proper voltage regulation is crucial for maintaining an efficient electrical supply, with high quality and avoiding damage to electrical appliances. Distributed RES can often compromise voltage quality, particularly during periods of significant and rapid variations in flow or when demand is low. To address these challenges, real-time grid operation requires equipment capable of fast and automatic responses to absorb reactive effects and provide both up- and down-regulation. Accessible resources for voltage control must be distributed throughout the grid, and investments in integrated network components, including storage, may be necessary. Demand-side flexibility can also be used to regulate voltage, in addition to conventional grid techniques. It is important to note that voltage regulation is primarily a local problem, and thus requires local solutions [16].

Congestion management

Despite the grid being built with sufficient capacity (n-1), traffic jams and shortages might still occur. Some circumstances, like grid maintenance, connecting distributed generation, or infrastructure projects, such as transportation, district heating, or gas, may be planned in advance and addressed weeks or months beforehand. In such cases, demand-side flexibility may be activated when grid capacity is reduced. Since grid capacity is not fully utilized at all hours of the day, flexibility to reduce or disconnect load may be required during high-load periods. Additionally, if demand grows faster than anticipated, expanding grid capacity may not be feasible in time. Additionally, the risk of unexpected overload or fault events may increase with more intermittent production and capacity-intensive demand in distribution networks. Therefore, provisions for activating demand-side flexibility must be made in advance to deal with unexpected occurrences quickly [16].

Grid capacity management
To avoid the need for costly grid expansions, flexibility can be incorporated into grid planning. With access to flexible resources, DSOs can delay or even avoid grid expansions while still ensuring safe grid operation. During peak load periods, which typically occur for a few hours in the morning and afternoon in areas with high residential demand, grid constraints can be reasonably predicted, and load can be transferred to available resources to reduce grid expenses [16]. However, for flexibility to be a reliable option, resources must be consistently available during times of system stress, and grid dimensioning is necessary to handle power peaks. Load shifting is essential for managing grid capacity, and storage systems can make this process more manageable. Congestion management also requires similar qualities but is a less frequent difficulty than grid capacity management [16]. Therefore, investments that do not require additional resources may be more desirable for congestion management. Simple peak shaving and storage systems, such as hydrogen storage, electrolysers, heat pumps with storage, batteries, and electric vehicles, can help shift load and manage congestion [16].

The increasing need for flexibility as the power system is changing has led to exploration and integration of innovative technologies. Hydrogen technology, namely electrolyser technology, is one such technology that shows promise. Electrolysers offer the potential to provide flexibility in the power system by enabling their characteristics behaviours for efficient hydrogen production. A more resilient and sustainable power system can result from the move to electrolysers and hydrogen technology, which offers up new opportunities for energy storage, demand response, and grid balancing [4].

Chapter 3

Hydrogen Technology in Power System Perspective

This chapter delves into the technology behind hydrogen production and storage. Electrolyser technology for hydrogen production will be the focus in this thesis. While all pertinent production methods are mentioned, special attention is given to the Proton Exchange Membrane (PEM) electrolyser. This technology is not only utilized in the ZeroKyst project in Lofoten but also holds significant potential for flexible operation, benefiting the electrical distribution grid. Moreover, the chapter examines the economic aspects associated with operating such an electrolyser, specifically addressing the feasibility of employing flexible operation instead of producing hydrogen at a nominal rate. This chapter also examines the performance of the electrolyser and discusses the parameters necessary for modeling its behavior. By exploring the theoretical aspects of electrolyser technology, a foundation is established for developing an accurate and realistic electrolyser model in Chapter 5.

3.1 Current Hydrogen Situation

3.1.1 Production

In today's society hydrogen production is almost entirely based on the use of fossil fuels, as illustrated in Figure 3.1. This is leading to significant emissions of greenhouse gases, and are expected to increase in the coming years in line with the increasing hydrogen production. The CO_2 emissions from hydrogen production accounted for 2.5% of the annual global emissions of 2021, equivalent to 900 Mt of CO_2 [18]. The demand for hydrogen is expected to double and reach 180 Mt annually by 2030 [18], thus it becomes important to transition to hydrogen production methods that minimize emissions. Such methods are blue and green hydrogen production that allows a reduction in emissions of 85-95% and 100%, respectively [18]. As the former is produced from natural gas with carbon capture, the latter is produced through electrolysis with renewable electricity and does not technically produce emissions. The graph in Figure 3.2 shows how the share of these technologies must increase by 2030 to reach the Net Zero Scenario by 2050 [19]. Consequently, significant deployment of blue and green hydrogen production must be carried out in the coming years.

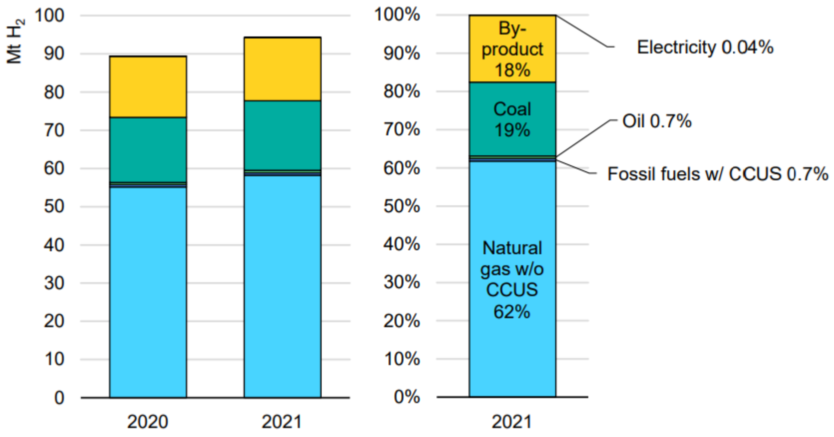

Figure 3.1: Hydrogen production by method worldwide.

Source: [19]

To integrate blue and green hydrogen, plans have already been made by the European Union to install electrolyser capacity of 6 GW and 40 GW by 2024 and 2030, respectively [20]. Also, their goal is to use solar and wind energy for this production. In this way, excess energy can be used to produce hydrogen in times of energy surplus and used in times of demand. Such storage can be on a seasonal or daily basis and will allow EU to rely more on renewable energy.

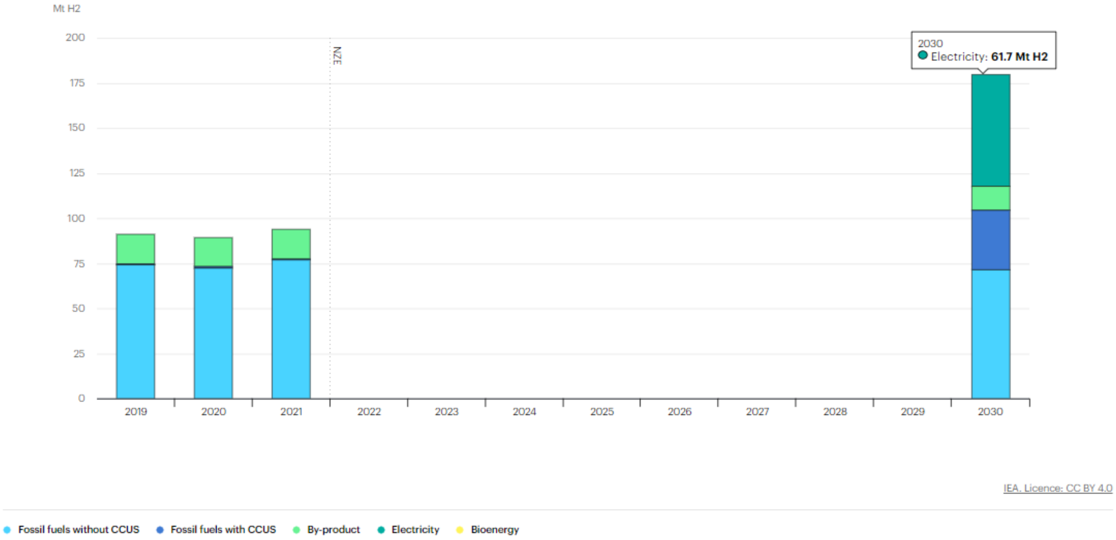

Figure 3.2: Hydrogen production method by 2030 in the Net Zero Scenario worldwide.

Source: [19]

For Norway the plans for installed electrolyser capacity are not as well defined as for EU. However, the government has established a hydrogen production roadmap that includes green and blue hydrogen generation. A series of steps have been outlined to support this plan's implementation. Firstly, establishment of five hydrogen production hubs for maritime sector and two projects on hydrogen production is planned by 2025 [19]. The government aims to create a network of safe and affordable hydrogen fueling sites for vessels and vehicles by 2030 [19]. The drive chain behind these implementations is the government's goal to cut GHG emissions by 50% and 90-95% by 2030 and 2050, respectively [21].

3.1.2 Safety Aspects

For the implementation of such hubs to be safe, different safety precautions should be taken into account. These precautions are significant for the handling of hydrogen due to its characteristics, that differ from other fuels like propane and gasoline. Hydrogen is more flammable and explosive than these fuels, having a flammability range of 4%-75% in a mix of air versus 2.2%-9.6% for propane and 1%-7.6% for gasoline [22]. Mixtures of gas and air outside these intervals will not be ignitable due to lack of oxygen. Thus, the explosion danger is significantly larger for hydrogen than that for the other two.

There are several incidents where hydrogen leakage have resulted in explosion. In June 2019 a hydrogen fueling station blew up in Sandvika, Norway [23]. Seismometers 11 and 28 km away from the fueling station detected the explosion, witnessing of the great forces involved in such an explosion. According to the consulting firm Gexcon, one of the bolts in the hydrogen tank was not properly installed [24], leading to hydrogen leakage forming a cloud of gas that eventually ignited and exploded. Another incident happening within the same month was a hydrogen explosion in Santa Clara, California [25]. The explosion took place while a tanker truck was being fueled, and firefighters spent more than an hour to stop the flames. Due to hydrogen's unique characteristics and the potential risks associated with its leakage and explosion, safety measures should be carefully carried out when handling this particular gas. For areas as Lofoten with severe weather at times, additional safety measures than those already in place could be considered to reduce risk of accidents, especially if storage tanks are located outside.

3.1.3 Hydrogen Storage

For hydrogen usage in marine vessels in Lofoten, storage tanks are most appropriate. Other storage methods are salt caverns and depleted gas reservoirs, but they require significant infrastructure, such as gas pipelines or a transportation network via vehicles or vessels. Consequently, a lower efficiency of the hydrogen is obtained, thus storing hydrogen close to the production and distribution site is desired. Storage tanks allows this to happen.

Generally speaking there are two ways to categorize storage tanks, i.e. those designed for ambient pressure and those designed for high pressure, namely pressurized tanks [26]. As the name suggests, the tanks designed for ambient temperatures are used for chemicals that under ambient conditions remain stable, such as crude oil, gasoline etc. The latter on the other hand is used for chemicals that to remain stable needs either cooling or pressurization, or both. Such substances might be liquid petrol gas, liquid natural gas, liquefied hydrogen as well as just hydrogen gas.

The pressure in a tank used for hydrogen storage can be 350 and 700 bar [27]. Despite storing hydrogen at 700 bar, the energy density is close on seven times higher for gasoline, as shown in Table 3.1. As a result vessels and vehicles that are fueled with hydrogen must have much larger gas tanks to carry the same amount of energy. To deal with this problem, hydrogen can be liquefied to increase its energy density. This comes at a cost of lower theoretical efficiency, as liquefaction plants consume 10 kWh/kg hydrogen liquefied [19].

Table 3.1: Energy density of hydrogen compared to gasoline [28, 29].

Type of fuel	**Energy density** $[kWh/m^3]$
Hydrogen at 700 bar	1,320
Gasoline at ambient pressure	9,100

3.2 Current Electrolysis Situation

Figure 3.1 indicates that in 2021, electrolysis technology was responsible for less than 0.1% of global hydrogen production. However, to achieve the Net Zero Scenario by 2050, Figure 3.2 suggests that approximately one-third of global hydrogen production should be based on electrolysis technology by 2030. Thankfully, many large-scale electrolysers are already slated for deployment by 2030, and according to Figure 3.3, the total installed electrolyser capacity will exceed 120 GW by 2030. Nevertheless, to reach the Net Zero Scenario by 2050, the electrolyser capacity must be increased to 700 GW by 2030 [30, 18]. Although the present planned projects may not attain this objective, the swift rise in expectations from the previous year implies that it could be within reach in the near future.

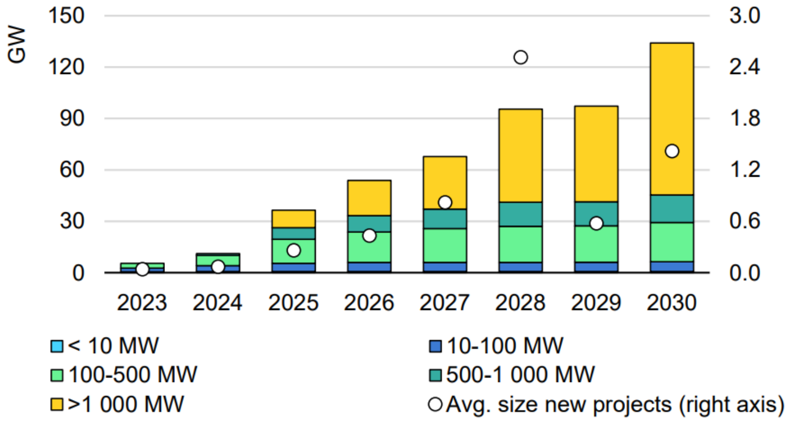

Figure 3.3: Electrolysis projects under planning or construction.

Source: [19]

3.2.1 Electrolyser Technologies

There are mainly four types of electrolysis technologies, i.e. alkaline electrolysis, proton exchange membrane electrolysis, solid oxide electrolysis cells and anion exchange membrane electrolysis, as shown in Figure 3.4. While their characteristics, prices and technology readiness levels varies, they all have some components such as electrodes, electrolytes and a membrane.

Alkaline electrolysers operate at 70-90 °C and at pressure of 1-30 bar [31]. An alkaline electrolyser has an operating load range of 10-110%, but experience lower efficiencies for lower loads and is thus not suited for large changes in load [18], meaning a such plant is best suited to operate with a fixed load. For loads close to 100% of nominal load, the electrical efficiency lies between 63% and 70% [31]. Alkaline elctrolysers have a technological readiness level (TRL) 9, meaning it has a market uptake, and made up 70% of the global electrolyser capacity in 2021 [19]. For flexibility purposes, the alkaline electrolyser uses a few seconds for ramp-up and ramp-down from minimum to maximum load or 13 to 20% of full loads per second [32]. The quick response time allows for the provision of power system services.

PEM electrolysers operate at 50-80 °C and at pressures up to 70 bar [31]. Their load range is larger than that of alkaline electrolysers; 0-160% of nominal load [18]. Overloading the PEM electrolyser is possible for a short time but require larger dimensions on electrical equipment such as cables and rectifiers and is not necessarily economical beneficial. The PEM plant is able to operate at a wider spectre of the load range without reduction of the electrical efficiency, but has in general a lower electrical efficiency of 56-60% [18].The technological maturity is similar as for alkaline electrolysers, but due to historical reasons PEM only make 25% of the global electrolyser capacity [19]. The PEM electrolyser uses a few seconds for ramp-up and ramp-dowm from minimum load to maximum load or from 10 to 100% of full load per seconds. This implies fast response time for flexibility.

Solid oxide electrolysis cells (SOEC) differs from the above two technologies by having a much higher operating temperature of 700-850 °C and a operating pressure of 1 bar [31]. Load range lies within 20-100% and electrical efficiency lies between 74-81%, but it is not including energy for steam generation [18]. SOECs has TRL 7, is still at a demonstration level, and thus has a smaller market share than the other two [19].

Anion exchange membrane (AEM) electrolysers can opeate between 40-60 °C and up to 35 bar, but is still at a prototype level. TRL of AEM electrolysers is 6, meaning it is at a large prototype stage [31].

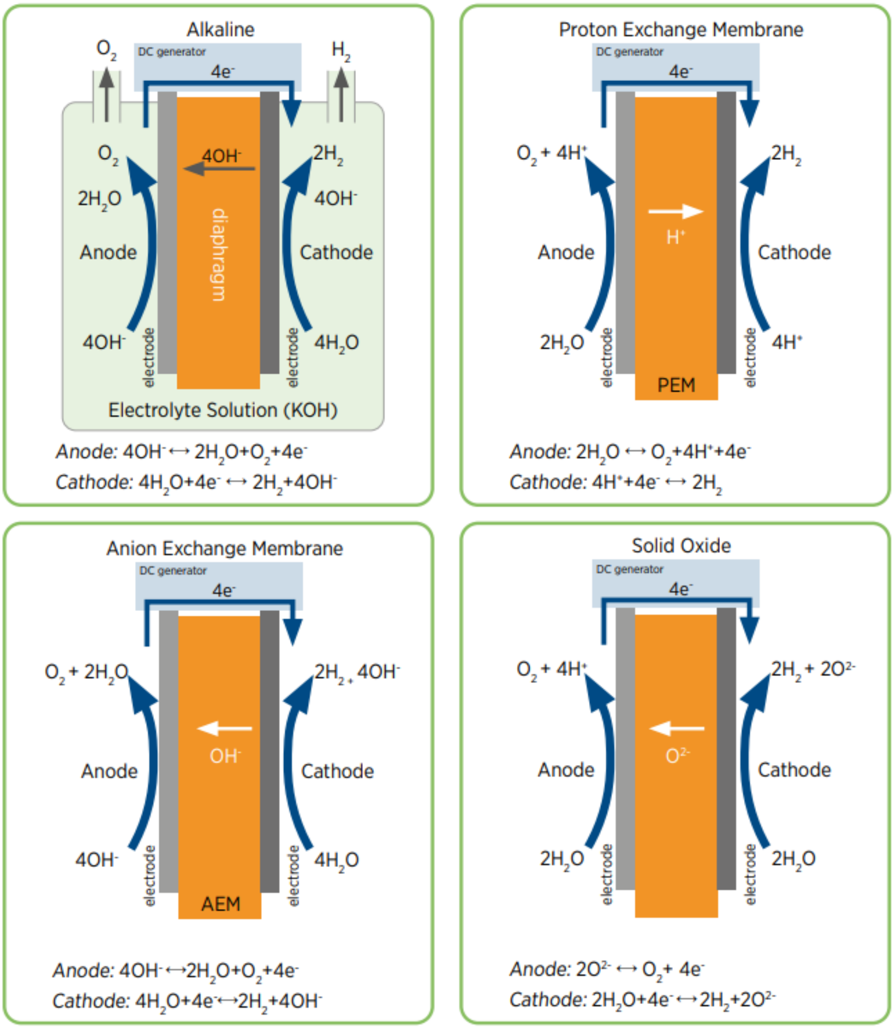

Figure 3.4: Electrolysis technologies.

Source: [31]

While alkaline electrolysers are considered the best option for larger plants, PEM electrolysers offer the advantage of easy deployment in various module sizes. This makes them well-suited for distributed hydrogen production, allowing multiple smaller units to be conveniently placed near the point of hydrogen consumption. By doing so, the reliance on extensive transportation infrastructure, such as pipelines, trucks, and marine vessels, is reduced. This aspect is likely one of the reasons why PEM electrolysis has been chosen for implementation in the ZeroKyst project. As this ZeroKyst project aims to have a competitive and flexible hydrogen supply, as mentioned in the Introduction, in Chapter 1, the PEM electrolysers are well-suited due to their favourable characteristics such as high current density, compactness, a thin membrane with high efficiency, fast response, and ability to operate dynamically [5].

3.2.2 Components in the PEM System

To gain a deeper understanding of how PEM electrolysis works, it is beneficial to break down the system into its individual components. The system comprises various components and subsystems, as illustrated in Figure 3.5 taken from [33]. The key components include:

- **Transformer and rectifier** that transform and convert high voltage Alternating Current (AC) to lower voltage and Direct Current (DC) to supply the electrolyser [33].
- **Electrolyser** that is responsible for splitting hydrogen and oxygen. The electrolyser is applied electric current and water.
- **Hydrogen/water separator** that separate the two substances and sends water back in to the water tank [33].
- **Oxygen/water separator** that separate oxygen and water. Oxygen is released to atmosphere in Figure 3.5, but may also be stored and used for fish hatchery facilities to increase the overall theoretical efficiency of the system, as intended in Lofoten [3].
- **Dryer** that will dry the hydrogen to the prefered dew point. Several beds will absorb water in this process [33].
- **Hydrogen storage** that stores hydrogen due to non-linear consumption and/or production.

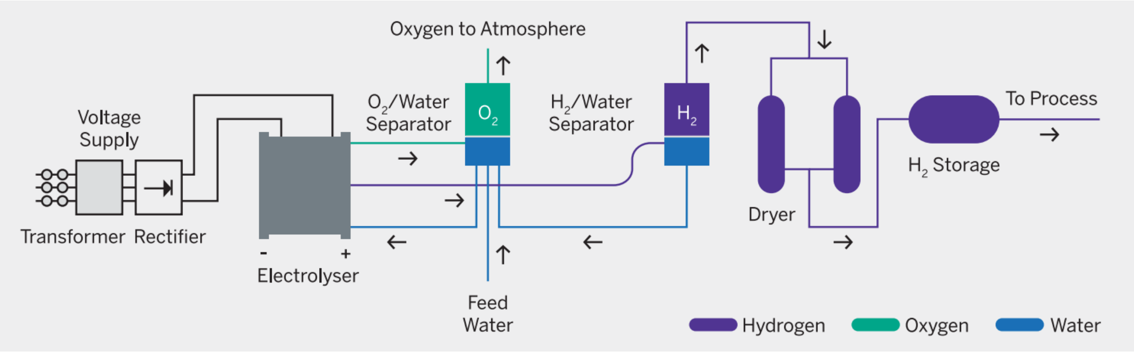

Figure 3.5: System representation of a PEM electrolyser plant.

Source: [33]

3.2.3 Electrolyser in a Power System Perspective

Electrolysers utilize electricity to produce green hydrogen and are considered variable loads from a power system perspective. They are connected to the main grid through an AC to DC power electronic interface, as shown in Figure 3.6 [34].

A complete representation of an electrolyser unit for electrical studies incorporates the system for power conversion, stack modeling, and balance of the plant. The electrolysis stack can be represented by an equivalent circuit consisting of the open circuit DC voltage and a series-connected resistor accounting for internal electrical losses. The DC-DC converter controls the power input by modulating the electrical current, and the AC-DC rectifier couples the electrolyser to the electrical grid. Thyristors or three-phase diode rectifiers linked to a DC chopper can provide the necessary DC current and voltage [35]. However, both types of converters have advantages, disadvantages, and additional challenges. The rectifier causes reactive power, while active power is required for the electrolysers to operate and generate hydrogen. As a load, the electrolyser consumes power from the grid, operating in the second and third quadrants of the PQ plane where P < 0 [34]. The dynamic nature of electrolysers makes them adjustable to changes in the power grid, providing flexibility and making them a valuable resource. By controlling the load profile or hydrogen production times, they can be utilized for load shifting and storage [36].

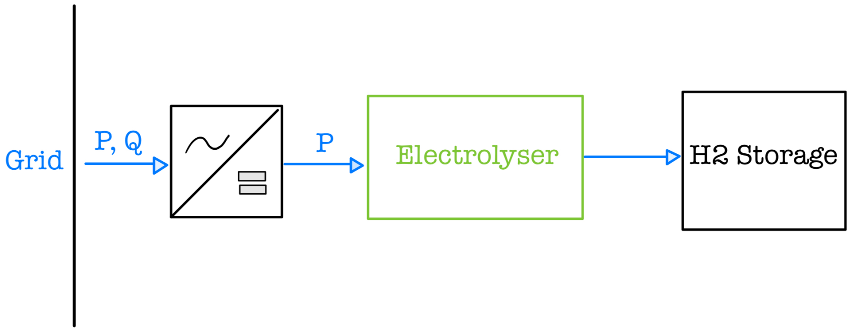

Figure 3.6: Overview of an electrolyser system connected to the grid.

Source: [34]

From an electrical network perspective, the rapid dynamics of PEM electrolysers are their most intriguing capability. These devices can quickly adjust the amount of electricity used in less than a second, as well as shut down and restart in a matter of seconds to minutes [35]. Additionally, they can operate at partial loading levels for extended periods. These characteristics present several opportunities for demand-side response schemes to support power system operation.

3.2.4 Performance of PEM Electrolysers

To incorporate a electrolyser as a dynamic asset in the power system, key factors for performance of a water electrolyser must be considered. Selecting the appropriate parameters to model a electrolyser from a power system viewpoint requires consideration of significant factors such as the electrolyser's effectiveness, durability, operational state, operating conditions, hydrogen production rate, response time, storage capacity, power generation, and energy demand [4].

Efficiency
An electrolyser's efficiency is determined by factors such as current density, cell temperature, and gas flow rate [37]. Production capacity and system efficiency determine a manufacturing facility's hydrogen output. The cell stacks lose efficiency over time, affecting production capacity and costs. Several factors, including overvoltages in individual cells, parasitic currents, and inefficiencies in stack and system design, limit the efficiency of a electrolyser [38].Operating current density and temperature affect the overall efficiency of a PEM electrolysis stack [39]. Commercial systems lack temperature regulation, affecting energy efficiency during changes in power demand [39].

Stack degradation and lifetime
Various factors can impact the lifespan of a PEM electrolyser, such as the quality of materials used during construction, the operating conditions it endures, and the level of maintenance it receives [40]. Electrolytic cell degradation occurs due to the aging process, which results in an increase

in resistance. The passivation of titanium-based components on the anode side, electrolyte and electrode performance deactivation because of contaminants in the inlet water, and structural alterations to the catalyst material have been recognized as the three main degradation mechanisms [38]. These aging effects, referred to as the voltage degradation rate, cause a decrease in efficiency over the stack's lifespan due to the increasing voltage over time. This decline in efficiency affects the lifespan and efficiency of the electrolyser stack [38].

Utilization: Operation State

According to [41], an electrolyser can function in three different states. The electrolyser is switched on and ready to create hydrogen in the first state, which is known as the production state. To maintain the requisite temperature and pressure when in production mode, the electrolyser must operate at a minimum production utilization rate of 10-15% of its total production capacity. The input power can range from 10% to 100% of the rated power of the electrolyser. The electrolyser is not creating hydrogen in the second state, known as hot standby, but both temperature and pressure are still present. The system requires more energy to stay in this state. The electrolyser is depressurized and cool in the final state, which is the idle state. In order to power control units and anti-freezing components in the appropriate areas, the system must be maintained in this condition using the minimal amount of energy possible. Restarting the system after it has been in the idle state is known as a cold start and requires a significant amount of energy to heat the electrolyser and restore the lost pressure needed to operate it effectively [41]. Dynamic operation of the electrolyser and cold starts are assumed to have a negative impact on the stack lifetime. To take grid services that call for partial load into account, quick response and standby operation must be taken into account. To function as a flexible resource while maintaining balance, the parameters from these different states should be considered. The parameters for the different states are listed below [4]:

Production state:

- Nominal power
- Minimum production utilization (% of full load power)
- Minimum input poower for partial operation (% of full load power)

Hot-standby state:

- Standby consumption (extra needed energy in % of full load)
- Minimum response time (from hot standby to full load or vica versa)

Idle state:

- Maximum number of cold starts in system lifetime

Electricity consumption

The amount of electricity consumed is a crucial factor that affects both the efficiency and volume of hydrogen production. When estimating energy consumption, it is essential to consider both stack efficiency and system efficiency. Cell degradation has minimal impact on the power output of a PEM stack, which can be accounted for in contracted power for ancillary services [42]. Current electrolysis stacks have an efficiency between 63 and 71%, which results in a specific energy consumption of 46 to 52 kWh/kg [43].

Power output

The size, design, and operating conditions of an electrolyser can affect its power output, and it is important to consider how to adjust it to meet changing power system demands [44].

Storage capability

When modelling the electrolyser as a flexible resource in the power system, it is important to take into account the storage capacity of the produced hydrogen. The storage capacity can be estimated by considering factors such as the volume and pressure of the storage tank, as well as the purity and pressure of the hydrogen gas. Raising the hydrogen outlet pressure can increase the volumetric energy density of hydrogen gas and the energy storage capacity of a hydrogen production system, without requiring additional compressors after the electrolysis process [38].

Response time

When modelling the electrolyser as a flexible resource in a power system, it is crucial to take into account its response time, which refers to how quickly it can adapt its output to changes in demand.

3.2.5 Parameters for Making a PEM Electrolyser Model

Based on the analysis conducted from [4], relevant parameters and decision variables for a PEM electrolyser model will be presented. It is crucial to model PEM electrolysers as a flexible resource in the distribution network, but working out the optimal strategy to fulfill hourly demand through production, storage withdrawals, or a combination of the two can be difficult. Investigating hydrogen production and storage capacities is crucial, and finding the optimal capacities that provide greater value than the expected consumption of hydrogen is desirable. Various decision variables, such as capacity, production quantity, storage quantity, and operational variables, are essential to model the water electrolyser. By incorporating both public and private sector stakeholders, the EU's "Fuel Cells and Hydrogen 2 Joint Undertaking" (FCH 2 JU) continuously updates accurate techno-economic values and targets for advancing PEM and alkaline electrolysis technologies. Parameters for modelling these systems, which include system and stack lifespan, efficiency, water consumption and input power is demonstrated in [41]. These parameters are based on EU studies and active projects. Additionally, a techno-economic model for PEM electrolysis is provided by [45]. Relevant parameters for technical and economic parameters from [45] and [41], [38] are presented in 3.2. Additionally, based on a literature review conducted in [4] and [1], relevant parameters for an electrolyser as a DG in the power system are also provided in Table 3.2.

Table 3.2: Overview of the parameters for modelling.

Technical and economical parameters	**Parameters affecting grid parameters**
Hydrogen production rate	Minimum partial load (safe load of the electrolyser)
Nominal voltage	Power demand (maximum)
Nominal current	System efficiency
Operating temperature	Response time
Hydrogen pressure	Standby consumption
Oxygen pressure	Lifetime stack
Current density	Max number of cold starts
	Min response time (from hot standby to full load or vica versa)

Source: [1]

3.2.6 Economical Feasibility

For the hydrogen produced from such a facility to be cost competitive, both design and operation should be optimized. For PEM electrolysers the electrolysis stack accounts for about 60% of the capital expenditure (CAPEX) [46]. By increasing the number of stacks, the CAPEX can be reduced by around 24%, 32% and 40% by implementing two, three or six stacks, respectively [46] (assumed using a 700 kW PEM electrolyser). To reduce the CAPEX further, cheaper materials in electrodes and membranes should be used, but this may need improvements in technology. To reduce the total cost of an electrolyser surplus heat and surplus oxygen can be used to utilize the value chain better [30], e.g. as planned in ZeroKyst [3]. Another factor that plays a role to reduce cost of electrolysers is the module size. The investment costs are inversely proportional with the module size and are dropping significantly up to 10 and 20 MW modules [31]. Beyond this point the effect increasing module size has on the investment cost is diminishing.

Another factor to consider is the number of hours the electrolyser operates at full load per year. According to Figure 3.7, the range of lowest hydrogen costs is between 2.5 and 6 thousand hours per year. Operating the electrolyser for less than this interval significantly impacts the cost of hydrogen production due to capital and operational expenditures. This effect decreases with an increase in total full load hours. Simultaneously, the cost of electricity increases as a higher number of load hours makes it impossible to avoid peaks in electricity prices throughout the year. Therefore, exceeding six thousand full load hours per year results in an increase in the cost of produced hydrogen. However, this increase is marginal, and it may be economically favorable to operate the electrolyser beyond the range of lowest hydrogen costs. It is important not to go below approximately two thousand load hours per year, as hydrogen production costs diverge significantly beyond this threshold.

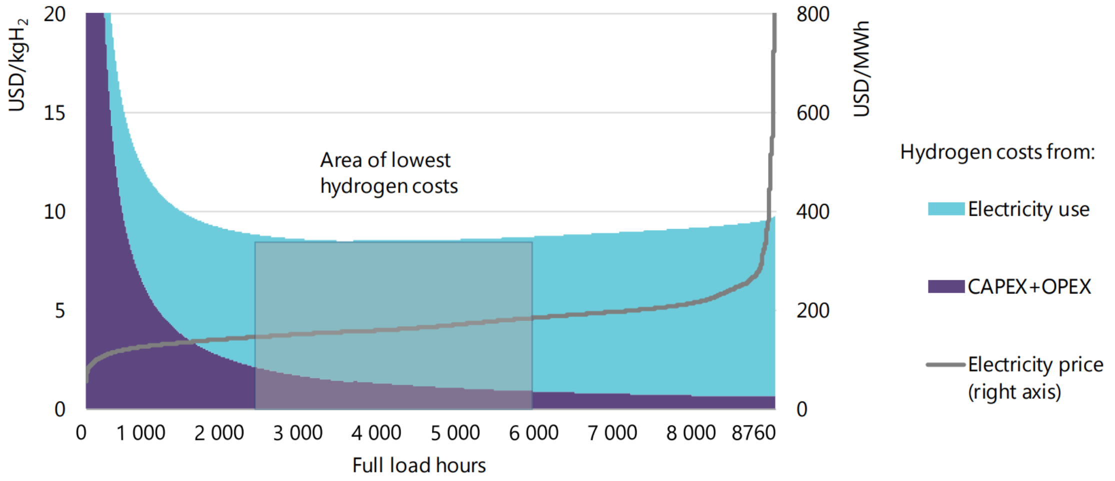

Figure 3.7: Hydrogen costs using grid electricity. An electrolyser efficiency of 64% and a CAPEX of USD 800/kW is assumed. Electricity prices are collected from Japan in 2018, and may not represent current prices. The uncerlying concept of the graph remains relevant.

Source: [46]

3.3 Flexible Operation of Electrolysers

3.3.1 Operating Load Range

Electrolysers are highly flexible due to their ability to operate over a wide range of loads and adjust their load quickly. This makes them a promising solution for grid balancing services, as they can match power consumption and demand and can be shut off during peak hours to avoid the need for unnecessary grid reinforcements.

Ramp time
Electrolysers offer high flexibility in load range, as their power consumption can be ramped up and down quickly when in standby mode or warmed up. However, when starting from a completely shut-off state with ambient temperature, known as a cold start-up, adjusting the power consumption takes longer compared to a warm start-up. The ramp-up time of a PEM electrolyser system in standby mode and pressurized state is within seconds, whereas an alkaline system requires approximately five minutes [47]. For larger PEM electrolyser plants operating at the MW scale, the ramp-up time is less than 10 seconds [47]. However, when starting from a cold state, the ramp-up time can take between 5 and 20 minutes.

While electrolysers can operate at a full range of loads up to their nominal load, their efficiency decreases when operating below 30% of their capacity [47], leading to higher energy consumption and increased hydrogen costs. However, the impact on hydrogen cost may vary depending on the duration of operation below this threshold.

Overloading electrolysers
Some PEM electrolysers have the ability to operate above their nominal load for short periods of time, but this requires additional cooling and a larger power supply. Operating an electrolyser above 150-160% of its nominal load can cause additional stress on the electrolyser stack, resulting in faster degradation [47].Therefore, while electrolysers are highly flexible in terms of load range, their efficiency may be reduced at low loads, and operating above the nominal load requires careful consideration to prevent damage to the electrolyser stack.

3.3.2 Operation to Support Grid Balance

As previously discussed, electrolysers offer a promising solution for grid balancing services due to their ability to ramp up and down power consumption quickly. To determine the economic viability of operating an electrolyser for this purpose, several factors must be investigated. The value of curtailed hydrogen resulting from ramping down production or operating at low loads to enable power consumption ramp-up should be determined. This value should be lower than the value gained from providing grid balancing services, or else it would not be economically beneficial.

Value of grid balancing services
The value of providing grid balancing services in a country is heavily dependent on the availability of controllable sources of power [48]. Conventional power plants such as coal and gas are relatively slow controllable, while hydroelectric plants are fast controllable, effectively acting as a giant battery. Thus, grid balancing services are more valuable in a country like Germany than in Norway, which has a large hydroelectric power generation capacity. This indicate that an electrolyser would have a greater economic potential to balance the grid in Germany compared to Norway.

Number of load hours

In Section 3.2.6, the economic viability of an electrolyser was discussed, and it was found that the number of full load hours in a year has a significant impact. As shown in Figure 3.7, an electrolyser should operate for a minimum of 2,000 full load hours annually to ensure economic feasibility. Below this threshold, the cost of hydrogen increases significantly. However, once the threshold is met, the impact of additional load hours on the cost of hydrogen is relatively small. In fact, the hydrogen price is lowest when the electrolyser is not operating at full capacity, which supports the idea of providing grid balancing services.

Norway's abundant hydroelectric generation may render grid balancing services from electrolysers less economical compared to other parts of Europe. However, as non-controllable renewable energy sources increase in the future electrical grid, the demand for rapidly adjustable loads may also rise. Consequently, the economic benefits of providing grid balancing services may also increase, making it more favorable to utilize the full potential of electrolysers to both produce hydrogen and stabilize the grid.

Construction contribution

Flexible operation of an electrolyser can also help reduce the impact of construction contributions that arise from the need to reinforce grid capacity to a facility. This can be achieved by utilizing 100% of the available capacity at all times, and ramping down or shutting off nearby electrolysers when electric boats arrive at a harbor to charge, and ramping back up once charging is complete, to maintain sufficient hydrogen production. This approach can minimize the impact of construction contributions. However, it is worth noting that the construction contribution is likely only a minor fraction of the investment cost of an electrolyser, and therefore, it may be less critical to fully utilize its capacity for this purpose. Nonetheless, it is important to strive for a more utilized grid in general to avoid unnecessary grid reinforcements, especially in the future electricity grid.

As mentioned earlier, the transition towards cleaner and more sustainable energy sources is of paramount importance, and the coastal fishing industry presents a significant opportunity for electrification. By incorporating hydrogen technology and electrolyser systems, there is potential to provide a reliable and environmentally friendly power source for the fishing fleets, reducing their reliance on traditional fuel combustion engines. In order to determine the appropriate hydrogen production capacity of the electrolyser system, it is crucial to assess the energy requirements of the fishing fleets. Understanding the energy demand of the fleets provides valuable insights into the amount of hydrogen that needs to be generated to support their electrification. This will be further analysed in the next chapter.

Chapter 4

Electrification of the Coastal Fishing Industry

This chapter provides an introduction to Lofoten, which is the area to be electrified in the ZeroKyst project. The current situation of coastal areas in Norway is presented, highlighting the need for transitioning to cleaner and more sustainable practices to reduce pollution. The specific energy consumption of the fishing fleets in Lofoten is examined, as this information is crucial for determining the required hydrogen production capacity to support their electrification. By understanding the energy demands of the fleets, it is possible to effectively plan the operation of the hydrogen production process, ensuring it aligns with the needs of the coastal area's electrification goals.

Figure 4.1: Typical village in Lofoten.

Source: [14]

Norway is a country with a long coastline and a thriving fishing industry. However, the energy transition is affecting these coastal areas and the fishing industry in various ways. The fishing industry is dependent on access to clean and reliable energy sources, and the transition to renewable energy sources is causing changes in the energy supply chain. With the increasing demand for environmentally-friendly practices, it is essential for the fishing industry to implement sustainable practices that minimize their impact on the environment.

Lofoten is a collection of islands situated in Nordland, stretching from Skomvær outside Røst in the southwest to Raftsundet in the northeast. Lofoten is home to approximately 24,600 residents, living in vibrant fishing villages and small towns scattered across the islands [49]. Figure 4.1 is an example of a typical small village in Lofoten, situated in proximity to the ocean. The region's mountainous terrain, which forms most of the islands, is encircled by a flat shore referred to as the beach area [50]. Lofoten is also renowned for its rich cultural heritage, including the traditional fishing industry and the unique architecture of the rorbu, a type of traditional fisherman's cabin.

The islands' silhouette appears to be a continuous, steep mountain range rising from the sea, which has earned it the moniker "Lofotveggen." The coastal climate in Lofoten is characterized by mild winters and relatively cool summers. The fishing industry dominates Lofoten's economy, providing around half of all industry jobs. The annual Lofoten fishing season for cod (skrei) takes place between January and April, attracting vessels from Lofoten and other regions [50]. In autumn, longer boats venture northward to Finnmark for fishing. Lofoten's charm lies in its stunning natural beauty, towering mountains, and thriving fishing industry, making it a must-visit destination.

ZeroKyst aims to achieve two main objectives: first, to reduce carbon emissions in the seafood industry by adopting hydrogen-electric propulsion, and second, to showcase solutions for mobile energy supply in Lofoten [2]. Table 4.1 provides an overview of the various fishing fleets that are to be electrified in the Lofoten region. Additionally, Figure 4.2 shows the location of these fleets.

Table 4.1: Shore areas to be electrified in the ZeroKyst project.

Nr.	**Fishing Fleet**
1	Ballstad
2	Sørvågen
3	Henningsvær
4	Fredvang
5	Ramberg
6	Værøy
7	Stamsund
8	Napp
9	Svolvær
10	Leknes
11	Lauvika
12	Røst

Source: [51]

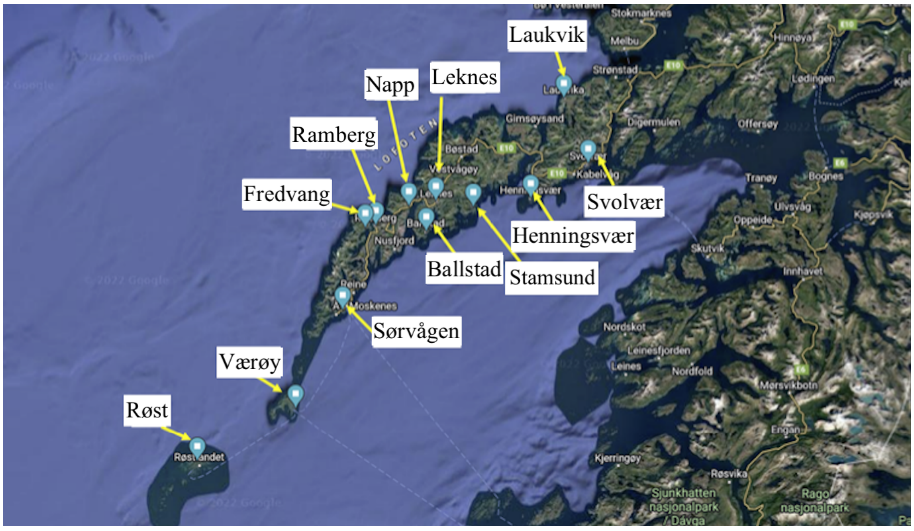

Figure 4.2: Shore areas to be electrified in the ZeroKyst project.

4.1 Situation in the Coastal Fishing Areas in Norway

Norway has a rich history of oceanic harvesting, with its seafood gracing plates across the globe on a daily basis. This industry serves as a vital source of income for many Norwegians as well as for the nation's economy. Nevertheless, Norway's seafood industry is responsible for a significant portion of the country's greenhouse gas emissions. In fact, the EU has mandated that Norway reduce its non-quota sector GHG emissions by 40% between 2005 and 2030 [2]. There are no reliable statistics on the direct emissions from fish farms in Norway, but the existing reports suggest that emissions linked to aquaculture activities in Norwegian waters range between 500,000 to 750,000 tonnes of CO_2 in 2021 from vessels [52]. According to new statistics gathered by Kystverket, CO_2 emissions from well-boats, which contribute significantly to aquaculture emissions, have increased by 67% from 2017 to 2021 [52].

Norway is also at risk of ocean acidification, which threatens the ocean's chemical balance, although it is unclear if fish are directly endangered. However, organisms further down the food chain have begun to suffer from acidification [2]. The maritime sector is responsible for significant amounts of ocean acidification, which is predicted to increase in the future [2]. Moreover, fishers in Lofoten have observed fish migrating north due to warmer waters, forcing them to fish in new locations further north. As a result, some fishers might find zero-emission propulsion systems an attractive option.

Diesel engines are the prevailing and traditional technology used in coastal fishing vessels in Norway, both for old and new vessels. A diesel fishing vessel of around 11 meters can consume up to 40,000 liters of diesel fuel annually, as it allows for efficient energy storage and can be stored anywhere onboard [53]. This propulsion system enables vessels to remain at sea for multiple days without the need for refueling, with infrastructure in place to facilitate refueling [2].

4.1.1 Transition

The maritime industry is in need of significant change to reduce pollution. In Norway, there is political support for this shift, and funding has been allocated for numerous projects [36]. The government's plan for infrastructure that supports alternative fuels in transportation was presented in 2019 by the ministers of transportation, climate, and environment [36]. Det Norske Veritas (DNV), a classification society, predicts a 7% increase in hydrogen consumption by the maritime industry by 2030 [54]. Meeting future emission reduction requirements demands a significant reduction in emissions from the maritime industry. Since the world's first electric car ferry, MS Ampere, started running in Norway in 2015, a number of totally electric and hybrid fishing vessels have been built. Additionally, there are hydrogen vessels under construction for the aquaculture industry, along with ammonia vessels [36].

Norwegian fishermen had tax exemption for a long time, but since 2020 they are required to pay a CO_2 tax on their diesel consumption. However, they receive compensation for this through Garantikassen for fiskere (GFF), an executive division of the Ministry of Trade and Industry that manages their social programs [36]. This compensation will be gradually phased out over the next few years. In addition, compensation for bunkering in Norway will be restricted and fishermen are not going to get CO_2 compensation if they do so abroad. This move aims to accelerate the transition towards greener practicces. However, fishermen are advocating for incentives for adopting green technologies rather than penalties for their emissions [36].

The rules governing the use of liquefied natural gas (LNG) as a fuel in the maritime industry took almost a decade to be established, with Norway leading the way in this innovative effort in the 1990s. Based on this history, it is not unreasonable to assume that modifying the rules for hydrogen vessels may also take some time [36]. Nonetheless, the time frame for these modifications should ideally be shortened to achieve rapid change in the maritime industry. Vessels have external energy source requirements, which means that hydrogen-electric vessels must also have an external generator [2].

Introducing new technology comes with a host of technical and economic challenges. The technology must deliver equivalent capabilities to conventional options while remaining emission-free, which presents a significant obstacle [6]. In the maritime industry, hydrogen propulsion is a relatively new and underdeveloped technology compared to diesel. Consequently, regulations for the best hydrogen solutions for vessels are still being developed. The operational cost for a hydrogen-electric vessel includes bunkering hydrogen and charging the battery, whereas diesel vessels only require diesel bunkering [6].

Currently, hydrogen is not cost-competitive with diesel, but the removal of fishermen's diesel subsidy could change this. Currently, diesel costs fishermen 7.9 NOK/kg, and future prices are expected to rise, making hydrogen price-competitive [36]. However, with current technology, the range of a hydrogen-electric propulsion system is shorter than that of a diesel engine [36]. As a result, fishermen may develop range anxiety. Even if they switch to hydrogen fuel, they want to maintain their usual fishing capacity. Unlike diesel, obtaining fuel from another ship is difficult if they run out. It is not possible to just take hydrogen tanks from a neighbouring ship [2]. For short-range ships and vehicles, like as ferries with rapid connections that can recharge regularly during the day, batteries may be sufficient. Compared to ferries, fishing vessels have a larger range need and less consistent operation [36].

Storing hydrogen presents a challenge, partly because it must be stored above deck to comply with regulations. This requires a large amount of space, which means that the vessel must be longer to accommodate the hydrogen. This can be problematic for fishermen, as it encroaches on their working area. In a hydrogen-electric fishing vessel, the fuel takes up more space than in a diesel vessel, further exacerbating the problem [2]. Establishing regulations for using LNG as a fuel in the maritime industry took nearly ten years, with Norway leading the way in pioneering work in the 1990s [2]. Given this experience, it is not surprising that changing the regulations for hydrogen vessels is a time-consuming process. To achieve a rapid transition in the maritime industry, the time frame for regulation changes ideally should be shorter. Vessels must have an external energy supply source, so even hydrogen-electric vessels require an external generator [2].

4.2 Analysis of Energy Consumption at Lofotoen

In order to comprehensively analyze how electrification of fishing fleets in Lofoten impacts the distribution grid, an assessment of the energy consumption for the fishing fleets is necessary. This analysis will enable a deeper examination of whether the electrolyser can effectively operate in a flexible manner while simultaneously meeting the energy demands of the fishing fleets. The power demand for the electrification of the fishing fleets at Lofoten is based on the Zerokyst summer project report [51] and calculation from the Specialization Project [4]. To protect the privacy of data for specific fishing fleets, they have been referred to as "Fishing Fleet x" in this thesis, as the project has not been published yet. The summer project [51] relied on end-of-year statements to identify the number of boats that had delivered catch at the harbor throughout the year. They also counted the number of days each fishing boat had spent landing fish. To estimate the energy requirements of these vessels, various operating profiles were used as a reference for different length groups. The study examined three distinct length groups: Under 11 meter, 11-14.99 meters and 15-20.99 meters.

Determining the exact amount of electricity and hydrogen energy required to replace diesel in fishing boats is a challenging task due to their unpredictable operating patterns. In the summer project [51], the energy needs of the "Lofoten Fleet" were estimated focused primarily on data from the "Climate Way Map" article, as well as diesel consumption data obtained from fishermen's experiences. However, the calculations in the project [51] were based on significant assumptions, so the numbers obtained provide only an indication and an overall overview of energy needs. Since energy requirements are based on the weight of catch, they can vary greatly depending on the fishing boats' daily success. The project [51] also relied on substantial assumptions when using data from MarineTraffic and end-of-year statements (Sluttseddeldata). The results are based on historical data and may not provide an entirely accurate picture of future outcomes. Nevertheless, members of the ZeroKyst summer project observed that the data from year to year followed the same trends, leading them to believe that it could provide some estimate for future years. The data used in the ZeroKyst summer project mostly comes from 2020, 2021 and 2022.

It is important to note that fishing activity varies throughout the year, which can affect the load demand profile. The ZeroKyst summer project distinguishes between Summer: May, June, July, August, Winter/Autumn: September, October, November, December, January and Lofotfiske: February, March, and April.

Since the power consumption varied much based on the different fishing seasons, the project [51] made a table of maximum and minimum energy requirments for the different fishing fleets based on monthly data. The summary of this data can be seen in Table 4.2.

Table 4.2: Energy needs for various marine vessel lengths.

	Under 11 m	**11-14.99 m**	**15-20.99 m**
min [kWh]	2,500	5,000	10,000
max [kWh]	6,000	10,000	15,000

Source: [51]

According to the data provided in the summer project [51], the amount of catch landed at each harbor varies significantly depending on the season. As a result, the need for networks and charging infrastructure may differ greatly from harbor to harbor. Generally, the highest demand for charging or fueling in Lofoten occurs during the Lofotfiske season and decreases significantly outside of that period. Figure 4.3 and 4.4 illustrate the energy consumption for the two fishing fleets in Lofoten with the highest energy consumption between July 2021 and June 2022, demonstrating how the season affects the variation in activity at the ports [51].

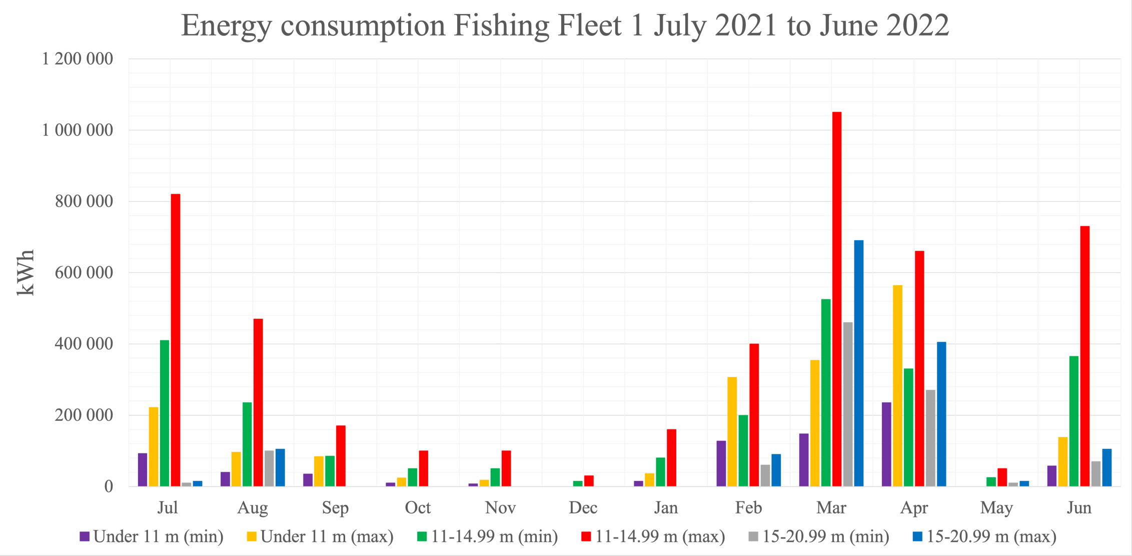

Figure 4.3: Energy consumption for Fishing Fleet 1 from July 2021 to June 2022.

Source: [51]

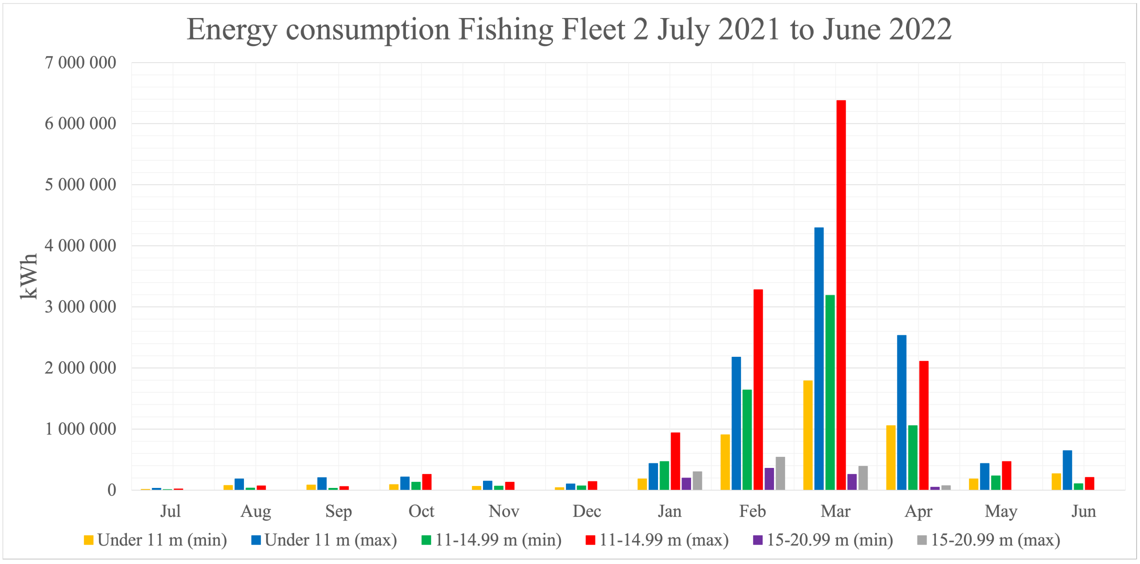

Figure 4.4: Energy consumption for Fishing Fleet 2 from July 2021 to June 2022.

Source: [51]

In the ZeroKyst summer project [51], the hydrogen needed, volume of the tanks and the number of hydrogen tanks for the fishing fleets were calculated based on the minimum and maximum energy consumption in Table 4.2 for the different length profiles. The results from the study are shown in Table 4.3 and 4.4.

Table 4.3: Amount of hydrogen required for minimum energy consumption for different vessel length profiles, as well as the corresponding hydrogen volume at 250 bar and 0 degrees.

For minimum energy consumption [kWh]			
	Under 11 m	**11-14.99 m**	**15-20.99 m**
Amount of hydrogen [kg]	112.6	225.2	450.5
Volume tanks [liter]	5,968.5	11,936.9	23,873.9
Number of hydrogen tanks	3	7	14

Source: [51]

Table 4.4: Amount of hydrogen required for maximum energy consumption for different vessel length profiles, as well as the corresponding hydrogen volume at 250 bar and 0 degrees.

For maximum energy consumption [kWh]			
	Under 11 m	**11-14.99 m**	**15-20.99 m**
Amount of hydrogen [kg]	270.3	450.5	675.7
Volume tanks [liter]	14,324.3	23,873.9	35,810.8
Number of hydrogen tanks	8	14	21

Source: [51]

Compared to diesel as an energy carrier, hydrogen presents a challenge in that it requires more space. According to [51], which assumes hydrogen tanks are pressurized at 250 bar, exploring higher pressures and liquid hydrogen could be advantageous in saving space on fishing vessels. To determine the required amount of hydrogen (in kilograms) for a given number of kWh, the analysis uses a lower heating value (LCV) of 33.3 kWh/kg for compressed hydrogen [51]. Taking an example where the operating profile of boats under 11 metres is examined, it is determined that the maximum energy requirement is 6000 kWh, see Table 4.2. To determine how much hydrogen is required for this quantity of energy consumption, Equation 4.1 is employed, where fuelcell represents the efficiency of the fuel cell used and is assumed to be 50% based on [51].

$$Amount\ of\ hydrogen = \frac{Energy\ consumption}{LCV_{hydrogen}} \cdot \eta_{fuelcell} \tag{4.1}$$

The amount of hydrogen for the maximum energy requirement for boats under 11 meters is then equal to:

$$Amount\ of\ hydrogen = \frac{6,000kWh}{33.3kWh/kg} \cdot 1.5 = \underline{270.3kg}$$

A similar process can be applied to calculate the daily amount of required hydrogen for fishing vessels of other length profiles as well.

Chapter 5

Simulation Model

The aim of this thesis is to investigate the potential impacts of electrifying a coastal fishing fleet on the Lofoten distribution network. To achieve this, a distribution system model is developed using PowerFactory DIgSILENT, a widely employed tool for power system analysis. The model is constructed based on data provided by Elmea, the local distribution system operator in the Lofoten area. The chapter begins by providing an overview of power system analysis, followed by a discussion on the selected methodology for power system analysis. Subsequently, both the current and future network models will be developed and presented, along with the corresponding data utilized in these models. Finally, the chapter will delve into the water electrolyser model, together with the data chosen for the electrolyser.

The model approach for this master's thesis uses the same methodology as done in the previous work for the research paper titled *"Coastal Electrification Using Hydrogen Technology and Distribution Grid Flexibility Potential"*, as shown in Appendix B. While the research paper provided the initial foundation, there have been notable updates in this master's thesis. Firstly, the network model used here is not based on the CINELDI network but rather on real data obtained from the Lofoten DSO, which adds an extra level of realism specific to this location. Additionally, the electrolyser network has undergone further analysis and development, resulting in an improved and more realistic electrolyser model. The inclusion of an IEEE publication reinforces the credibility and scientific validity of this study.

5.1 Power Flow Analysis

Power flow analysis is a crucial aspect of power system analysis and design. It involves the calculation of voltages, currents, and power flows in an electrical network. The analysis aims to determine the steady-state operating conditions of the network, including the magnitude and phase angle of voltage at each bus, and the active and reactive power flows in each branch [55]. There are several methods used to perform power flow analysis, including the Gauss-Seidel method, Newton-Raphson method, and the Fast-Decoupled method. These methods differ in their computational complexity and convergence properties.

One important aspect of power flow analysis is the consideration of various network components and their characteristics, such as transformers, generators, and loads. Additionally, the analysis must take into account the network topology and the operating conditions, including any faults or contingencies that may occur. Power flow analysis is essential for the planning and operation of power systems. It helps to ensure that the network is operating within its limits and can provide reliable and efficient power to consumers. Furthermore, it can aid in the identification of potential issues or areas for improvement in the network [55].

PowerFactory is a simulation software widely used in power system analysis and design. It has advanced power flow analysis capabilities that enable the user to perform power flow analysis on large power systems with high accuracy and efficiency. PowerFactory also has a user-friendly interface that allows the user to easily model various network components, such as generators, transformers, and loads, and consider various operating conditions, including faults and contingencies [56].

The power flow analysis utilizes a one-phase network model, where the system's buses each rely on four different variables: phase angle (θ), voltage magnitude ($|V|$), and active and reactive power (P and Q) [6]. The reference bus, often referred to as the slack bus, is the only one in the system and has a voltage of $|V|$=1 and an angle of θ=0 (in p.u. (per unit)) [6]. The PV bus, which typically represents generation buses, has known values of $|V|$ and P. PQ buses, also known as load buses, are the last type of bus and have known values for P and Q. To solve for the unknowns, the power balance equations are utilized, which are derived using the fundamental network matrix equations [57]:

$$P_k = |V_k| \sum_{n=1}^{N} |Y_{kn}||V_n| cos(\delta_k - \delta_n - \theta_{kn}) \tag{5.1}$$

$$Q_k = |V_k| \sum_{n=1}^{N} |Y_{kn}||V_n| sin(\delta_k - \delta_n - \theta_{kn}) \tag{5.2}$$

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

Once the equations are solved for each bus with known P and/or Q values, all voltage magnitudes and angles of the network can be determined, and the unknown P and Q values can be calculated directly [57]. This enables further analysis of the network. However, due to the non-linear nature of the equations, numerical methods must be employed to solve them [6]. The Newton-Raphson load flow analysis method is used by PowerFactory and is renowned for its precision and dependability in power system analysis. By employing an iterative process, the algorithm resolves the nonlinear power flow equations, making it a popular choice for analyzing power systems. This method determines the voltage, current, and power at various locations throughout the power system network [56].

5.1.1 Newton Raphson Method

An iterative process called the Newton-Raphson (NR) method is used to calculate numerical approximations of the roots of real-valued functions. By applying the following formulae, the power balance equations for buses with known P and Q values can be resolved through this method [6]:

$$\vec{x_i} = \begin{bmatrix} \vec{\delta_i} \\ |\vec{V}|_i \end{bmatrix} \tag{5.3}$$

$$\vec{u_i} = \begin{bmatrix} \vec{P} - \vec{P}(\vec{x_i}) \\ \vec{Q} - \vec{Q}(\vec{x_i}) \end{bmatrix} = \begin{bmatrix} \Delta\vec{P_i} \\ \Delta\vec{Q_i} \end{bmatrix} = \mathbf{J}(\vec{x_i}) \begin{bmatrix} \Delta\vec{\delta_i} \\ \Delta|\vec{V}|_i \end{bmatrix} \tag{5.4}$$

$$\vec{x_{i+1}} = \begin{bmatrix} \vec{\delta_{i+1}} \\ |\vec{V}|_{i+1} \end{bmatrix} = \vec{x_i} + \begin{bmatrix} \Delta\vec{\delta_i} \\ \Delta|\vec{V}|_i \end{bmatrix} \tag{5.5}$$

- i: Iteration count.
- $\vec{x_i}$: Vector of unknown voltage angles and magnitudes for current iteration.
- $\vec{P}, \vec{Q}$: Vector of accurate P and Q values for known buses.
- $P(\vec{x}), Q(\vec{x})$: Vector of calcuate P and Q based on values from and Equations 5.1 and 5.2.
- $\mathbf{J}(\vec{x_i})$: Jacobian matrix retrieved using derivates of the power balance equations calculated using $\vec{x_i}$
- $\Delta\vec{\delta_i}, \Delta|\vec{V}|_i$: Mismatches of known power injections and calculated power injections.
- $\vec{x_{x+1}}$: Updated values for voltage angles and magnitudes after current iteration.

The method will converge more quickly the closer the initial values are to the solution, hence values from a prior solution with comparable load and generation values are frequently chosen to a flat start. [57]. The algorithm begins by making initial guesses for all angle and voltage values, which are often set to a flat start where all angles are 0 and voltages are 1 (in p.u.) [6]. In PowerFactory, round-off errors for all buses produced by the improved non-decoupled Newton-Raphson solution technique with power or current mismatch iterations are typically less than 1 kVA [56].

5.2 Model Data

5.2.1 Securing Critical Infrastructure

To create a more realistic network model, actual data was obtained from DSO Elmea, which provided parameters for both electrical equipment and load data. However, to ensure the security of critical infrastructure for the distribution grid, sensitive information was not disclosed. As a result, the location of the radial was not revealed in this thesis, and buses were named B1, B2, B3, etc., while lines or cables were named Line 1, Line 2, Line 3, etc. This precautionary measure was taken to prevent malicious attacks on crucial parts of the grid by keeping this information from becoming public knowledge.

5.2.2 Data from DSO

Elmea provided data for both electrical equipment and load data, including cables, lines, and transformers. The data was extracted from NetBas, a comprehensive database that encompasses technical information on various electrical equipment, along with essential data required for conducting advanced simulations and analyses. The data encompassed several parameters for the lines and cables, such as:

- Nominal voltage
- Max operating current
- Conductor type (aluminium/copper)
- Conductor dimension (95/150/240/400 mm^2)
- Length
- Reactance
- Resistance
- Location
- Surrounding (earth/sea)

In order to simplify the model, multiple loads were aggregated and treated as a single load, which is not expected to significantly impact the end of the radial where most of the analysis was conducted. Additionally, this approach serves as a precaution for ensuring safety, as discussed in Section 5.2.1. The load data files provided by Elmea contained hourly averages of power consumption in kWh over a period of one year, which enables the examination of specific dates, such as Christmas Eve and National Day, and to create both worst-case and best-case scenarios.

5.3 Network Model for Current Grid Scenario

The data obtained from the DSO constitutes the foundation for the creation of a network model. The network model is developed based on the radial 22 kV distribution grid in Lofoten. Although the model depicted in Figure 5.1 is a single-line diagram, the actual lines are three-phase. The network comprises nine primary connection points, designated as B1-B9, and a total of 19 buses interconnecting the lines, cables, and a transformer.

The model is created in DIgSILENT PowerFactory, utilizing the values Elmea extracted from NetBas. As a result, the cables and lines are constructed using actual parameters, leading to a more precise simulation. The radial configuration that we are examining in the model commences with a transformer connected to an external grid.

The model employs a 210 MVA 132/22 kV transformer with a vector group of YNd11, which is connected to bus two (B2) that supplies load two (L2). The transmission from bus two to bus three (B3) involves a combination of cables and overhead lines. The overhead lines used in this model are of the FEAL 1x150 type, consisting of a steel core for strength and outer layers of aluminum to enhance electrical conductivity. The cables used in the model are either made of copper or aluminum, with the aluminum cables having a cross-section of either 240 or 400 mm^2. The copper cable, on the other hand, has a cross-section of 95 mm^2, which increases its impedance and reduces its current carrying capacity. As we move further down the radial, additional lines and cables of varying lengths become apparent. These lines are interconnected in buses, with certain loads being connected to them. It is important to note that the system voltage remains constant at 22 kV from the transformer along the entire radial.

The realism of the network model developed in this study is validated by Elmea, the DSO of the Lofoten area. This confirmation ensures that the model represents a realistic representation of the distribution network. Additionally, the model's predicted voltage drops are compared to actual measurements to confirm their similarity. The close agreement between the simulated and measured voltage drops further supports the model's realism. This validation enhances the model's reliability and enables informed decision-making regarding network planning and operation.

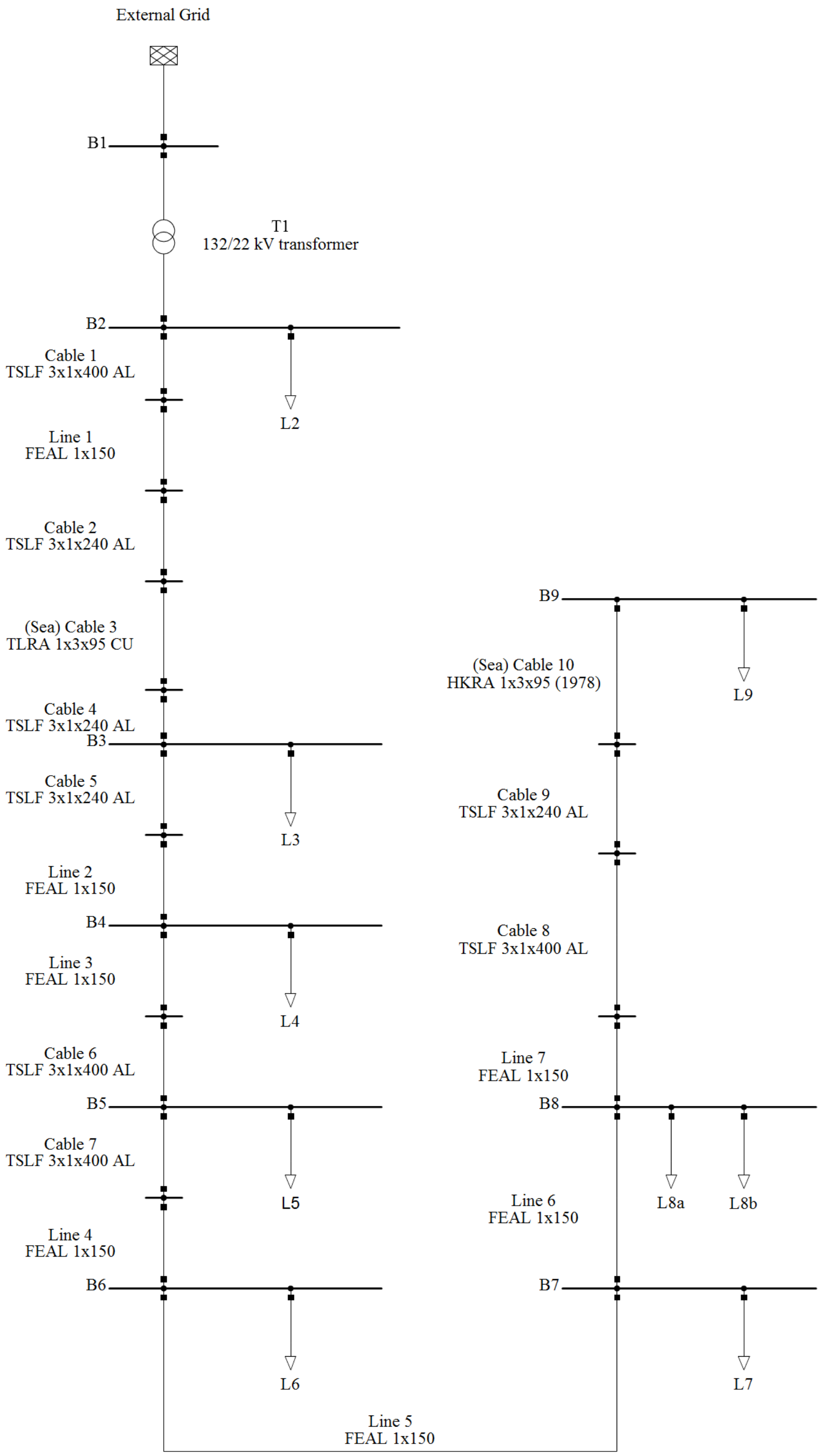

Figure 5.1: Current network model of the investigated radial.

5.3.1 Simplifications and Assumptions

This subsection will detail the various simplifications and assumptions made during the modelling process. The model utilizes network data sourced from the manufacturer's data sheets, which do not account for component ageing. As a result, impedances and losses in the lines and transformers are likely to be underestimated in the model compared to the actual grid [6].

As the model represents the grid using a one-phase approach, all phases are assumed to be symmetric, including voltages, currents, loads, line data, etc. However, in practice, the network is not completely balanced since loads are not distributed equally throughout phases, network data may fluctuate between phases, and regional grid phase voltages may occasionally vary slightly [6]. As a result, the model will not accurately reflect potential voltage issues arising from uneven distribution across phases.

Certain substations loads are modelled by summing the individual loads within their respective radials rather than directly metering the substations. This gives a lumped network, which is a simplified network. As a result, line losses for these radials are not accounted for in the calculations. While this may have a negligible impact on bus voltages, as the losses are insignificant compared to the loads and don't consume much power overall, it should be noted that this simplification is only applied to a small number of substations [6].

5.4 Network Model for Future Grid Scenario

In Section 2.1, it has been detailed that the future power system is expected to accommodate a larger amount of distributed generation. This implies that power generation will be situated in closer proximity to its intended usage, resulting in a significant increase in the demand for power distribution across the network. As a consequence, the distribution network will be put under greater pressure, and the loadings on its lines will be significantly higher. This development is likely to require significant investments and upgrades in the power grid infrastructure to ensure that it is equipped to handle the increased demand and loadings effectively. To ensure that the thesis remains relevant for future solutions, a scenario has been developed to account for the anticipated increase in line loading and loads. This scenario takes into account the expected changes in the power system, which are likely to result in a greater demand for power distribution and, as a result, higher loadings on the lines. By incorporating this scenario, the thesis can effectively address the challenges that the future power system is expected to present and provide recommendations that are well-suited to the changing landscape of the industry.

In the network model for future grid scenario, the network model in Figure 5.2 is used as a reference. In Subsection 2.1.3 it estimated a load increase of 114% within the year 2050. Therefore, network model for future grid scenario, the network loads is increase 114%. As mentioned in the introduction, the ZeroKyst project has set its sights on developing a zero-emission driveline. Given that Lofoten is a coastal area and some locations, such as Værøy and Røst, rely heavily on ferry transportation, it is highly probable that ferries will be electrified and incorporated into this driveline. In the network model for future grid scenario, it is therefore added a Ferry Charging Point (FCP) with a capacity of 1.5 MW [58]. Based on the findings from [58], it is a common practice for ferries to charge for 10 minutes each time. In Chapter 6, 10-minute charging scenarios will be implemented to simulate and analyze the effects on the system.

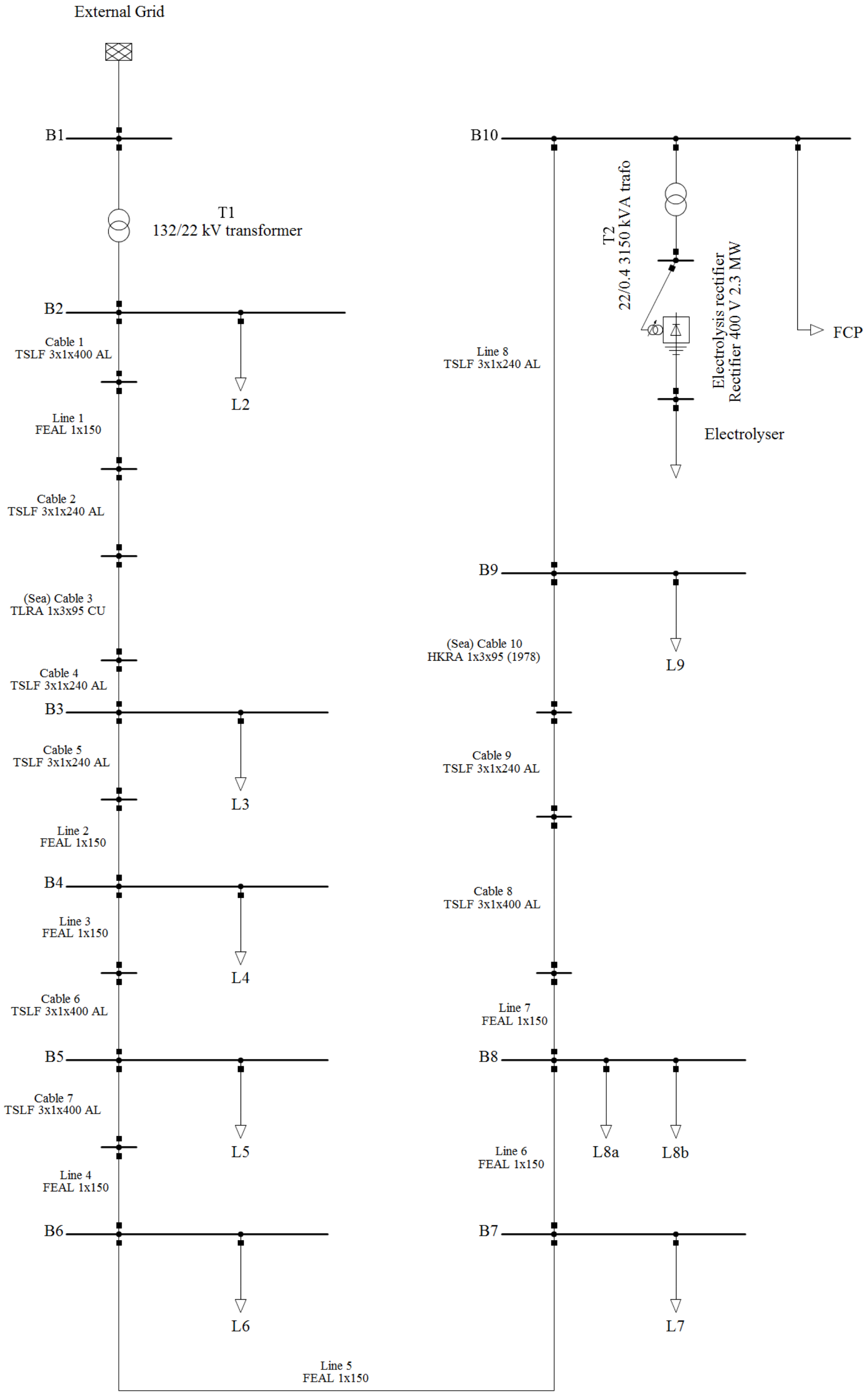

Figure 5.2: Network model for future grid scenario.

5.5 Electrolyser Model

For the modelling of the water electrolyser several models can be considered. The dynamics of a PEM electrolyser are attributed to the coupling of different physical phenomena, represented by a complex system with non-linear relations. Mathematically, the electrolyser plant can be described in the following domains [59, 60]: Electro-chemical domain, Electrical model representing auxiliary system, thermal domain, mass transfer domain, and fluidic models. The flexibility of a water electrolysis plant is defined by its capacity to function at varying power levels, primarily reliant on the stack's capabilities.

In this thesis, we considered using DIgSILENT Simulation Language [61] (DSL) modeling for the electrolyser. DSL modeling is typically utilized for time-continuous controls and processes, as stated in [56]. However, since the main focus of this thesis is to examine how the network is impacted, we opted to simplify the control of the electrolyser to a "black box" approach, where only the power consumption is used to control the electrolyser. The model successfully preserves the characteristics of an electrolyser, including its ability to rapidly ramp up and ramp down.

The data for the electrolyser is sourced from a NEL PEM MC500 electrolyser system, as shown in Appendix A, which offers the M Series platform in a containerized format, allowing for easy outdoor installations. The M Series PEM technology used in the solution is reliable, turnkey, and requires minimal maintenance, making it suitable for a range of applications such as renewable energy storage, industrial process gas, and hydrogen fueling, as stated in [62]. Given that the electrolyser must produce hydrogen for the electrification of all fishing fleets in the future, a larger electrolyser is chosen. To determine the maximum load that the electrolyser can consume, the Net Production Rate is multiplied by the Average Power Consumption at Stack per Volume of H2 Gas Produced (see Appendix A). Equation 5.6 illustrates the maximum loading for the electrolyser used in this analysis, with the data obtained from [62].

$$492Nm^3/h \cdot 4.5kWh/Nm^3 = \underline{2,214kWh/h} \tag{5.6}$$

In Subsection 3.2.3, it was mentioned that the electrolyser is connected to the grid through a transformer and an AC-DC converter, as shown in Figure 3.6. To accurately model the fluctuating load of the electrolyser, both components have been taken into account, as illustrated in Figure 5.3. The transformer for the electrolyser converts input 22 kV AC to 400 V AC, thus T2, which connects the electrolyser to the grid, must have a rating of 22/0.4 kV [62, 63]. To determine the appropriate apparent power for T2, Table 5.1 from [63] was consulted. Initially, a transformer with an apparent power of 2 MVA was considered, which resulted in a loading of $> 90\%$ for the transformer. However, as a distribution transformer, the loading should lay in the interval $50-60\%$ so as to operate optimally, with core losses equal to copper losses [64]. Therefore, a higher rated apparent power was chosen. The AC-DC rectifier must have a rated active power of at least 2.2 MW to accommodate the power demand of the electrolyser load, requiring a rated current of 4.4 kA. From Table 5.1, it can be seen that a 3.15 MVA transformer has a rated current of 4,872 A, which is suitable for the rectifier. By selecting a transformer with a rated apparent power of 3.15 MVA, the transformer loading was reduced to 50%, which is appropriate for a distribution transformer. The resulting electrolyser model is represented in Figure 5.3.

Table 5.1: Standard apparent power ratings for Medium Voltage (MV)/Low Voltage (LV) transformers and related nominal output currents [63].

Apparent power [kVA]	**In [A]**	
	237 V	**410 V**
1,250	3,045	1,760
1,600	3,898	2,253
2,000	4,872	2,816
2,500	6,090	3,520
3,150	7,673	4,436

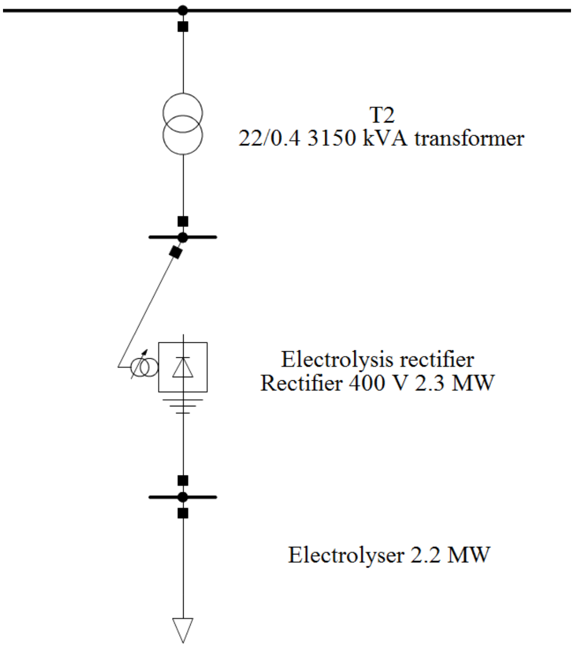

Figure 5.3: Electrolyser model. Three components are considered; a 22/0,4 kV transformer, a rectifier and a general load drawing active power.

Exploring the response of the network to the electrolyser is particularly intriguing when it is connected at the end of radial lines, as this is where the network is vulnerable. In this study, the electrolyser is connected to busbar 9 in the network system via a 400-meter-long cable, which terminates at a substation. This configuration allows for a comprehensive examination of the network's behaviour and performance under these challenging conditions.

5.5.1 Simplifications and Assumptions

Simplification for modelling the water electrolysis is necessary to reduce the complexity of the model and enable efficient computation. One simplification is to model the electrolyser as a black box where only the hydrogen production and power consumption are considered, as mentioned in Section 5.5. This will give a simplified model where the specifications and details of the internal processes mentioned in Section 5.5 are reduced to a black box. As stated in Subsection 3.3.1, the water electrolyser has a rapid ramp-up and ramp-down time. As such, the model assumes that range variations occur instantaneously.

Another assumption done for the electrolyser is to model the electrolyser as an ideal device that converts all electrical power input into hydrogen with perfect efficiency. While this is unrealistic, it is a useful simplification for understanding the potential hydrogen production from a given input power.

Chapter 6

Simulation Scenarios and Results

In order to evaluate the potential for flexibility solutions within the Lofoten distribution network, three scenarios have been developed: Scenario 0, Scenario 1 and Scenario 2. Scenario 0 serves as the reference scenario and represents the current power system without the implementation of an electrolyser. This scenario allows the examination of the performance and limitations of the grid before introducing any changes. Scenario 1 builds upon the base case power system from Scenario 0 but includes the implementation of an electrolyser. By introducing the electrolyser, its impact on the system can be assessed.

Scenario 2 is the primary focus for the analysis. Scenario 2 incorporates the same power system as Scenario 1 but includes increased load data based on projections performed by Statnett, as discussed in Section 2.1.3. The reason for placing emphasis on this case study is that when lines and cables operate closer to their rated values, the flexible operation of an electrolyser becomes more significant. This scenario allows the analysis to fully explore the extent to which an electrolyser can operate flexibly and the resulting impact on the grid.

The present study explores Scenario 2 across multiple time frames, including daily, weekly, and yearly intervals. This expanded analysis enables the investigation of seasonal patterns and hourly fluctuations, providing a more thorough understanding of the system's performance. By examining these extended time periods, we can gain comprehensive insights into how the system operates in different seasons and over longer durations.

In all scenarios, voltage profiles are analyzed using a heat map technique to ensure they operate within acceptable limits. The loading profiles of the lines are carefully examined to evaluate their capacity in handling the load flows. Additionally, losses are observed and compared across the three scenarios. This comprehensive assessment allows for a thorough comparison and understanding of the impact of each scenario on voltage, line loading, and overall losses. Heat maps, voltage profile diagrams and line loading diagrams are generated in PowerFactory.

6.1 Scenario 0: Base Case

6.1.1 Description

The reference scenario has been established based on the highest power consumption day of 2022, which occurred on Wednesday, February 16th. To accurately represent this scenario, the hourly demand for all loads within the network has been included for the entirety of that day which can be seen from Figure 6.1, based on the data provided by Elmea. In general, the demand is lowest during the night, and it is increasing around 20% during the day. It is worth noting that the graph represents a typical weekday, when the majority of individuals are typically at work.

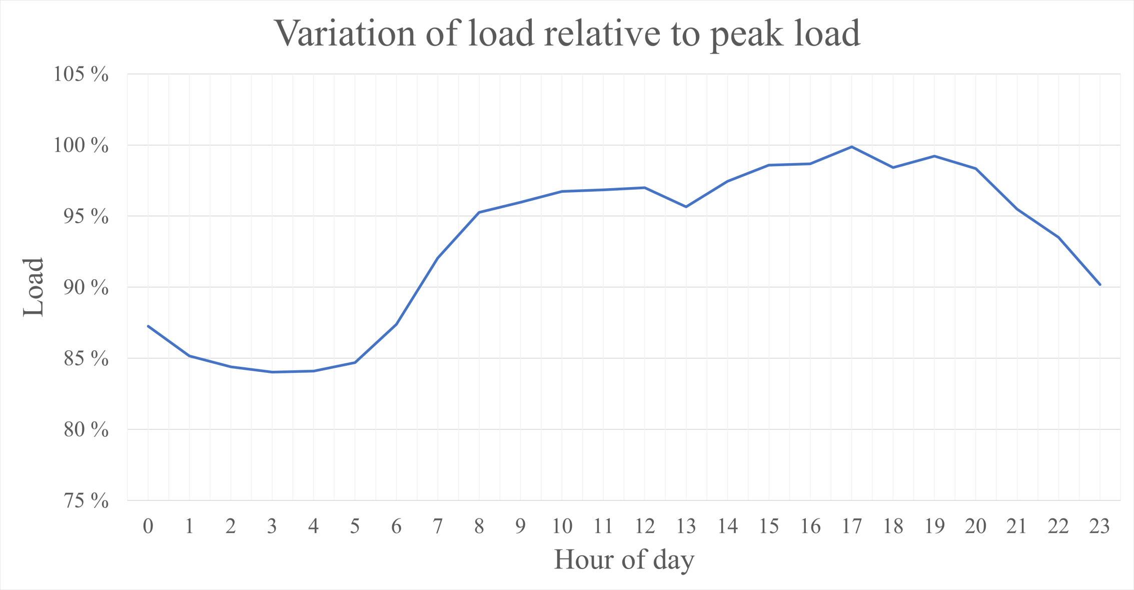

Figure 6.1: Hourly variation of load on radial relative to peak load.

6.1.2 Results

Figure 6.2 represent the heat map for Scenario 0 on the worst day of 2022, where the currrent network model is used. In Figure 6.2 the left side of the map displays scales representing upper and lower voltage thresholds, as well as the loading range. Additionally, the white boxes provide information on three key parameters: active power [MW], reactive power [Mvar], and current [kA]. Below the line and cable names a number displays their respective loading percentages. These parameters apply to all subsequent heat maps.

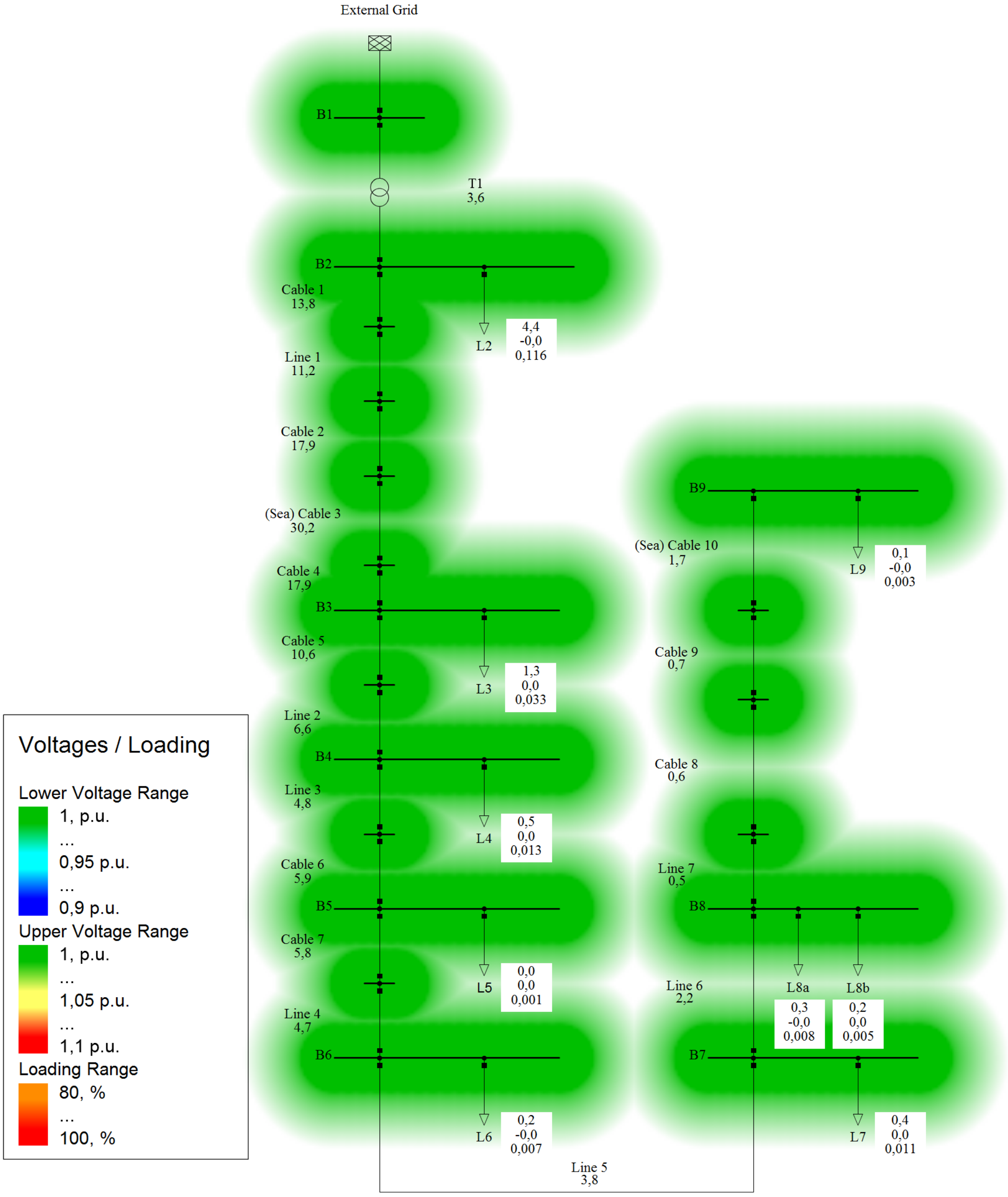

Figure 6.2: Heat map illustrating voltage level across the network.

As can be seen from Figure 6.2 the legend on the left indicate that the load flow simulations demonstrate good system performance. The voltage level remains within acceptable limits, indicating a well-balanced network and properly functioning equipment. Moreover, the loading falls within the acceptable range, indicating that the system has sufficient capacity to meet its power demands without overloading or overstressing the equipment. These findings suggest that the network model is operating efficiently and can handle peak loads without compromising the system's reliability or stability. The colouring legend on the left of Figure 6.2 applies to all further heat map analyses.

6.2 Scenario 1: Current Network with Implemented Electrolyser

6.2.1 Description

The next scenario involves implementing the water electrolyser system into the existing network. Based on the results obtained from Scenario 0, it is evident that the load on the lines is relatively low. Based on these findings, it can be concluded that the network is robust and stable given its current load levels. Consequently, the electrolyser is tested under the same network conditions as the base case, which involves the worst day in 2022. In Scenario 1, the PEM electrolyser will be operated at net production, which corresponds to a loading of 2.214 kWh/h, as described in Section 5.5.

6.2.2 Results

Figure 6.3 and Figure 6.4 shows loading of lines and heat map for the current network in Lofoten with implemented electrolyser system, respectively.

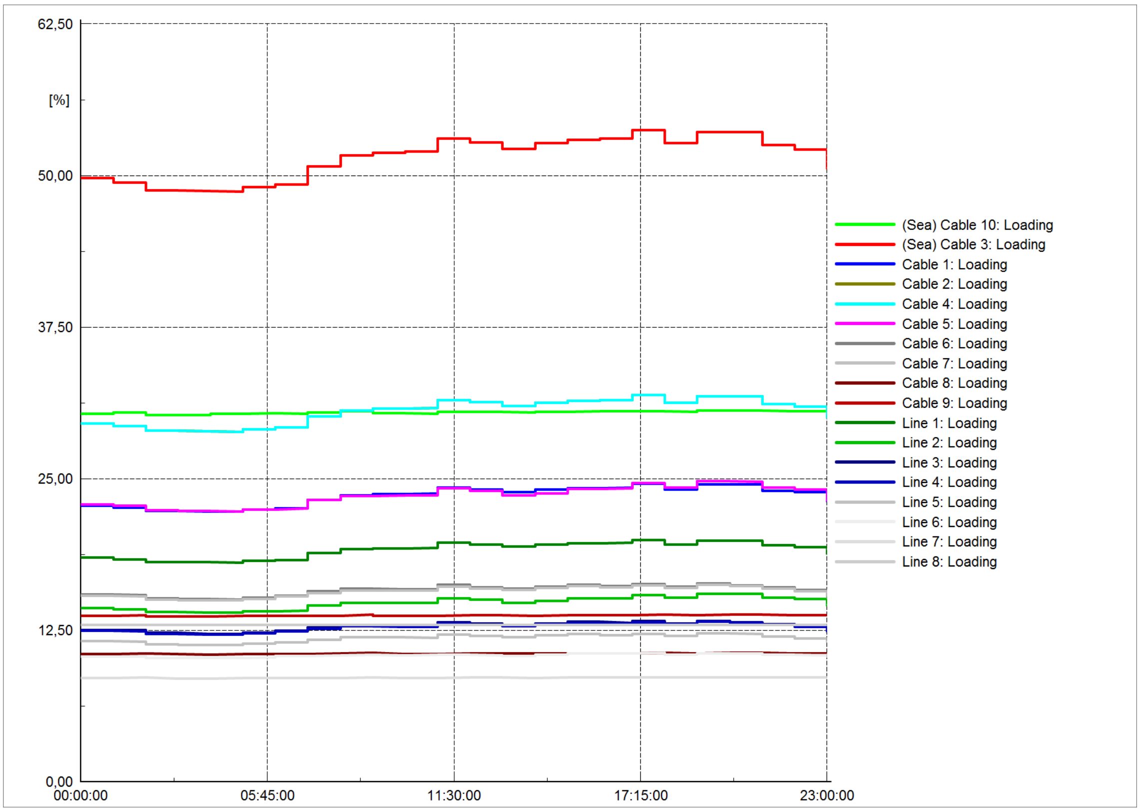

Figure 6.3: Loading of lines throughout the day.

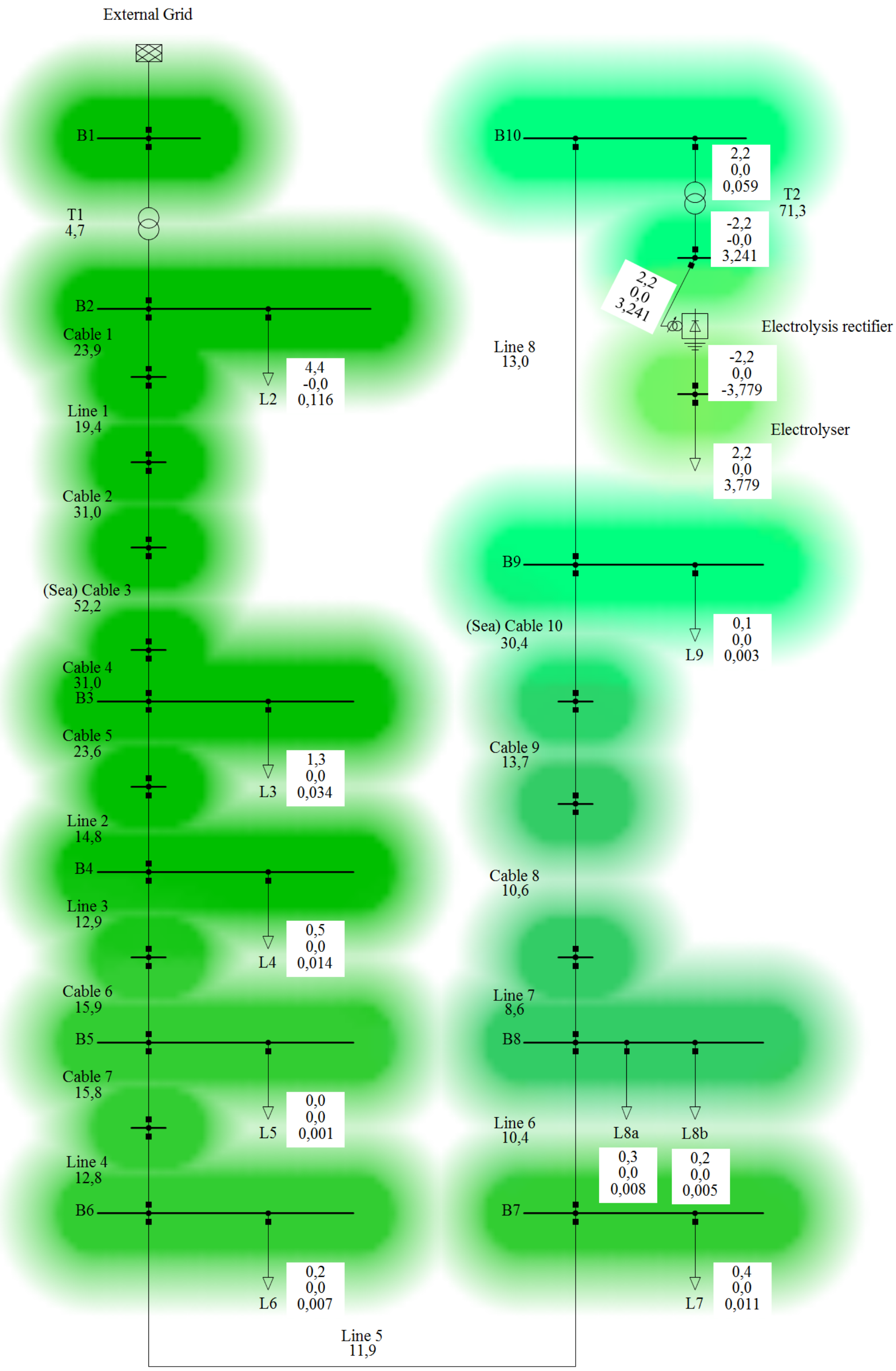

Figure 6.4: Heat map illustrating voltage level across the network.

As can be seen from Figure 6.4 the presence of a 2.214 MW electrolyser at the end of the radial causes a slight lightening of the green color on the buses further away from the source. This indicates a minor voltage drop, but its impact on the system is negligible since the system still operates within the voltage limits. Transformer T2 and the Electrolyser rectifier are highlighted by two white boxes, displaying primary and secondary values for P [MW], Q [Mvar], and I [kA]. The rectifier shows a primary AC current of 1,608 kA and a secondary DC current of 1,875 kA. The variation in current can be attributed to the current contributions generated by the capacitors within the rectifier circuit. These capacitors play a vital role in smoothing out the current ripple.

The heat map shows no red colouring present, indicating that the loading of the lines is not near the maximum of their capacitites. This is further corroborated by the information presented in Figure 6.3 where all lines have loading below 60%.

6.2.3 Discussion

In the current network, the chosen electrolyser can operate at maximum net production without exceeding the line loadings or causing significant voltage drops observed on the worst day of 2022. Hence, considering the robustness of the current network in Scenarios 0 and 1, it may not be necessary to investigate additional cases within this network in terms of flexible operation. In order to explore potential flexibility solutions, the network must exhibit a need for such solutions. In the current network model, this need is not evident. As a result, investigating flexibility potentials may be more relevant in Scenario 2, where the network will be operating at maximum loading in a future scenario. This will allow for a more comprehensive analysis of the network's ability to handle varying loads and provide insights into potential flexibility solutions that can be implemented in real-world scenarios.

6.3 Scenario 2a: Future Network, Daily

6.3.1 Description

Scenario 2 utilizes the same model as Scenario 1, but with increased loads according to the literature review in Section 2.1.3. Thus the following simulations are based on the highest scenarios for power consumption in 2050, assuming equal contributions of the increases throughout the country. Resultingly in Scenario 2 loads are increased by 114% compared to that of Scenario 1. Additionally, as mentioned in Section 5.4 a FCP of 1.5 MW is added on the very end of the radial, located on Bus 10. This future network will be used for Scenario 2a, Scenario 2b and Scenario 2c.

The worst-case scenario is examined for the future network system. The worst-case scenario examines the worst day in 2022, which is also analyzed in the Base Case and Scenario 1. The worst-case scenario considers two cases: the first involves the electrolyser and ferry charging at full capacity throughout the worst day, while the second involves seven rounds of ferry charging with the electrolyser undergoing various ramp-up and ramp-down operations during the day. By varying the electrolyser's loadings, the associated effects on the network's performance and stability can be observed. This analysis aims to identify the optimal operating conditions for the electrolyser that can ensure reliable and efficient grid operation while meeting the hydrogen demand for the ferry charging.

To take advantage of the fast flexibility response of the PEM-electrolyser as discussed in Subsection 3.2.1, the time characteristics are examined in minutes per day. However, since the available data for network loading is only given in hours, it is assumed that the same load is distributed evenly throughout each minute of that given hour on the worst day in 2022. The analysis focuses on different cases of charging the ferry and production from the electrolyser. It is assumed that the ferry charges for 10 minutes during each charging cycle [58]. On the other hand, the electrolyser has a very short ramp-up and ramp-down time, which is assumed to be momentary for the analysis.

6.3.2 Results

In Figure 6.5 the heat map for the future network model on the worst-day of 2022 is presented. Here the electrolyser is operating at 100% and the ferry charging drawing 100% power throughout the day.

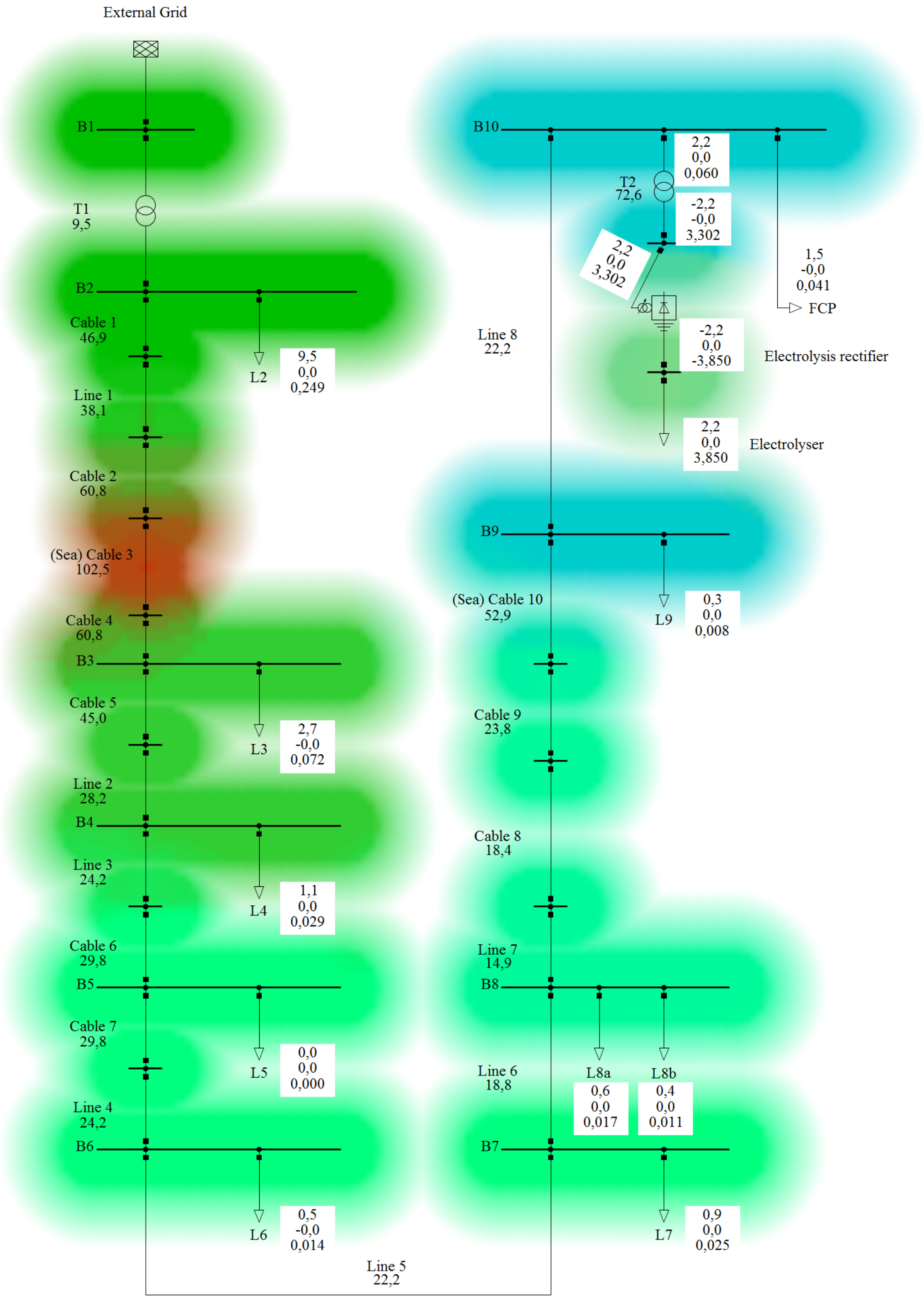

Figure 6.5: Heat map illustrating voltage level across the network.

Based on the heat map shown in Figure 6.5, several observations can be made. Firstly, Sea cable 3 is observed in the colour red, and is loaded at 102.5%. This indicates that the line is operating above its rated capacity, potentially causing thermal stress on the line. Such overloading can lead to voltage drops and increased power losses. Additionally, in Bus 10 and Bus 9, the voltage levels are measured to be at 0.95 p.u., which corresponds to the lower voltage limit. It is crucial to avoid voltage levels that are too low as this can result in inadequate performance of electrical devices, potential instability within the system, and increased power quality issues [16]. Therefore, it is important to address these issues as loading above 100% and operating close to the lower voltage limit can have detrimental effects on the grid. Mitigation measures such as grid reinforcement, load shifting, or voltage regulation should be considered to ensure the reliable and stable operation of the distribution system.

Further analysis is conducted on flexible solutions for the electrolyser, taking into account a more realistic scenario where the ferry charges seven times a day instead of drawing 100% power throughout the entire day. In this case, the electrolyser is operated at different loadings to examine its impact on the network. Figure 6.6 and Figure 6.9 show loading of the lines and voltage profile respectively with the electrolyser operating at 100% at each ferry charging. In the two following paragraphs, alternative operating modes of the electrolyser are presented for comparative analysis against the electrolyser operating at 100% capacity.

The electrolyser's downregulation is implemented through two approaches. Firstly, it is adjusted to ensure that the loading of Sea Cable 3 remains below 100% capacity. This downregulation is performed based on the values provided in Table 6.1, obtained through graphical analysis of the bars exceeding the 100% dotted line in Figure 6.6. These values are approximations. The resulting effect can be observed in Figure 6.7 and 6.10 where the loading of the lines and the voltage profiles is shown respectively.

Table 6.1: Ferry charging times and the corresponding loading of the electrolyser to keep load of cable 3 below 100% of rated values.

Ferry charging time	**Electrolyser operation**
08:00 - 08:10	91%
10:00 - 10:10	88%
12:00 - 12:10	81%
14:00 - 14:10	82%
16:00 - 16:10	78%
18:00 - 18:10	82%
20:00 - 20:10	73%

Secondly, the electrolyser's power consumption is reduced by the amount of power consumed by the ferry during charging. Consequently, the electrolyser's capacity is lowered by 1.5 MW, allowing it to operate at 0.7 MW or 32% of its rated value during ferry charging. As a result, the electrolyser operates at approximately 97% capacity throughout the day. The load profile and the voltage profile for this specific case are depicted in Figure 6.8 and 6.11, respectively.

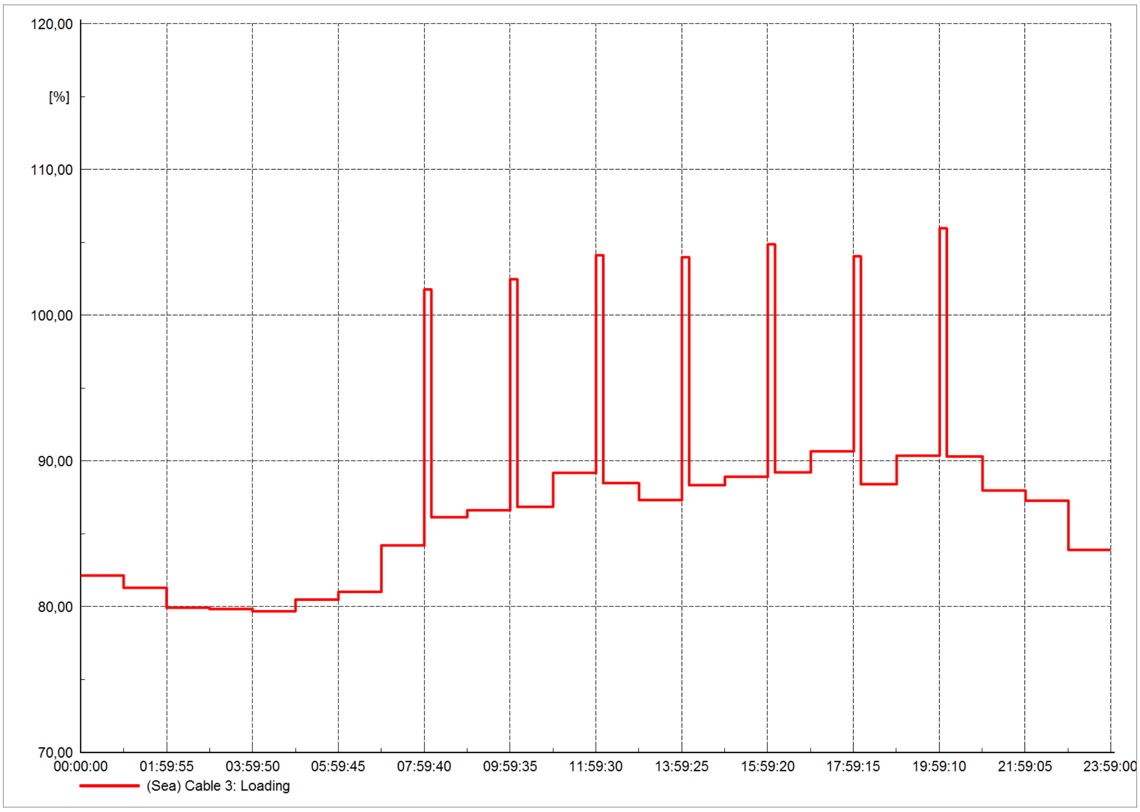

Figure 6.6: Loading of Cable 3 with pulsating ferry charging. Electrolysis continuously operating at 100%, leading to cable overloading at times when ferry is charging.

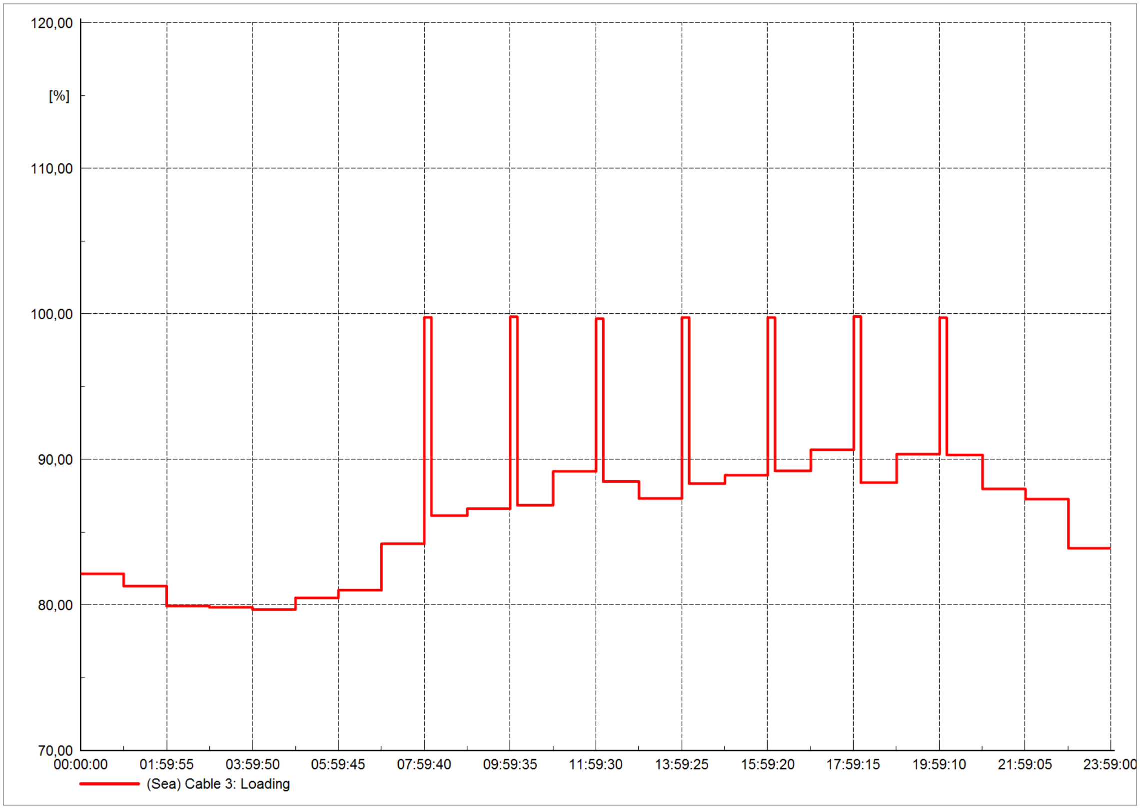

Figure 6.7: Loading of Cable 3 with pulsating ferry charging. Electrolysis down-regulated in accordance with Table 6.1 to not overload Cable 3.

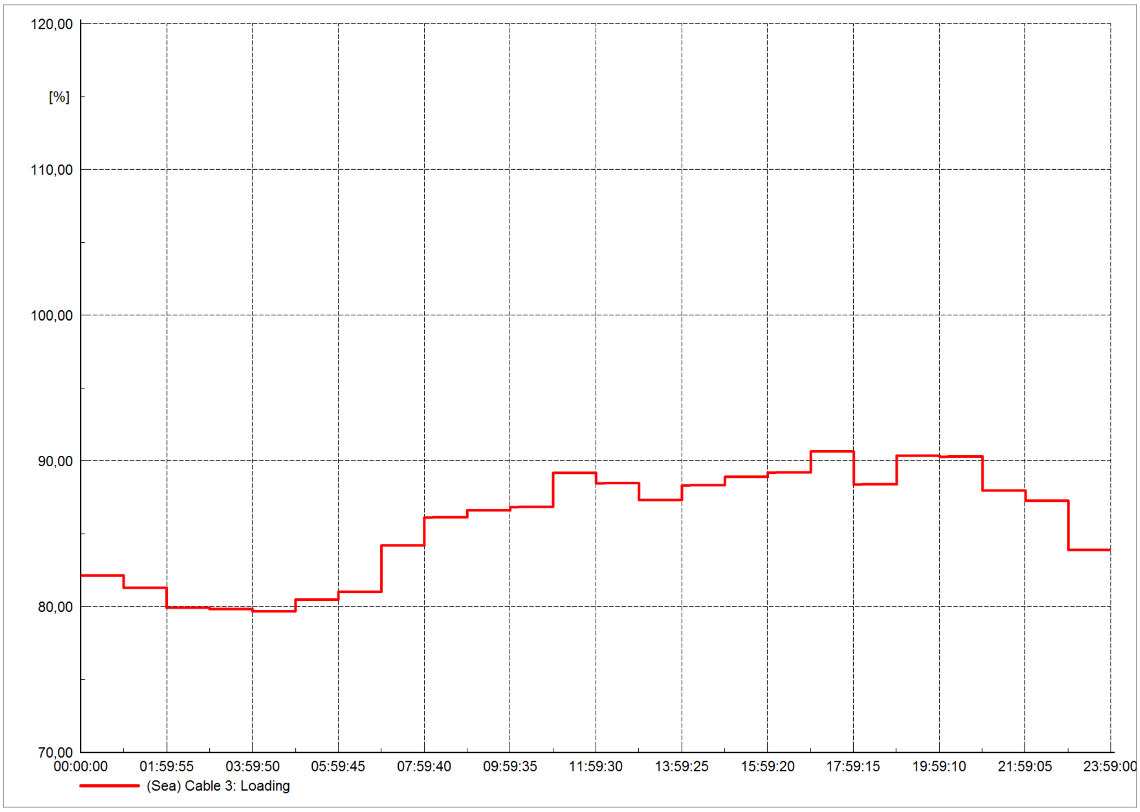

Figure 6.8: Loading of Cable 3 with pulsating ferry charging. Electrolysis down-regulated with the power which the ferry charges.

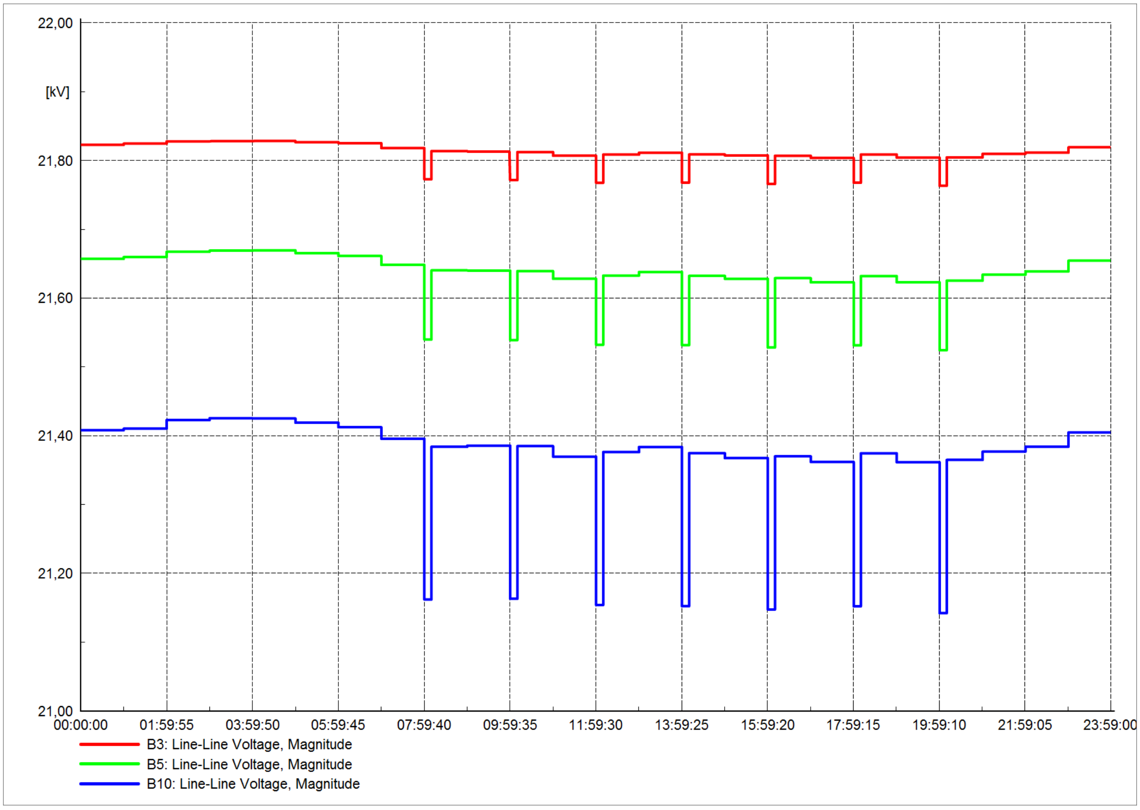

Figure 6.9: Bus voltages with pulsating ferry charging and electrolyser operating at 100%.

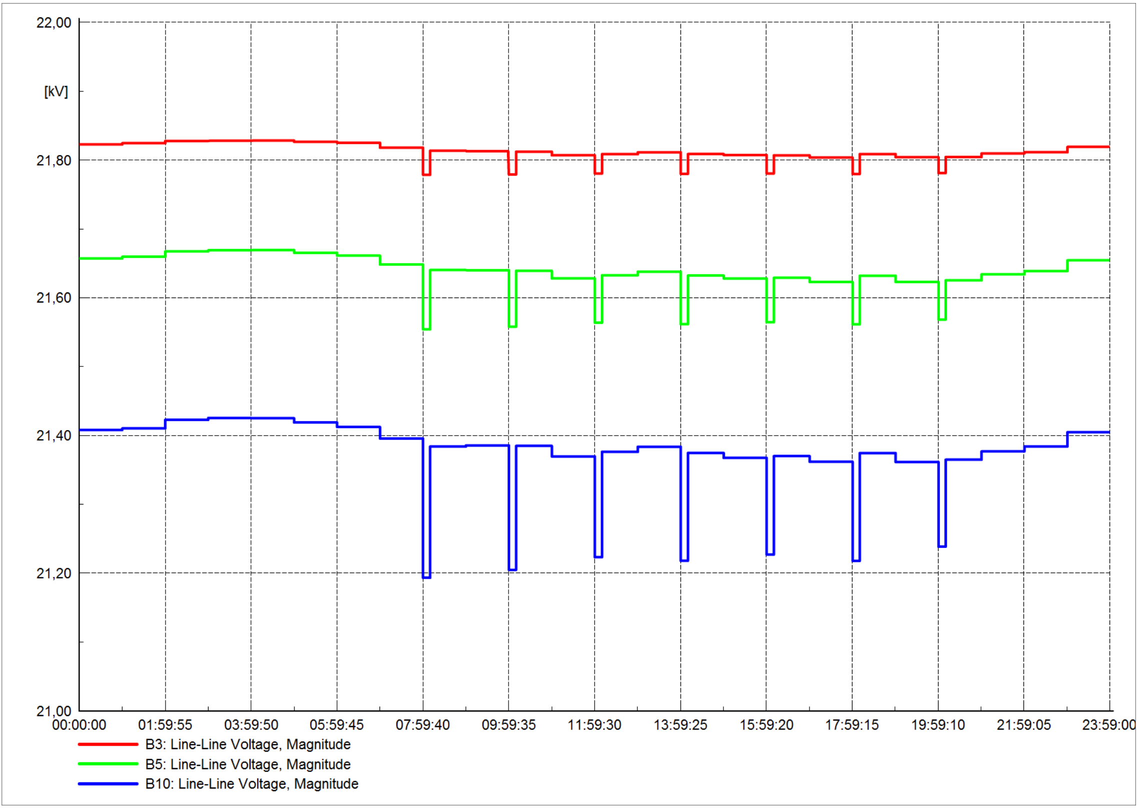

Figure 6.10: Bus voltages with ferry charging and electrolyser down-regulated in accordance with Table 6.1 to not overload cable 3.

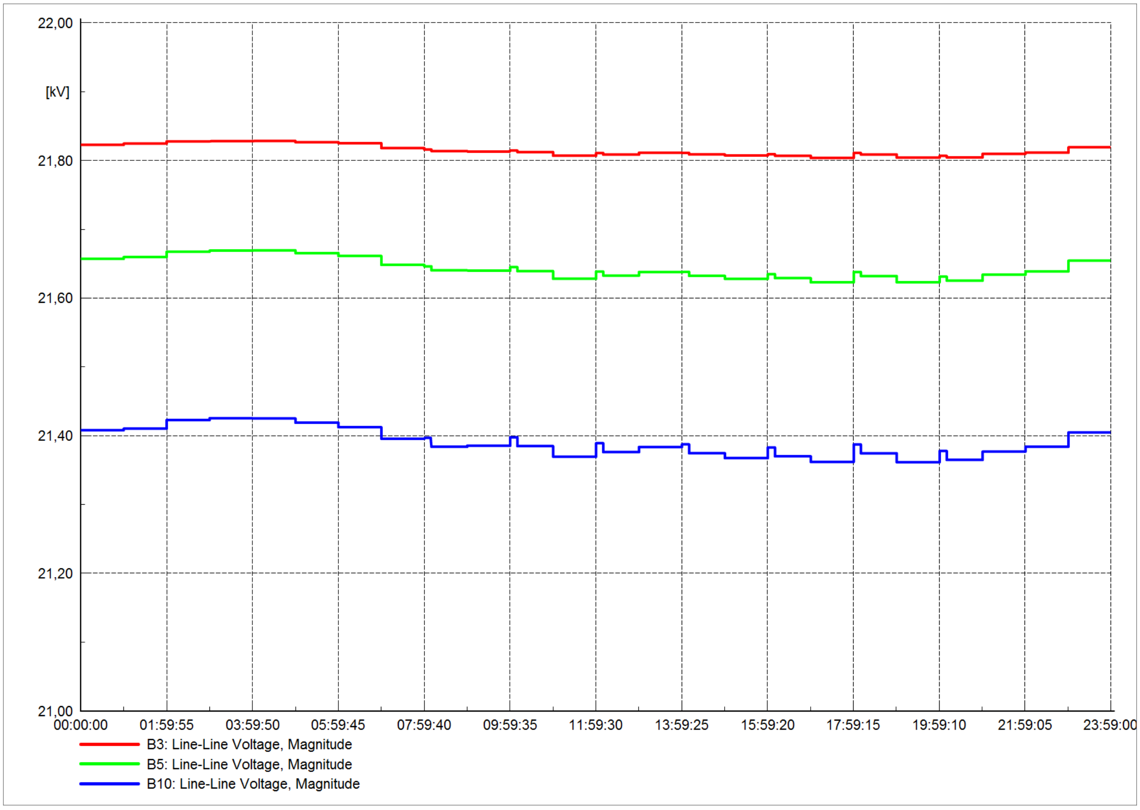

Figure 6.11: Bus voltages with ferry charging and electrolysis down-regulated with the power which the ferry charges.

Figure 6.6 provides a visualization of Sea Cable 3, which is identified as the most critical line in the network when the ferry charges seven times a day with the electrolyser operating at 100% production. The loading of Sea Cable 3 is observed to exceed 100%, indicating potential issues such as thermal stress, voltage drops, and increased losses. To mitigate this situation, a strategy is implemented to reduce the electrolyser's consumption, thereby decreasing the loading on Sea Cable 3. This adjustment is reflected in Figure 6.7 and Figure 6.8, where the loading of Sea Cable 3 remains below the critical 100% threshold. The fast response time of the electrolyser enables rapid ramp-down, allowing it to effectively reduce peaks in the network. Figure 6.7 demonstrates the instantaneous ramp-down of the electrolyser when the ferry charges, resulting in a loading trend just below 100% for Sea Cable 3. Similarly, Figure 6.8 showcases the electrolyser compensating for the ferry charging, resulting in a loading trend without noticeable pulses.

Figure 6.9 provides insights into the voltage behavior of the network during ferry charging events. It is observed that each time the ferry charges, there is a noticeable voltage drop in the network. The magnitude of these voltage drops increases as the buses are located further away from the source. Buses 3 and 5 exhibits smaller voltage drops compared to Bus 10, and this trend persists for all buses preceding Bus 10 in the network. However, when the operation of the electrolysers is reduced, as depicted in Figure 6.10 and Figure 6.11, the voltage drops become smaller. This implies that by adjusting the electrolysers' power consumption, the network experiences mitigated voltage drops during ferry charging events. Figure 6.11 demonstrates a slight peak in voltage during the 10-minute duration of the ferry charging. This is attributed to a reduced power flow through the electrolysers' transformers, resulting in less voltage drop across these transformers.

Since all three scenarios are based on an analysis of hourly time characteristics from the worst day of 2022, a comparison between these scenarios is possible. Table 6.2 presents the total losses in Scenario 0 and the corresponding percentage increase in losses for Scenario 1 and 2. Scenario 2a exhibits a substantial increase in total losses, with a magnitude of 2,300% in MW and 1,650% in MVAr. To further illustrate the differences, Figure 6.12 depicts the line loading for the three scenarios: Scenario 0, Scenario 1 and Scenario 2a. It is evident from the figure that the loading in all the lines is significantly higher in Scenario 2a compared to the other two scenarios. These findings highlight the potential challenges and increased strain on the grid in this particular scenario. The higher loading and increased losses indicate the need for further analysis and potential mitigation measures to ensure the reliable and efficient operation of the power system under such conditions.

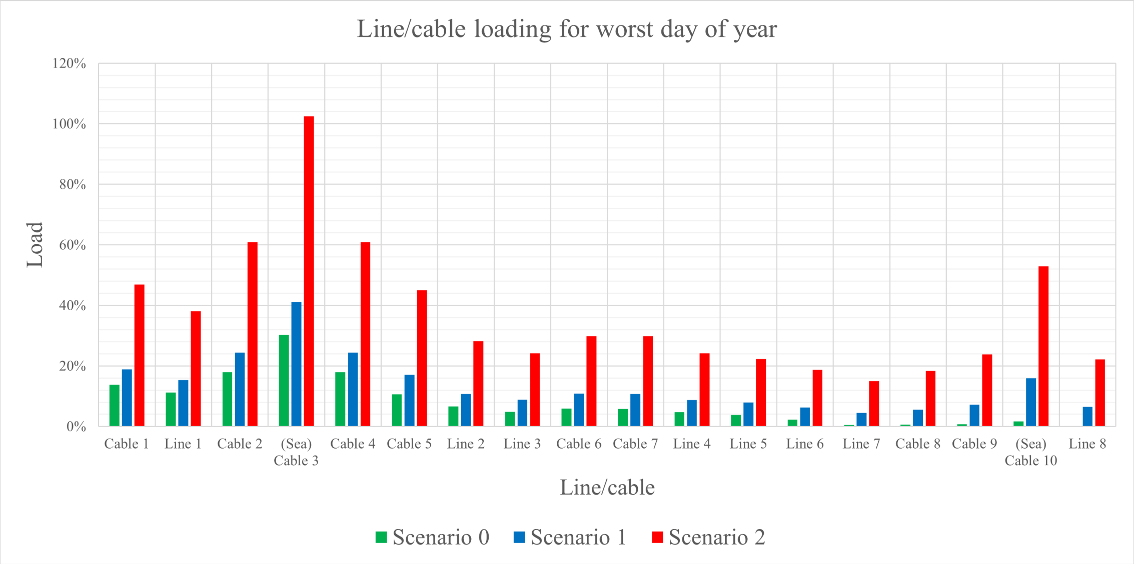

Figure 6.12: Line/cable loading for worst day of year.

Table 6.2: Total system losses in Scenario 0 and the relative increase to Scenario 1 and Scenario 2.

Unit	**Scenario 0**	**Scenario 1**	**Scenario 2**
MW	0.01	600% ↑	2,300% ↑
MVAr	0.04	475% ↑	1,650% ↑

6.3.3 Discussion

Based on the simulation results obtained from Scenario 2a, it is evident that the electrolyser's operation can be analyzed in the context of flexible solutions. One notable finding is that optimizing the electrolyser's power consumption can minimize voltage drops during ferry charging events, resulting in improved voltage levels and enhanced performance of electrical devices across the network. This observation highlights the significant impact of electrolyser operation on network voltage stability. The simulation results also demonstrate the electrolyser's fast response time, as evident from the daily analysis. This rapid response enables the electrolyser to effectively support voltage control in the network, as reflected in the voltage profiles obtained. By adjusting its production rate, as demonstrated in this analysis, the electrolyser can promptly respond to voltage fluctuations and help maintain stable voltage conditions.

Additionally, the simulation results reveal that the electrolyser experiences lower loading during nighttime compared to daytime on the worst day in 2022. This suggests that implementing hydrogen storage can allow the electrolyser to produce more hydrogen during nighttime while reducing production during peak hours in the day. The results clearly indicate that by adjusting the electrolyser's production rate, it is possible to achieve lower voltage drops and reduced line loadings. This demonstrates the potential of the electrolyser, in combination with hydrogen storage, as a flexible solution for voltage control and peak consumption avoidance. By optimizing the electrolyser's operation and leveraging the capabilities of hydrogen storage, the system can dynamically respond to fluctuations in electricity demand, ensuring more stable voltage levels and alleviating excessive loading on the network. This highlights the significant role of the electrolyser in enhancing grid resilience and efficient energy management.

However, it is crucial to note that in the specific case being studied, the electrolyser and the FCP are connected to the same bus, facilitating effective voltage regulation, as illustrated in Figure 6.11. If the electrolyser were connected to a different bus than the FCP, its impact on downstream buses' voltage would be diminished compared to the scenario where they share the same bus. Consequently, if the electrolyser is situated on a different bus from the FCP, it would not be capable of fully compensating for the voltage drop induced by ferry charging. This limitation curtails the potential of utilizing an electrolyser for voltage control within the grid. Therefore, if the electrolyser is intended for such purposes, it is preferable to position it on the same bus as a significant load, such as a ferry charger.

Furthermore, in Section 2.3.2, congestion management was discussed as one of the flexibility categories. The electrolyser can play a critical role in congestion management by rapidly disconnecting or reducing its load when congestion occurs. In situations where the grid experiences high demand or limited capacity, the electrolyser can swiftly adjust its hydrogen production to alleviate the strain on the system. The results from Scenario 2a demonstrate this capability, where the electrolyser could promptly shut down or decrease its production during times of high line loading due to ferry charging. By reducing its load, the electrolyser effectively acts as a flexible resource that helps balance supply and demand in the grid, thereby supporting congestion management.

6.4 Scenario 2b: Future Network, Weekly

6.4.1 Description

Scenario 2b employs the identical network model used in Scenario 2 with the electolyser operating at 100%, but focuses on analyzing the grid's performance during weekdays and weekends. This investigation aims to visualize the variations in consumption patterns that could potentially impact the flexible operation of the electrolyser. To achieve this, the average load data from Monday through Friday is utilized to represent a typical weekday, while the consumption average of Saturday and Sunday is calculated to represent a typical power consumption during weekends. The analysis incorporates load data collected from Monday, February 14, to Sunday, February 20, 2022.

6.4.2 Results

Heat maps depicting the average weekday and average weekend cased for the Future Network with the electrolyser operating at 100% are presented in Figures 6.13 and 6.14, respectively. Further, Figures 6.15 and 6.16 illustrate the loading levels of the three lines with the highest loadings during an average weekday and an average weekend in the worst month.

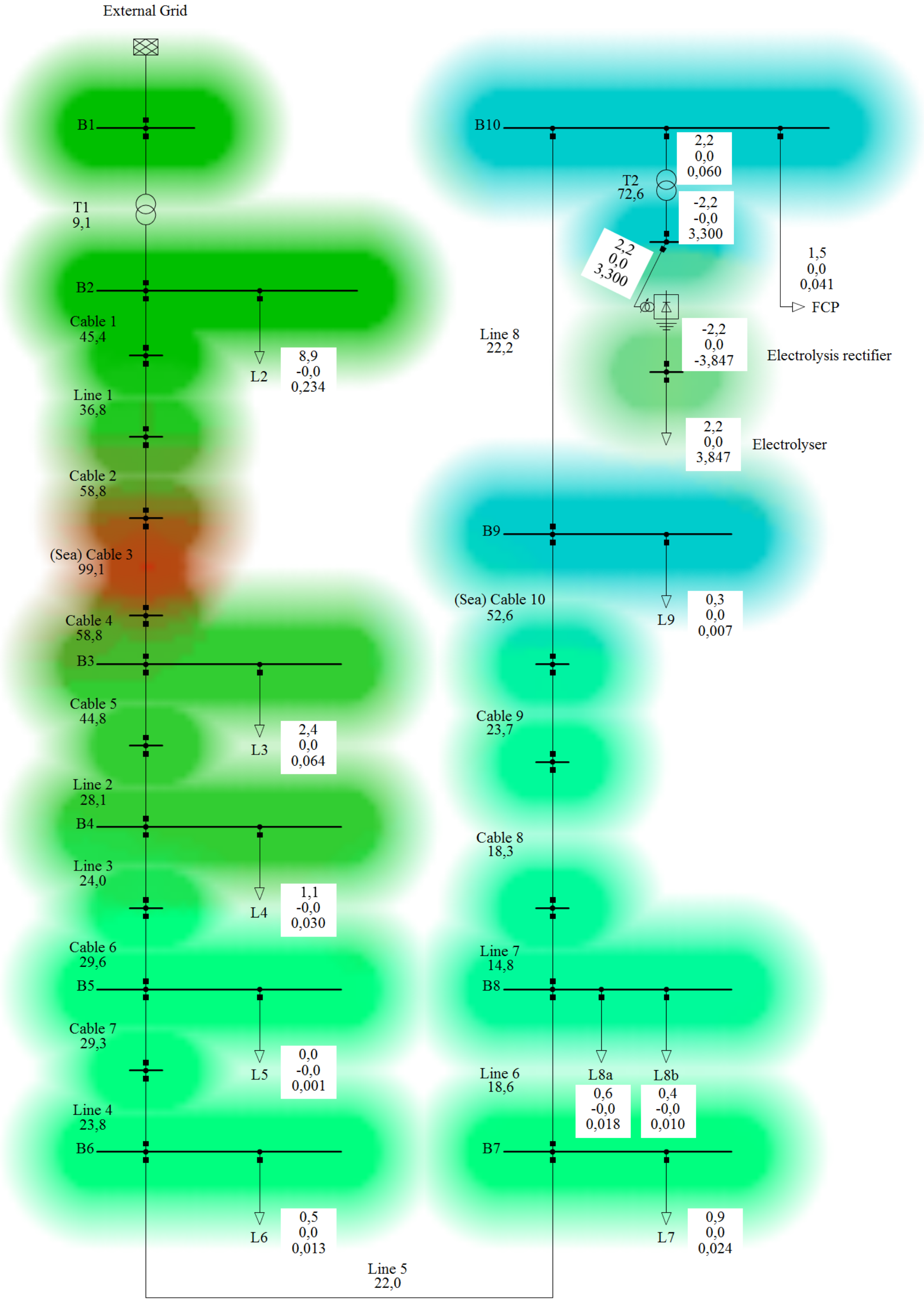

Figure 6.13: Heat map illustrating voltage level across the network, for an average weekday.

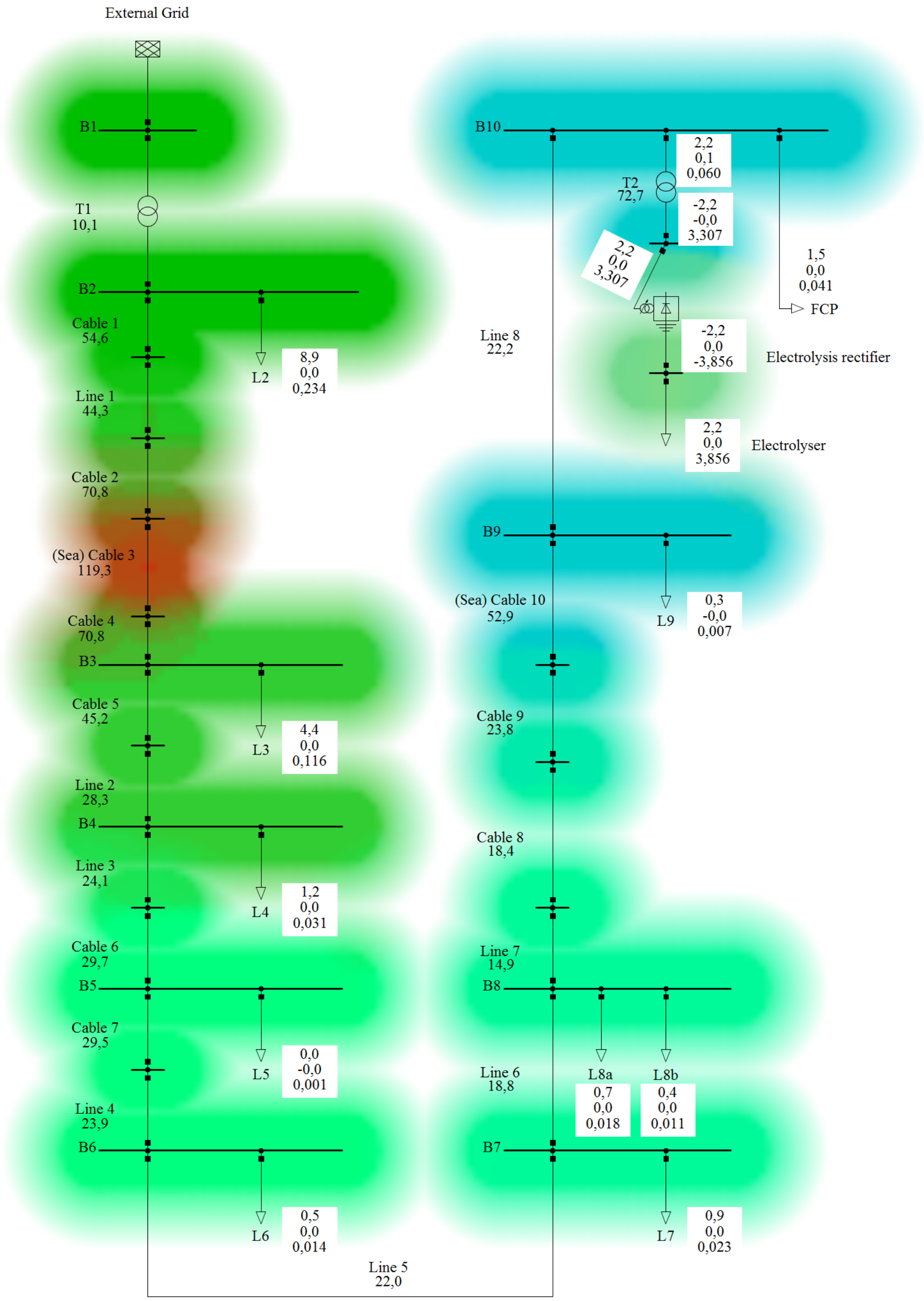

Figure 6.14: Heat map illustrating voltage level across the network, for an average day in a weekend.

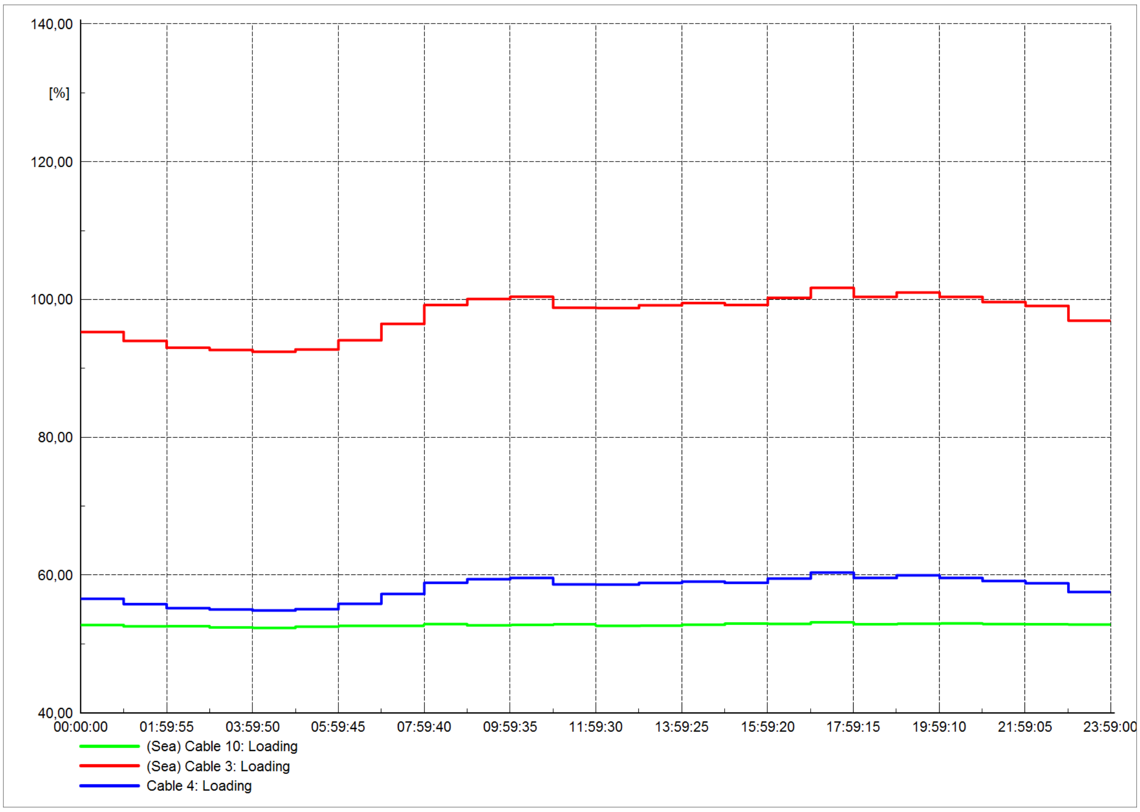

Figure 6.15: Loading of lines for an average weekday.

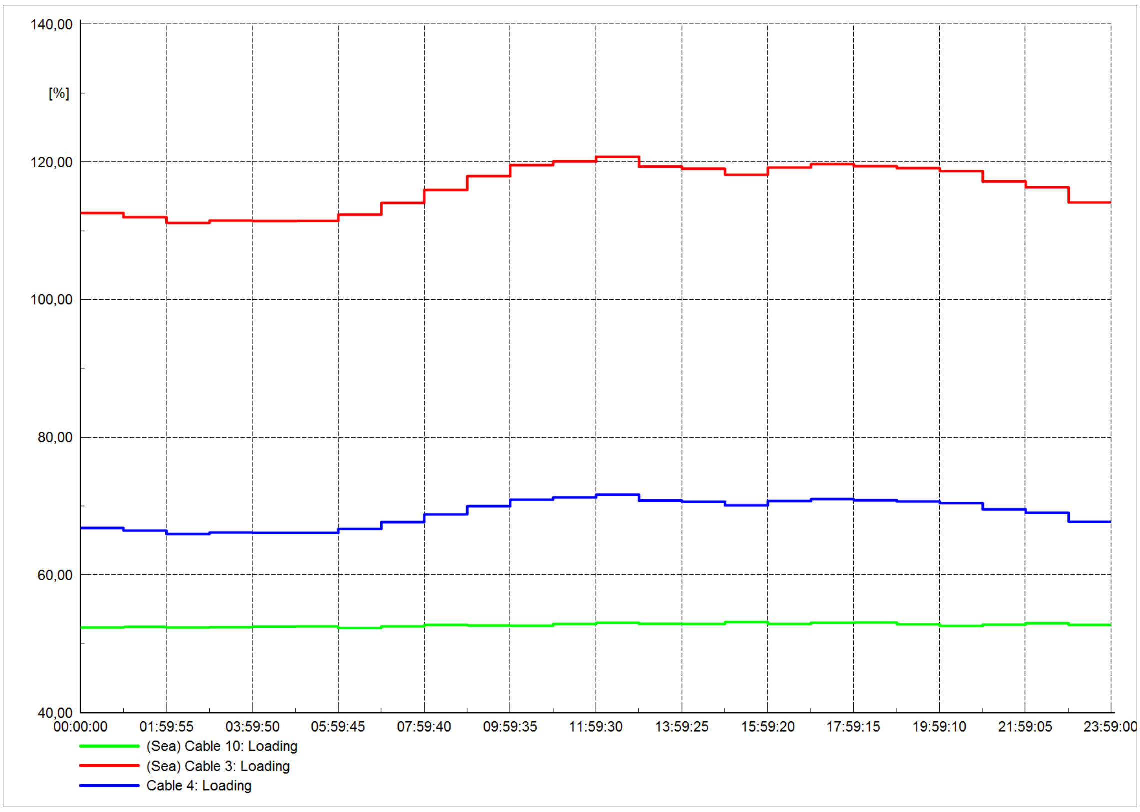

Figure 6.16: Loading of lines for an average day in a weekend.

The analysis reveals important insights into the network's performance during these periods. Notably, Sea Cable 3 is consistently represented by the color red in both Figure 6.13 and Figure 6.14, indicating that its loading exceeds 100%. This high loading suggests that the cable is operating at above its maximum capacity, which can pose risks such as thermal stress and increased losses. In addition, Bus 9 and Bus 10 are depicted by the colour blue, indicating that the voltage magnitudes at these buses are close to the lower limit. Voltage levels near the minimum limit can result in inadequate performance of electrical devices, potential system instability, and compromised power quality.

Figure 6.15 and 6.16 highlight some key differences between weekdays and weekends in terms of line loading. During weekdays, the maximum loading observed on the lines reaches up to 100%, indicating that the lines are operating at their full capacity. However, during weekends, the loading levels are even higher, with some lines reaching up to 120% loading. This suggests that the network experiences higher demand and stress during weekends compared to weekdays. The discrepancy in network loading between weekdays and weekends can be attributed to the nature of electricity consumption in households. It is likely that the majority of network loading comes from residential users, and during the weekend, people tend to stay at home throughout the day. This prolonged presence at home leads to increased electricity usage and higher demand on the network. In contrast, on weekdays, when individuals typically leave their homes for work or other activities, the electricity consumption from residential households tends to be lower. This reduced demand during weekdays can be the contributes to the lower loading levels observed in the network during those times.

6.4.3 Discussion

The weekly Scenario reveal a general trend of higher loadings during the daytime compared to the nighttime. This indicates that electricity consumption is typically higher during the day, potentially due to increased commercial and residential activities. As a result, it may be more beneficial to allocate higher electrolyser production capacity during weekdays and daytime periods to effectively meet the demand and manage the network's loadings.

Understanding these variations in loading patterns can assist in optimizing the operation and planning of the electrolyser system. By adjusting the production levels to match the specific demands during weekdays and considering the higher loadings during weekends, efficient and tailored strategies can be implemented to ensure reliable and sustainable operation of the network.

As discussed in the theoretical framework, specifically in Subsection 2.3.2, it is understood that peak load periods may temporarily limit the grid's capacity despite the overall increasing demand. These grid constraints can be reasonably predicted, and accessing resources that can transfer loads during these periods can help mitigate grid expenses. In this regard, the utilization of load trends for both weekdays and weekends, considering the electrolyser's 100% operation in the network, allows for planned flexibility in regular grid operations. By analyzing the line loading trends, it is observed that the line loading exceeds 100% during weekdays, indicating a potential strain on the grid's capacity. To address this, it becomes possible to plan for lower hydrogen production during weekends, leveraging the flexibility provided by hydrogen storage.

Planned load shifting approach enables more efficient management of grid capacity, ensuring a more balanced distribution of resources and alleviating potential constraints. Integrating hydrogen storage as a resource for grid capacity management offers several advantages. It allows for strategic load shifting, enabling the grid to optimize its operations and balance the supply and demand dynamics effectively. By adjusting hydrogen production and storage utilization based on load trends, the grid can better accommodate fluctuating demands and mitigate potential overload situations during peak periods.

6.5 Scenario 2c: Future Network, Yearly

6.5.1 Description

In the yearly case, understanding the monthly production of hydrogen from the electrolyser in relation to the monthly demand from the fishing fleets is an important factor in evaluating the viability of this solution. Among all the fishing fleets, Fishing Fleet 1 from Section 4.2 has the highest energy consumption, making it an ideal candidate for further analysis of hydrogen demand. To accurately compare hydrogen production to demand, it is essential to determine the actual amount of hydrogen that the reference PEM electrolyser is capable of producing. This can be achieved through a thorough analysis of the system's technical specifications and performance data. By obtaining a clear understanding of the electrolyser's capabilities, it is possible to determine the extent to which it can satisfy the hydrogen demands of Fishing Fleet 1 and potentially other fleets in the region.

In Figure 6.17, both the maximum energy consumption for Fishing Fleet 1 and the accumulated monthly load demand in the network are displayed. The load demand curve provides valuable insights into the network's trend, highlighting the months with the highest loads. To conduct a yearly analysis, the accumulated monthly consumption values are utilized in the network data trend. This allows for the identification of the months with the highest consumption, which is a significant point of interest. Note that the data for the energy consumption of Fishing Fleet 1 is taken from July 2021 to June 2022, and the accumulated energy consumption for the network is taken from January 2022 to December 2022. It is fair to assume that the energy consumption is the same for these periods because seasonal variations tend to be somewhat similar from year to year. Thus the analysis will be conducted for January 2022 to December 2022, with data for the hydrogen demand taken from July 2021 to June 2022.

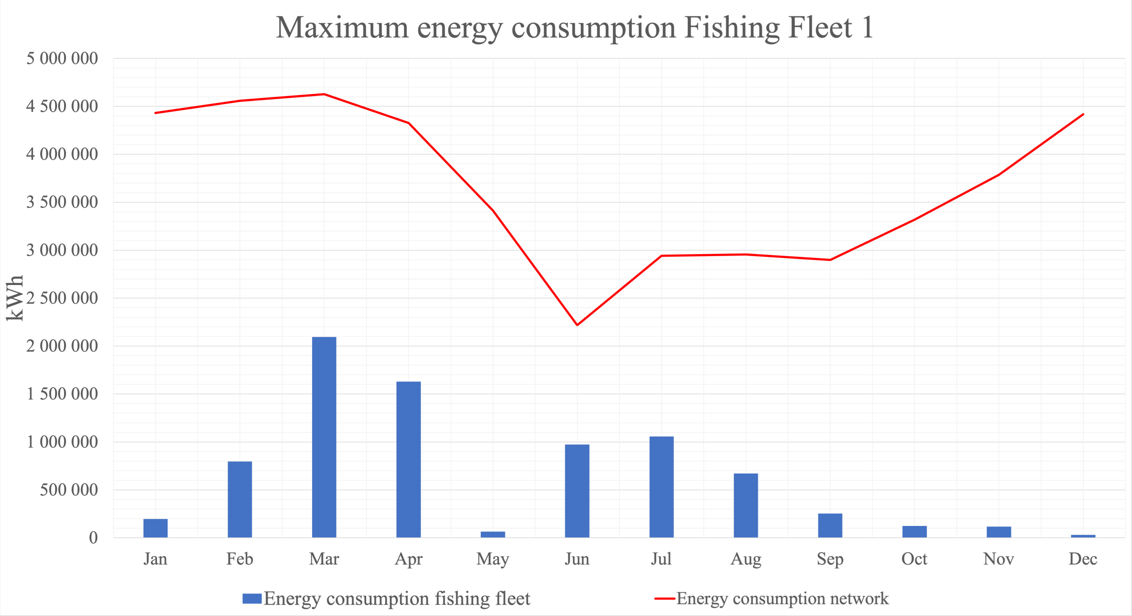

Figure 6.17: Maximum energy consumption for Fishing Fleet 1 and energy consumption in network for 2022.

To compare hydrogen production with demand, monthly production for the reference PEM electrolyser and hydrogen demand is investigated. The chosen reference electrolyser (see Apenndix A), has a net hydrogen production rate of $1062kg/24h$ or $492Nm^3/h$. Additionally, it has a average power consumption at stack per volume of H_2 gas produced equal to $4.5kWh/Nm^3$, as seen from

Appendix A. This gives a net production rate of:

$$1062kg/24h \cdot 31days = 32,922kg/month \tag{6.1}$$

$$492Nm^3/h \cdot 4.5kWh/Nm^3 \cdot 31days = 1,647,216kWh/month \tag{6.2}$$

For calcualting the hydrogen demand for Fishing Fleet 1, Equation 4.1 from 4.2 from Section 4.2 is used. This results in a hydrogen demand from July 2021 to June 2022 shown in Figure 6.18.

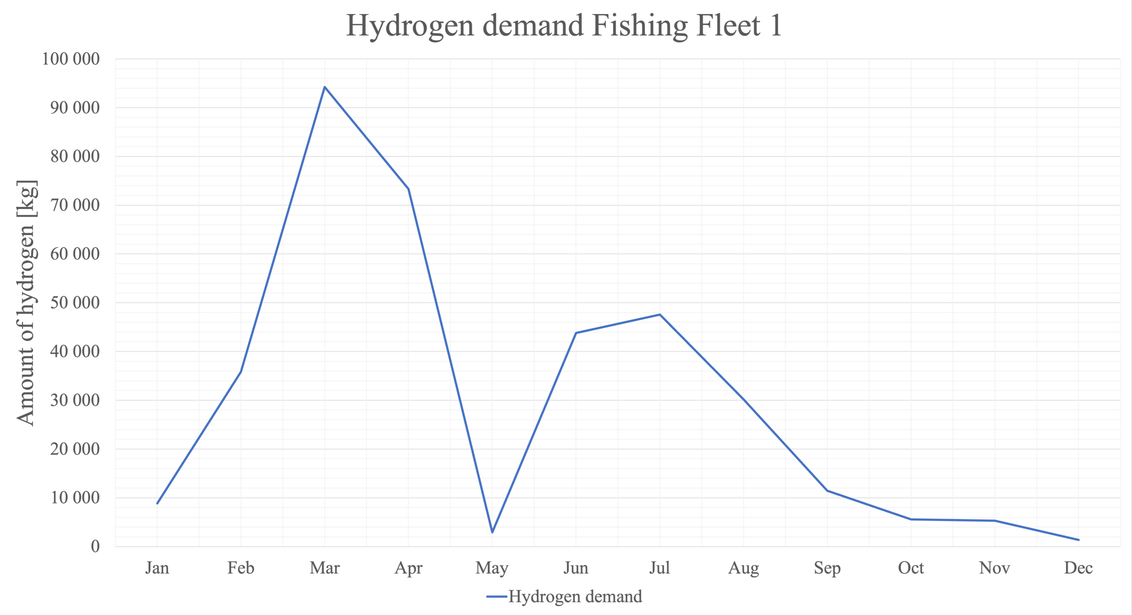

Figure 6.18: Hydrogen demand based on maximum energy consumption for Fishing Fleet 1 from July 2021 to June 2022.

A case based on yearly analysis is worth exploring, as one of the benefits of a water electrolyser is its ability to store energy in the form of hydrogen. This enables production to be scaled down during periods of high demand and scaled up again during times of low demand. As shown in Figure 6.17, network loading peaks from January to April and reaches its lowest point in June, with July and August having higher load demands. This suggests that the electrolyser could potentially reduce consumption from January to May to compensate for high demand. This will be further investigated in this yearly analysis scenario.

Further, in the yearly analysis of power system analysis, the average of the accumulated power demand for each month is utilized, rather than the maximum value for each month. This is because accumulated values offer a better understanding of the overall consumption trends throughout the year. Maximum values only show the peak value for each month, which may not be representative of the typical consumption pattern for that month. However, accumulated values provide a cumulative total of consumption for each month, offering a more accurate depiction of the total consumption for the year and the trend over time. This knowledge is vital for planning and optimizing the power system to meet demand and ensure a reliable power supply.

6.5.2 Results

Figure 6.19 shows the heat map for Scenario 2c, where voltage profiles and loadings in the lines are illustrated. Figure 6.20 represents the loading of the lines based on the average monthly power consumption. This visualization provides an overview of the network's performance throughout the year, highlighting areas of potential concern and indicating the distribution of load across the grid.

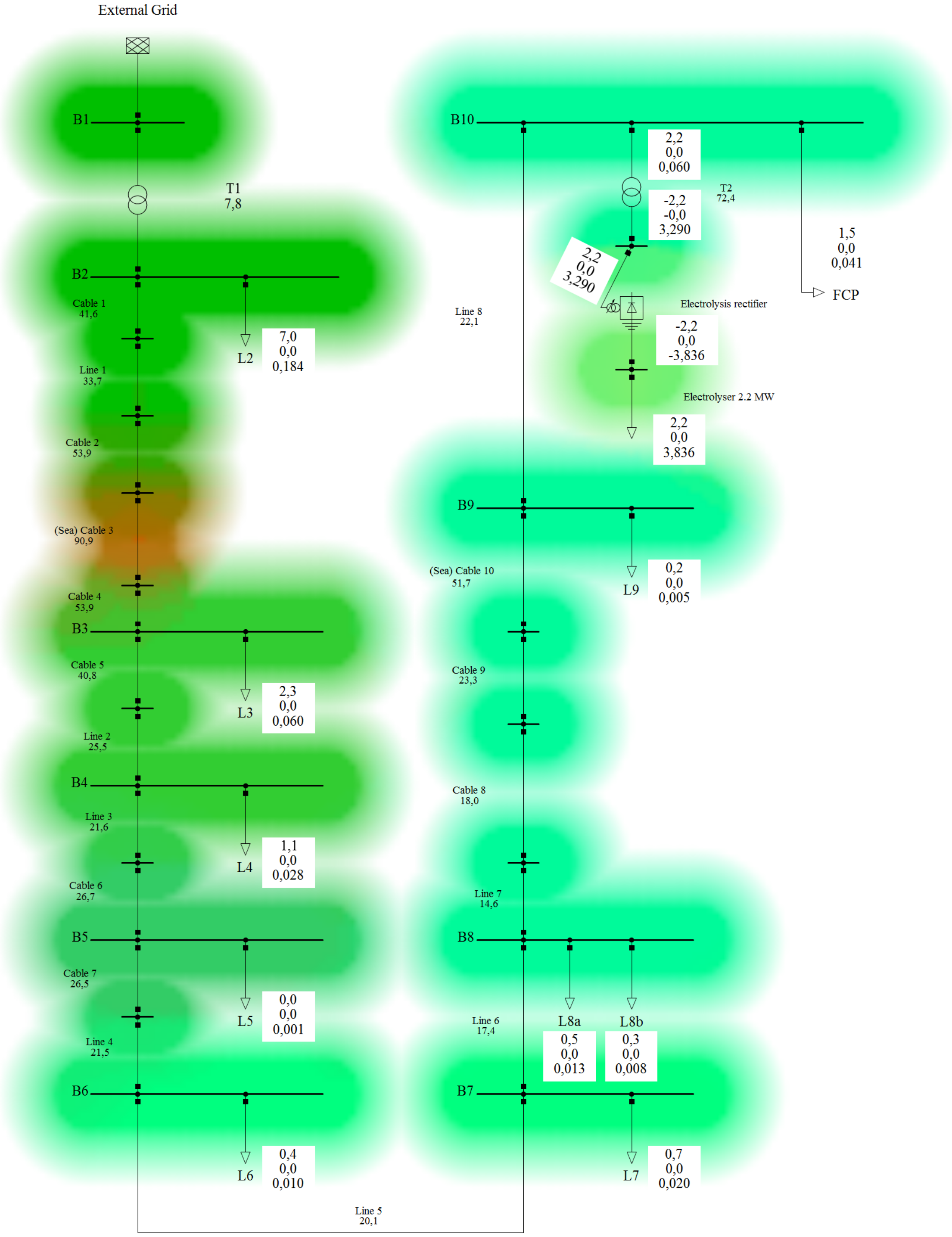

Figure 6.19: Heat map illustrating voltage level across the network.

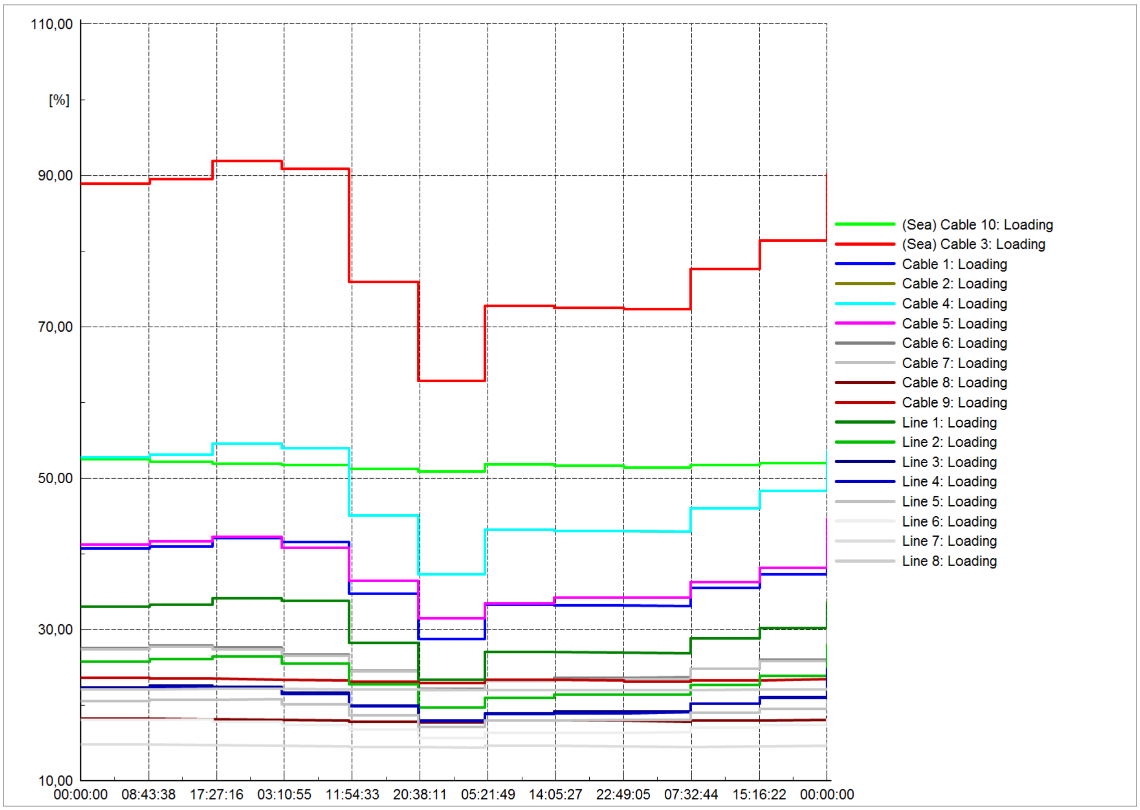

Figure 6.20: Annual loading of lines/cables when electrolyser is operated continuously at 100%.

The heat map in Figure 6.19 and Figure 6.20 clearly illustrate that Sea Cable 3 is operating close to its maximum capacity of 100% during the first four months of 2022. While the other line loadings are well below 60%, which is considered a safe level, it is important to note that these are just the average values of the accumulated energy consumption for the network loading. There may be instances where the load on the lines is much higher, potentially exceeding the 100% limit. This can pose a significant risk to the grid, as a loading above 100% on the lines can cause thermal stress on the lines, leading to voltage drops and increased losses.

In order to optimize grid capacity utilization, it is desirable to minimize the variation in power consumption throughout the year, as depicted in Figure 6.20. To achieve this, the electrolyser can be operated with a variable load to flatten out the load profile.

Based on the hydrogen demand for Fishing Fleet 1 shown in Figure 6.18, the calculation of hydrogen production required by the chosen electrolyser can be determined. When the electrolyser operates at 100% production, it generates 32,922 kg of hydrogen per month, as explained in the previous Subsection 6.5.1 and shown in Table 6.3. As mentioned in Subsection 6.5.1 the calculation of the hydrogen demand utilizes Equation 4.1 from Section 4.2. Over the course of a year, the total hydrogen production amounts to 395,064 kg, as seen from Table 6.3.

Table 6.3: Difference between hydrogen demand and 100% electrolyser production in 2022.

Month	**Hydrogen demand [kg]**	**100 % electrolyser production [kg]**	**Difference**
January	8,821	32,922	24,101
February	35,824	32,922	-2,902
March	94,239	32,922	-61,317
April	73,312	32,922	-40,390
May	2,925	32,922	29,997
June	43,789	32,922	-10,867
July	47,570	32,922	-14,648
August	30,198	32,922	2,724
September	11,431	32,922	21,491
October	5,581	32,922	27,341
November	5,311	32,922	27,611
December	1,350	32,922	31,572
Total	360,351	395,064	34,713

To consider flexibility solutions for the electrolyser, it is essential to examine the surplus energy available after meeting the hydrogen demand of the Fishing Fleet 1. Calculation of Equation 6.3 indicates that 8% of the hydrogen production can be allocated for flexibility solutions.

$$\text{Hydrogen for flexible solutions} = \frac{\text{Electrolyser 100\% production - Hydrogen demand}}{\text{Electrolyser 100\% production}} \cdot 100\% \quad (6.3)$$

$$\text{Hydrogen for flexible solutions} = \frac{395,064 - 360,351}{395,064} \cdot 100\% \approx \underline{\underline{8\%}}$$

To ensure sufficient hydrogen production for the specific fishing fleet, the electrolyser needs to operate at a minimum of 100% − 8% = 92% capacity each month. In terms of load shifting, this indicates that the electrolyser can shift 8% of its production. Consequently, the operating range of the electrolyser for meeting the hydrogen demand of Fishing Fleet 1 extends from 84% to 100%. Figure 6.21 is utilized to compare the electrolyser's 100% production with the hydrogen demand, allowing us to identify the months that may necessitate load shifting. By examining the chart, we can determine the periods when the hydrogen demand surpasses the electrolyser's maximum production capacity. This information provides insight into the potential need for load shifting strategies during specific months. It is important to note that these calculations are based on the maximum hydrogen demand of the fishing fleet with the highest energy consumption. In the case of fishing fleets with lower energy consumption, the utilization of an electrolyser with similar dimensions would offer increased flexibility owing to its lower hydrogen demand. The same principle applies to the current Fishing Fleet chosen, albeit with a larger electrolyser.

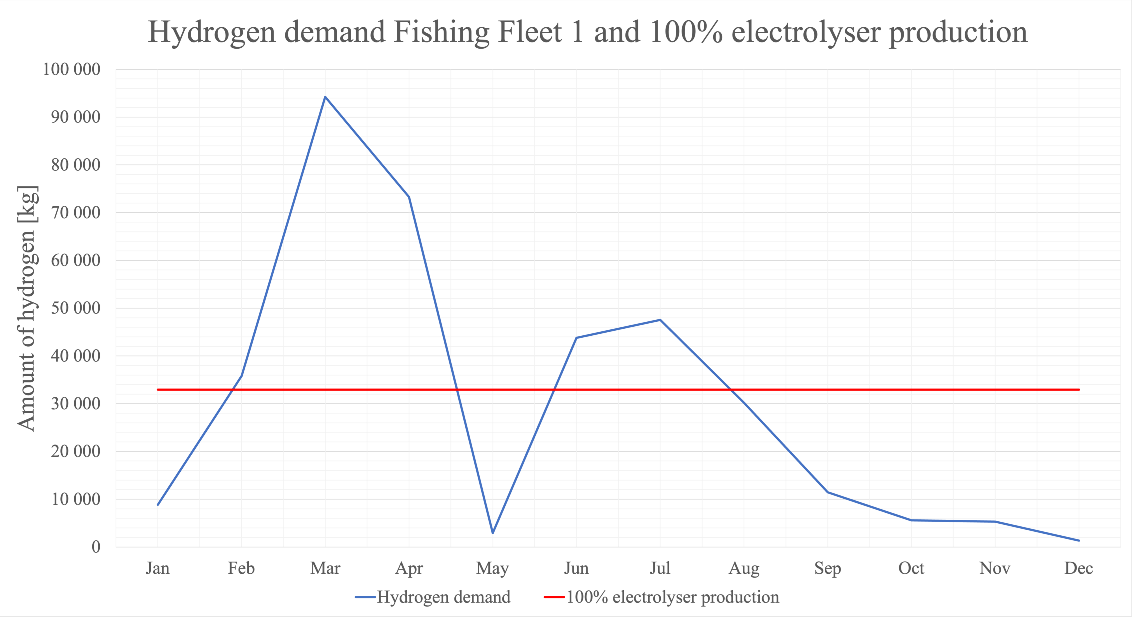

Figure 6.21: Hydrogen demand for Fishing Fleet 1 and hydrogen production capacity of electrolyser.

By considering the analysis of available load shifting potential and the hydrogen demand trend depicted in Figure 6.21, an optimized hydrogen production plan is derived. The simulation utilizes the input parameters outlined in Table 6.4, and the resulting loading outcomes after load flow calculations are illustrated in Figure 6.22. This comprehensive evaluation enables the development of an optimized hydrogen production strategy that incorporates the potential for load shifting through hydrogen storage, resulting in an enhanced efficiency and a secure and consistent supply.

Table 6.4: Input parameters for electrolyser when providing yearly flexibility.

Month	**Electrolyser loading**			
	Fixed		**Variable**	
	%	**MW**	**%**	**MW**
January	92	2.024	87	1.914
February	92	2.024	85	1.870
March	92	2.024	74	1.628
April	92	2.024	78	1.716
May	92	2.024	100	2.200
June	92	2.024	100	2.200
July	92	2.024	100	2.200
August	92	2.024	100	2.200
September	92	2.024	100	2.200
October	92	2.024	100	2.200
November	92	2.024	100	2.200
December	92	2.024	80	1.760
Average	92	2.024	92	2.024

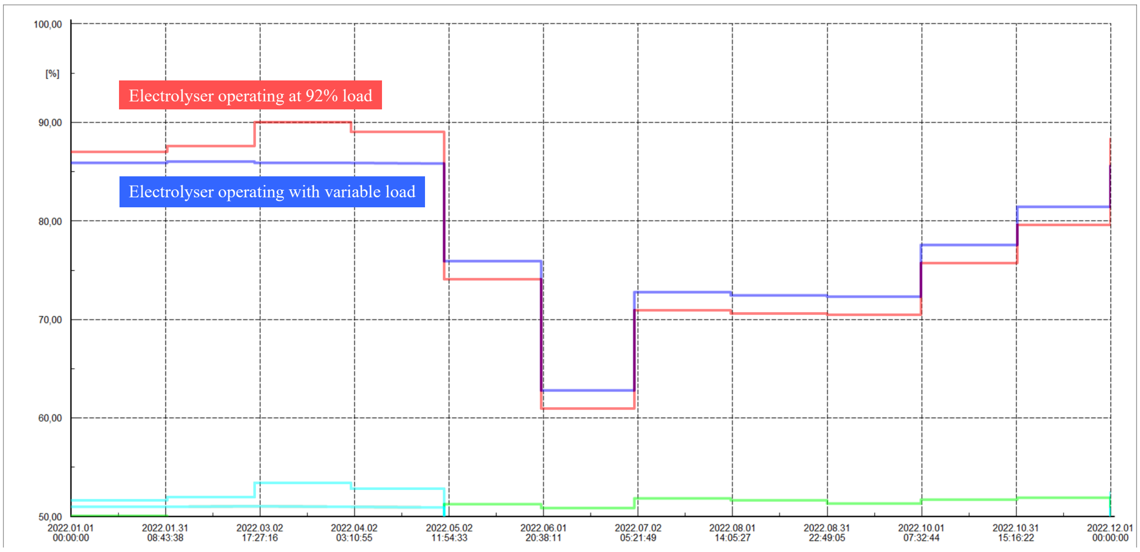

Figure 6.22: Monthly average loading of Cable 3 with fixed and variable electrolyser loading.

The accompanying graph in Figure 6.22 illustrates a comparison between line loading scenarios: one with a constant electrolysis load set at 92% and another with a variable electrolysis load adjusted based on Table 6.4. The graph demonstrate the extent to which load shifting is feasible while ensuring the production of the necessary amount of hydrogen.

The adjusted electrolyser production, considering flexible solutions, is presented in Table 6.5, illustrating the monthly and yearly hydrogen production. The data clearly indicates that the electrolyser generates sufficient hydrogen throughout the year to meet the demand of Fishing Fleet 1. However, Figure 6.23 reveals that there are a few months, such as February, March, and April, where the electrolyser falls short of meeting the demand. Fortunately, with the presence of hydrogen storage in the system, it becomes possible to produce excess hydrogen during months with lower demand, typically in the summer period, and store this energy for later use during the Lofotfiske months. This strategic approach ensures a continuous and reliable supply of hydrogen throughout the year.

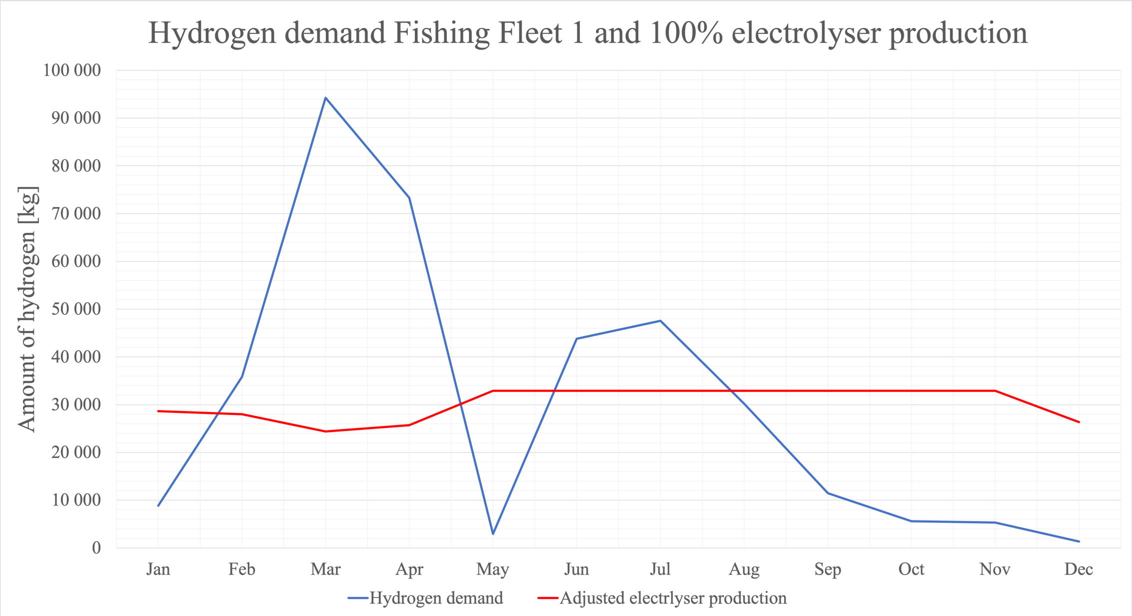

Figure 6.23: Hydrogen demand for Fishing Fleet 1 and adjusted electrolyser production.

Table 6.5: Difference between hydrogen demand and adjusted electorlyser production in 2022.

Month	**Hydrogen demand [kg]**	**Adjusted electrolyser production [kg]**	**Difference**
January	8,821	28,642	19,821
February	35,824	27,984	-7,840
March	94,239	24,362	-69,877
April	73,312	25,679	-47,633
May	2,925	32,922	29,997
June	43,789	32,922	-10,867
July	47,570	32,922	-14,648
August	30,198	32,922	2,724
September	11,431	32,922	21,491
October	5,581	32,922	27,341
November	5,311	32,922	27,611
December	1,350	26,338	24,987
Total	360,351	363,459	3,108

6.5.3 Discussion

As discussed in Section 3.2.6, an electrolyser must operate for a minimum of 2,500 full load hours annually to achieve hydrogen production at a sufficiently low price. However, exceeding 6,000 full load hours tends to increase the hydrogen price as operation moves beyond the range of the lowest hydrogen cost. In the specific case studied, the electrolyser is required to operate at an average of 92% capacity to meet demands. It is important to note that this demand is based on a worst-case scenario where the electrolyser plant is expected to supply the entire fleet, which may not be practical considering that fishing vessels are not stationary.

Operating the electrolyser at 92% capacity corresponds to approximately 8,000 full load hours per year, resulting in slightly higher hydrogen costs compared to operating within the range of the lowest hydrogen costs. However, if a slightly higher hydrogen cost does not significantly decrease the total sale, it may be advantageous to exceed this range. In other words, the electrolyser would likely generate more income the more hydrogen it produces, but at higher costs for the consumer.

Alternatively, another option is to install a larger electrolyser plant capable of producing the required amount of hydrogen while operating at a lower number of full load hours. If the capacity were doubled, the electrolyser(s) would only need to operate at 4,000 full load hours annually, placing them in the middle of the range of the lowest hydrogen cost. Consequently, hydrogen prices would be lower, but this would come at the expense of higher investments in the technology. Furthermore, doubling the capacity would also increase the potential for load shifting performed by the electrolyser, thereby enhancing its flexibility in balancing the electrical grid.

Although the selected electrolyser did not demonstrate impressive load shifting capabilities, the concept remains significant and is expected to become increasingly important in the future. If more consumers can operate with a higher degree of flexibility, grid reinforcements can be postponed due to higher utilization of the electrical grid. However, for the electrolyser to effectively perform load shifting, certain economic incentives need to be in place. Without such incentives, the trade-off would be between economic favorability and a better-utilized and more stable system, with consumers and DSO having differing opinions on the matter.

In this specific scenario, the selected electrolyser effectively produced enough hydrogen to meet the energy requirements of the fishing fleet without surpassing the line loading limits. Furthermore, the integration of the electrolyser did not lead to significant voltage drops, as demonstrated by the heat map depicted in Figure 6.19. As previously discussed, the flexibility options for this specific case were somewhat limited. However, it is important to note that the flexibility potential increases during specific periods since the fishing fleet's demand is not at its maximum throughout the entire month, as was examined in this yearly scenario. The yearly analysis results indicate that it is indeed feasible to generate hydrogen to fulfil the fishing fleet's demand while still retaining some flexibility options.

6.6 Overall Discussion

The overall analysis of the network and electrolyser system reveals several key findings and implications for flexible operation. In Scenarios 0 and 1, the current network model demonstrates robustness and efficient operation, indicating that further investigation of flexibility solutions within this network may not be necessary. However, Scenario 2, which represents a future scenario with maximum loading, presents an opportunity to explore the network's ability to handle varying loads and identify potential flexibility solutions.

The simulation results from Scenario 2a highlight the significant impact of the electrolyser's operation on network voltage stability. By efficiently regulating the electrolyser's power consumption it can minimize voltage drops during ferry charging events, leading to improved voltage levels and enhanced performance of electrical devices across the network. The electrolyser's fast response time enables it to effectively support voltage control, making it a valuable resource for maintaining stable voltage conditions. Additionally, implementing hydrogen storage in combination with the electrolyser allows for load shifting, reducing voltage drops and line loadings during peak hours while increasing hydrogen production during nighttime.

It is important to note that the effectiveness of the electrolyser for voltage control depends on its connection to significant loads, such as a ferry charger. If the electrolyser and the FCP are connected to different buses, the electrolyser's impact on downstream buses' voltage would be diminished. Therefore, positioning the electrolyser on the same bus as a significant load is preferable for optimal voltage compensation. Furthermore, the electrolyser can play a critical role in congestion management by rapidly adjusting its load during periods of high demand or limited capacity. By promptly shutting down or reducing its production, the electrolyser acts as a flexible resource that helps balance supply and demand in the grid, supporting congestion management efforts.

Analyzing the loading patterns in the grid over the course of a day reveals higher loads during daytime compared to nighttime, indicating increased electricity consumption during the day. Allocating higher electrolyser production capacity during weekdays and daytime periods can effectively meet the demand and manage the network's loadings. Understanding these variations in loading patterns allows for optimized operation and planning of the electrolyser system, ensuring reliable and sustainable network operation.

To achieve low hydrogen production costs, the electrolyser must operate for a minimum number of full load hours annually. However, exceeding a certain threshold of full load hours may increase hydrogen prices. In Scenario 2c, yearly study, the electrolyser operates at 92% capacity, resulting in slightly higher hydrogen costs. Operating at a lower number of full load hours by installing a larger electrolyser plant can reduce the per unit price of hydrogen, as it allows the electrolyser to produce hydrogen when the elctricity price is low. However this requires higher investments due to a larger electrolyser. Additionally, a larger electrolyser capacity can enhance the load shifting capabilities and thus further improve flexibility in balancing the electrical grid.

Although the specific electrolyser in this study did not demonstrate significant load shifting capabilities, the concept remains important for grid operation in the future. Economic incentives play a vital role in facilitating efficient load shifting. While consumers are often inclined towards economic advantages, DSOs prioritize optimal utilization and stability of the electric grid. To get them to coordinate, it may be necessary to use such economic incentives.

Chapter 7

Conclusion and Further Work

7.1 Conclusion

This thesis examines the extent to which electrification of the coastal fishing fleet in Lofoten affects the local distribution network. Three scenarios have been explored in this study. Scenario 0, also known as the Base Case, reveals significant voltage levels across the entire network, with the loading of lines remaining well below their rated values even on the day with the highest loads in 2022. This scenario serves as a reference point for the other two scenarios, providing a basis for comparing network behavior before the installation of an electrolyser.

Scenario 1, the Current Network with Implemented Electrolyser, involves connecting a 2.2 MW electrolyser at the end of the radial. The results indicate a slightly lower busvoltage compared to Scenario 0. However, the voltage level across the network remains sufficiently high, and no cables or lines are overloaded. Therefore, Scenario 1 demonstrates that the electrification of Fishing Fleet 1 can be ca rried out within the existing grid without any significant disadvantages.

Scenario 2, the Future Network, considers an increase in power consumption by 2050, with the loads used in Scenarios 0 and 1 increased by 114%. Additionally, a 1.5 MW Ferry Charging Point is added to the same bus as the electrolyser. As a result, Cable 3 becomes overloaded, and Bus 9 and 10 experience a significant voltage drop during ferry charges. It is evident from Scenario 2, with the Future Network that the electrification of Fishing Fleet 1 leads to cable overloading and insufficient bus voltages in the grid. Therefore, measures must be taken when approaching the year 2050 to address the impact of fleet electrification on the local distribution network.

When considering the flexible operation for a water electrolyser to minimize the aforementioned impacts efficiently, the need for such operation becomes particularly important when looking at Scenario 2, which takes into account the year 2050. However, several strategies for flexible operation of the electrolyser have been demonstrated to successfully mitigate the impacts of electrification through hydrogen production. One effective approach is down-regulation of the electrolyser while the ferry is charging. This not only prevents cable overloading but also eliminates voltage drops caused by the sudden connection of a ferry charger. Down-regulation during periods of sudden temporary load increase in the network has proven to be effective in addressing these issues without significantly impacting total hydrogen production. Another strategy involves load shifting on a yearly basis. This approach demonstrates a modest reduction in line loading during peak consumption months. By redistributing the load, the capacity of the grid can be better utilized, smoothing out the peaks and lifting the bottoms by a few percentage points. However, load shifting did not yield as significant results as short-term down-regulation in mitigating the impacts.

In conclusion, the electrification of the coastal fishing fleet does not impose a substantial impact on the distribution grid at present. However, when considering Scenario 2, it becomes evident that flexible operation of the electrolyser is imperative for an electrified fishing fleet without the need for extensive reinforcement of the distribution grid.

7.2 Further Work

The findings of this thesis suggest that a water electrolyser system in the Lofoten area possesses significant flexibility potential. However, it is important to acknowledge the assumptions of the analysis conducted. To fully understand the extent of flexible operation in the water electrolyser, it is recommended to perform an analysis encompassing the entire distribution network. This comprehensive approach will allow for a thorough examination of the network effects. Additionally, exploring other flexible operations of the water electrolyser, such as frequency control for the transmission system, would provide valuable insights.

As highlighted in the discussion, it is essential to address the economic feasibility of employing an electrolyser for such purposes. Moreover, various factors that will change between the present moment and the scenarios projected for 2050 should be considered. By then, the implementation of RES are likely to increase, electrolyser technology are likely to improve and the distribution grid are likely have more distributed generation customers. Technological advancements and an increasing complexity of the electrical grid are also anticipated. Further it is possible to conduct a more realistic storage model for the hydrogen storage system explored in this thesis. This would involve determining the appropriate type and size of tanks, as well as considering other technical aspects related to hydrogen storage. Furthermore, if the efficiency of the electrolyser system improves in the future, it would be interesting to investigate the possibilities of converting stored hydrogen back into electricity to support the electricity grid.

Another area that deserves additional investigation is the real-time control of an electrolyser. While it may seem straightforward to match power consumption retrospectively to produce sufficient hydrogen while showcasing flexibility, continuous control of the electrolyser necessitates a control system. This system would be responsible for making decisions regarding when the electrolyser should operate at 100% capacity and when it can be flexible to support the grid. Hence, it is advisable to develop a more detailed electrolyser model in the future, considering the control aspect. To achieve further optimization of hydrogen production and storage, future work could involve creating an optimized model that takes into account various constraints, such as hydrogen price, network loading, hydrogen demand, and hydrogen production. This comprehensive approach would provide a more holistic understanding of the system.

Overall, addressing these aspects will contribute to a more comprehensive analysis and enhance the potential for electrifying the fishing fleets and implenting a water electrolyser system in the Lofoten area.

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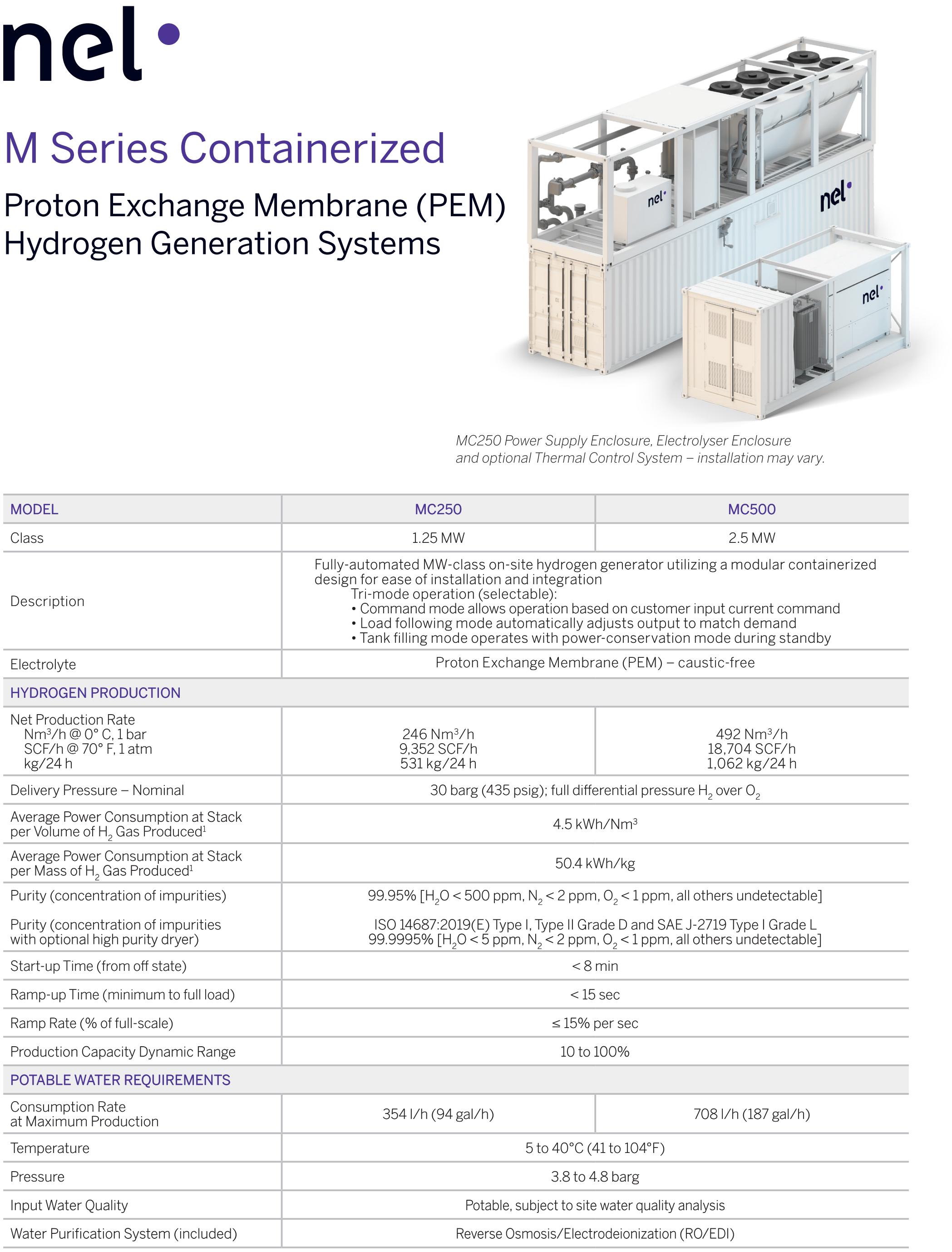
Appendix

A Data sheet: M-series PEM Hydrogen Generation System, Nel



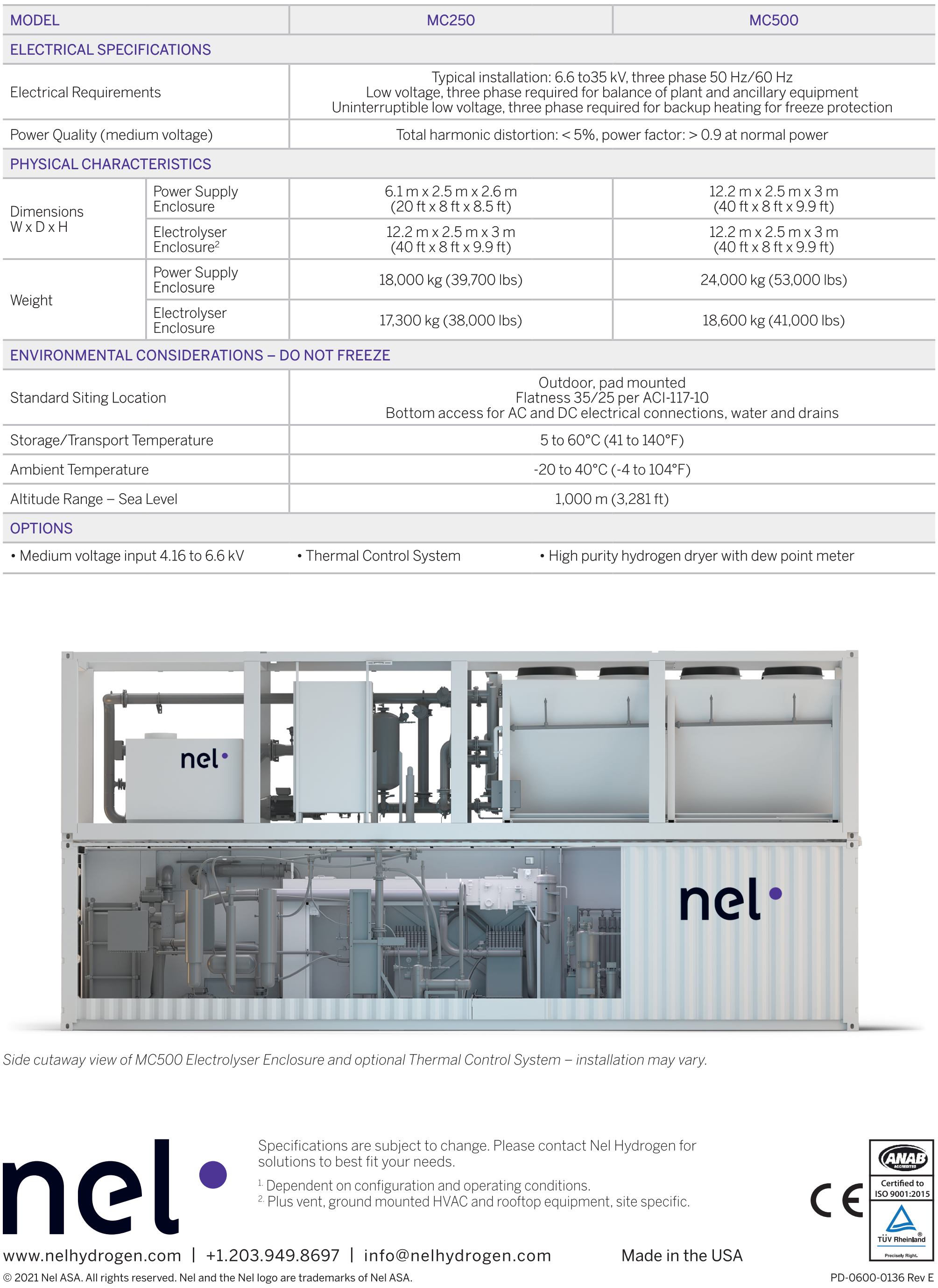
nel

M Series Containerized

Proton Exchange Membrane (PEM)
Hydrogen Generation Systems

MC250 Power Supply Enclosure, Electrolyser Enclosure and optional Thermal Control System – installation may vary.

MODEL	MC250	MC500
Class	1.25 MW	2.5 MW
Description	Fully-automated MW-class on-site hydrogen generator utilizing a modular containerized design for ease of installation and integration Tri-mode operation (selectable): • Command mode allows operation based on customer input current command • Load following mode automatically adjusts output to match demand • Tank filling mode operates with power-conservation mode during standby	
Electrolyte	Proton Exchange Membrane (PEM) – caustic-free	
HYDROGEN PRODUCTION		
Net Production Rate Nm^3/h @ 0° C, 1 bar SCF/h @ 70° F, 1 atm kg/24 h	246 Nm^3/h 9,352 SCF/h 531 kg/24 h	492 Nm^3/h 18,704 SCF/h 1,062 kg/24 h
Delivery Pressure – Nominal	30 barg (435 psig); full differential pressure H_2 over O_2	
Average Power Consumption at Stack per Volume of H_2 Gas Produced[1]	4.5 kWh/Nm^3	
Average Power Consumption at Stack per Mass of H_2 Gas Produced[1]	50.4 kWh/kg	
Purity (concentration of impurities)	99.95% [H_2O < 500 ppm, N_2 < 2 ppm, O_2 < 1 ppm, all others undetectable]	
Purity (concentration of impurities with optional high purity dryer)	ISO 14687:2019(E) Type I, Type II Grade D and SAE J-2719 Type I Grade L 99.9995% [H_2O < 5 ppm, N_2 < 2 ppm, O_2 < 1 ppm, all others undetectable]	
Start-up Time (from off state)	< 8 min	
Ramp-up Time (minimum to full load)	< 15 sec	
Ramp Rate (% of full-scale)	≤ 15% per sec	
Production Capacity Dynamic Range	10 to 100%	
POTABLE WATER REQUIREMENTS		
Consumption Rate at Maximum Production	354 l/h (94 gal/h)	708 l/h (187 gal/h)
Temperature	5 to 40°C (41 to 104°F)	
Pressure	3.8 to 4.8 barg	
Input Water Quality	Potable, subject to site water quality analysis	
Water Purification System (included)	Reverse Osmosis/Electrodeionization (RO/EDI)	



MODEL		MC250	MC500
ELECTRICAL SPECIFICATIONS			
Electrical Requirements		Typical installation: 6.6 to35 kV, three phase 50 Hz/60 Hz Low voltage, three phase required for balance of plant and ancillary equipment Uninterruptible low voltage, three phase required for backup heating for freeze protection	
Power Quality (medium voltage)		Total harmonic distortion: < 5%, power factor: > 0.9 at normal power	
PHYSICAL CHARACTERISTICS			
Dimensions W x D x H	Power Supply Enclosure	6.1 m x 2.5 m x 2.6 m (20 ft x 8 ft x 8.5 ft)	12.2 m x 2.5 m x 3 m (40 ft x 8 ft x 9.9 ft)
	Electrolyser Enclosure[2]	12.2 m x 2.5 m x 3 m (40 ft x 8 ft x 9.9 ft)	12.2 m x 2.5 m x 3 m (40 ft x 8 ft x 9.9 ft)
Weight	Power Supply Enclosure	18,000 kg (39,700 lbs)	24,000 kg (53,000 lbs)
	Electrolyser Enclosure	17,300 kg (38,000 lbs)	18,600 kg (41,000 lbs)
ENVIRONMENTAL CONSIDERATIONS – DO NOT FREEZE			
Standard Siting Location		Outdoor, pad mounted Flatness 35/25 per ACI-117-10 Bottom access for AC and DC electrical connections, water and drains	
Storage/Transport Temperature		5 to 60°C (41 to 140°F)	
Ambient Temperature		-20 to 40°C (-4 to 104°F)	
Altitude Range – Sea Level		1,000 m (3,281 ft)	
OPTIONS			
• Medium voltage input 4.16 to 6.6 kV		• Thermal Control System	• High purity hydrogen dryer with dew point meter

Side cutaway view of MC500 Electrolyser Enclosure and optional Thermal Control System – installation may vary.

Specifications are subject to change. Please contact Nel Hydrogen for solutions to best fit your needs.

[1] Dependent on configuration and operating conditions.

[2] Plus vent, ground mounted HVAC and rooftop equipment, site specific.

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Coastal Electrification Using Hydrogen Technology and Distribution Grid Flexibility Potential

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ABSTRACT

This paper aims to analyze the impact of electrifying a coastal fishing fleet on the distribution network. The objective is to address a production and capacity planning challenge by optimizing hydrogen production over the system's lifetime, while also exploring the possibility of utilizing the hydrogen storage to enhance system flexibility. The scope includes: scenarios to assess how the electrification of the coastal fishing fleet affects the distribution network, and conducting simulations to investigate the load flow problem connecting a water electrolyser to the grid. The study will also examine the potential for flexibility in the Lofoten area, utilizing the electrolyser for flexibility purposes from a DSO perspective.

Key words - distribution grid, hydrogen, flexibility

I. INTRODUCTION

In order to achieve a fully renewable power grid, it is necessary to combine large-scale renewable power plants with the use of primary Renewable Energy Sources (RES) as small-scale distributed generation (DG) [1]. Norway, a country with a lengthy coastline and abundant resources, has a rich history of seafood exportation. However, the majority of Norwegian fishing boats currently use diesel propulsion systems, resulting in fishing vessels contributing approximately 2% of Norway's annual emissions, or 878,000 tons of CO2, in 2020 [2].

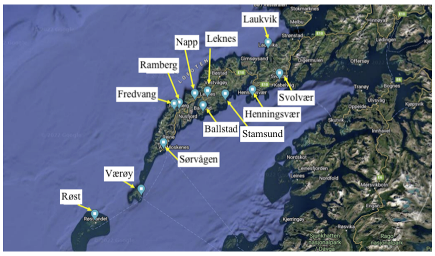

Figure 1: Location of the fishing fleets in Lofoten taken from Zerokyst project.

The study is a part of the project [1] aiming to decarbonize the seafood industry, electrify and demonstrate optimal energy solutions in Lofoten. The project includes developing a zero-emission driveline, a new fishing vessel, and preparing 10 vessels for conversion, along with conversion and maintenance services and a complete solution for flexible electricity and green hydrogen supply. It will help to reduce emissions from fishing and aquaculture vessels by 50% by 2030, potentially generating values of 100 million NOK [2]. The paper is organized as follows: Chapter 2 discusses the changing power system in response to the global climate crisis, while Chapter 3 is focused on the theory behind hydrogen technology as a potential solution. Chapter 4 presents the methodology for the network modelling and the model of the electrolyser. The main results of the study are emphasized in Chapter 5. Finally, the main conclusions of the study are summarized in Chapter 6.

II. POWER SYSTEM IN CHANGE

The power system is in need of a change, as the traditional centralized model based on large-scale power plants and transmission lines is no longer sustainable in the face of climate change, market and rapid technological advancements [3]. One of the key challenges that the future power system must address is grid stability, particularly in the context of increasing penetration of RES and distributed energy resources (DER). To achieve this, the future power system is likely to be characterized by a more decentralized architecture, with a greater emphasis on the use of distributed energy resources like solar panels, wind turbines, and battery storage systems [1]. These RES will play a critical role in balancing variable loads in the distribution network and ensuring that voltage quality is maintained, even as the system experiences fluctuations in power supply and demand [3].

Ultimately, the success of the future power system will depend on the ability of industry stakeholders, grid operators, regulators, and policymakers to work together to design and implement a more resilient and sustainable energy infrastructure that is capable of meeting the needs of a rapidly evolving world.

Hydrogen technology is emerging as a promising energy storage and flexibility solution, particularly in the context of

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[1] ZeroKyst. Flexible and competitive hydrogen supply. 2022. URL: https://zerokyst.no/

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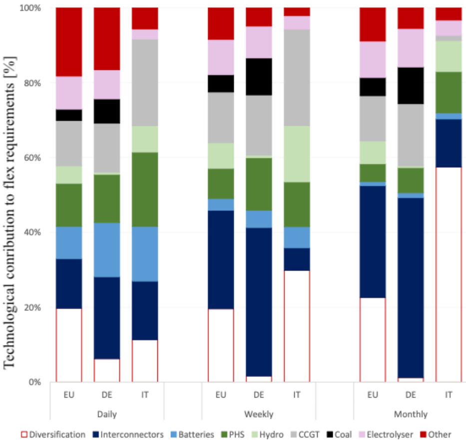

Figure 2: Contribution to flexibility requirements [4].

the growing shift towards RES as can be seen from Figure2. With the ability to be produced using renewable electricity and water, hydrogen can be used to store excess energy during times of high production and then be used as a fuel or feedstock for various industrial processes when demand increases [3]. Green hydrogen, which is produced through the electrolysis of water using RES, is particularly appealing as it offers a sustainable and carbon-free alternative to traditional fossil fuels [5].

However, electrolysers also introduce a new variable load in the distribution network, as their energy demand can be varied based on electricity consumption [6]. To manage this variable load, smart grid technologies and energy management systems are needed to ensure that the electricity supply and demand are balanced in a stable and sustainable manner [7].

III. HYDROGEN TECHNOLOGY

The use of hydrogen as an energy storage and carrier, particularly through the production of green hydrogen using electrolysers, represents a promising avenue for achieving a more sustainable and resilient energy system. However, this will require careful management and coordination of the energy network to ensure that the distribution network is able to accommodate the variable load introduced by electrolysers.

A. *Electrolyser*

The EU Hydrogen Strategy aims to decarbonize hydrogen production and increase its use in industries that use a lot of energy, setting targets of 6 GW and 40 GW of renewable hydrogen electrolysers by 2024 and 2030 [8]. Norway has expertise in the hydrogen value chain, including electrolysers, and aims to produce green hydrogen to satisfy emission reduction requirements. The maritime industry will see a 7% increase in hydrogen consumption by 2030, and there is a pressing need to drastically reduce emissions [2]. However, the introduction of hydrogen-electric vessels is fraught with technical and economic difficulties, and the rules for using them as fuel will take some time to establish [9]. Hydrogen production cost is still considerably higher than low-carbon and fossil-based hydrogen produced from natural gas due to the cost of renewable power and the initial capital expenditure.It was noted that hydrogen storage has a high energy density, making it a good option for storing large amounts of energy in small spaces [10]. Hydrogen storage systems also have high energy storage performance and can contribute to voltage and frequency stabilization. In EU, hydrogen is expected to play a crucial role in reducing greenhouse gas emissions and can also serve as a flexibility provider in the energy market as can be seen from Figure 2.

Water electrolysis is the process of using electric power to generate synthetic H2. Alkaline and proton exchange membrane (PEM) electrolysis are two low-temperature technologies used for power-to-H2 conversion [11]. Alkaline electrolysers are well-established, have high long-term stability, and can produce hydrogen at a high rate, but have a small partial load range and slow dynamic response times. PEM electrolysers have higher power densities and efficiency, a good partial load range, and quicker dynamic response times, making them suitable for hydrogen production pathways based on wind turbines [11]. PEM electrolysers have the interesting capability of fast dynamics in the electrolysis process, allowing for adjustments to the amount of electricity used in less than one second [6]. This opens up potential demand-side response schemes to assist the operation of electrical power systems. A complete representation of a PEM electrolyser unit includes the power conversion system, modelling of the stack, and balance of the plant [6]. The efficiency of a PEM electrolyser is limited by various factors, including overvoltages, parasitic currents, and inefficiencies in the stack and system design [12]. The lifetime of a PEM electrolyser is affected by factors such as the quality of materials, operating conditions, and level of maintenance [13]. An electrolyser can function in three different states: production state, hot-standby state, and idle state, and parameters from each state need to be considered for the system to function as a flexible resource.

B. *Flexibility possibilities in Lofoten*

When modelling of PEM electrolysers as a flexible resource in a distribution grid one of the challenges is finding the best combination of meeting hourly demand through production, storage withdrawals, or a combination of both. Hydrogen production and storage capacities are important parameters to investigate, and it is desired to find the optimal capacities that yield a higher value than estimated hydrogen consumption. Different decision variables for modelling the water electrolyer includes capacity, production quantity, and storage quantity, as well as operational variables to track the state of the electrolyser equipment. The EU's "Fuel Cells and Hydrogen 2 Joint Undertaking" (FCH 2 JU) has established reliable techno-economic values and targets for developing PEM and alkaline electrolysis technologies, regularly updated and involving public and private industry stakeholders [14]. [14] presents parameters for modeling these systems based on EU studies and ongoing projects. Key parameters include system and stack lifetimes, water consumption, efficiency, and input power. [16] also presents a techno-economic model for PEM electrolysis, including technical and economic parameters. Relevant parameters for technical and economical paramenters found from [15], [14], and [12] can be found in Table I. Based on a literature review, relevant parameters for a electrolyser as a distribution generation in the power system are also presented in Table I.

Table I: Overview of the parameters for modelling.

Technical and economical parameters	Parameters affecting grid parameters
Hydrogen production rate	Minimum partial load (safe load of the electrolyser)
Nominal voltage	Power demand (maximum)
Nominal current	System efficiency
Operating temperature	Response time
Hydrogen pressure	Standby consumption
Oxygen pressure	Lifetime stack
Current density	Max number of cold starts
	Min response time (from hot standby to full load or vica versa)

Water electrolyser has the possibility to contribute as a flexible resource for the distribution network grid. Here we refer to flexibility as the ability to operate the water electrolyser plant at different power levels [16]. Water electrolysers can produce hydrogen during off-peak hours to be used during peak hours, acting as a flexible resource for load shifting and storage. Additionally, electrolysers can provide dynamic responses that can support demand response, local voltage support, and frequency support. Electrolysis also generates excess heat that can be utilized for waste heat recovery, increasing system effectiveness and supporting a green hydrogen economy. Finally, hydrogen production and storage has the possibility of developing a flexibility market in Lofoten area where end-users can become a prosumers and provide flexibility by managing loads, and allowing the DSO to request and activate the needed flexibility. As well as it could be extended to DSO-TSO coordination and participation in the system services provision.

IV. NETWORK MODELLING: CASE STUDY

This study aims to investigate the potential effects of electrifying a coastal fishing fleet on the distribution network in the Lofoten. To achieve this, a network model of the distribution network is created using the PowerFactory DIgSILENT, which is commonly used for power system analysis. The study also explores various scenarios related to integrating electrolysers into the network.

A. *Network model*

The network in the Lofoten area is a medium to low voltage distribution network, therefore the reference model CINELDI[2] is used to develop the network model and test the scenarios. The CINELDI MV reference system is a dataset that characterizes a typical Norwegian radial electric power distribution system that operates at 22 kV. A reference network commonly used for power grid analysis in Norway. It is a simplified representation of a real power system, including its limitations. Table II shows the main characteristic of the base reference system.

Table II: Main characteristics of the base system.

Parameter	Value
Number of nodes	124
Voltage level (base voltage)	22 kV
Base power	10 MVA
Number of load points	54
Total load demand, real power	6.407 MW
Total load demand, reactive power	2.106 MVAr
Power factor of loads	0.95 (lagging)

The simplified network is a lumped network model that comprises of only 50 nodes, in contrast to the actual CINDELDI network which has 124 nodes. For this paper, we utilize a model with 50 nodes at a nominal voltage of 22 kV, and obtain load profiles from these nodes for network analysis.

B. *Electrolyser model*

The water electrolyser is modelled as a flexible load where the scenarios are based on different loadings/percentage of maximum consumption for the electrolyser. The data for the electrolyser is taken from a NEL MC250 electrolyser system. MC electrolysers offer the M Series platform in a containerized format, enabling effortless outdoor installations. With the M Series PEM technology, the solution is reliable, turnkey, and requires minimal maintenance. This makes it suitable for various applications such as renewable energy storage, industrial process gas, and hydrogen fueling [17]. It is chosen a larger electrolyser as it must produce hydrogen for electrification of all fishing shores in the future, see locations in Figure 1.

For finding the maximum load the electrolyser will consume, the Net Production Rate is multiplied with the Average Power Consumption at Stack per Volume of H2 Gas Produced. The maximum loading for the electrolyser used for this analysis is shown in Equation 1, and the data is taken from [17].

$$246Nm^3/h \cdot 4.5kWh/Nm^3 = \underline{1107kW} \tag{1}$$

C. *Scenarios*

In order to assess the potential demand flexibility in the distribution network of Lofoten, several scenarios have been created. These scenarios take into account the anticipated electrification of the maritime sector in Lofoten, as well as throughout Norway and Europe in the years ahead. The scenarios examine the possible distribution grid conditions.

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[2] Cineldi, https://www.sintef.no/projectweb/cineldi/

Scenario 0: To establish the reference scenario, the peak powers for the network model are chosen, which is called the Base Case. In this case, the water electrolyser is not connected to the distribution grid.

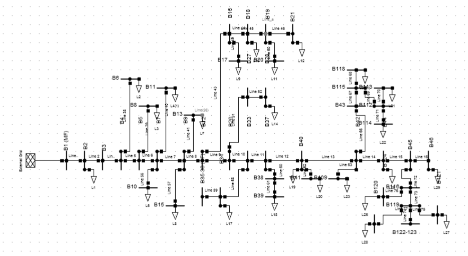

Figure 3: Base case scenario.

Scenario 1: Involves conducting an assessment of the location for the electrolyser. This assessment will include running load flow analyses for both the network system and the electrolyser, using peak loads to determine their respective capabilities.

Scenario 2: Involves connecting three Fast-charging Stations (FCSs) to the critical buses identified in Scenario 1. This presents an opportunity for the Lofoten area to develop a business related to the regional energy infrastructure being designed by ZeroKyst, which includes fast charging points. The FCSs will be centralized, high-power electric vehicle charging stations based on the values from the CINELDI Reference network. Each FCS will typically include 12-16 charging points with a capacity of $0.125MW$.

Scenario 3: Three FCSs and two Ferry charging Points (FCPs) will be linked to the critical buses identified in Scenario 1. Including ferry charging points is essential, as we are exploring the possibility of electrifying more ferries in the Lofoten area, which could offer exciting business opportunities in the future.

V. SIMULATION RESULT AND DISCUSSION

Figure 4 is the resulting voltage profiles for the 4 scenarios. Figure 5 shows the resulting loadings for the different lines in the network system. Table III is a summary of Total losses from the Base Case and then the increase in percentage from the base case compare to the other scenarios.

Table III: Total losses for the different scenarios.

Total Losses			
Base case	**Scenario 1**	**Scenario 2**	**Scenario 3**
0. 16 MW	↑ 50%	↑ 68.8%	↑ 731%
0. 11 MVar	↑ 54.5%	↑ 72.7%	↑ 736%

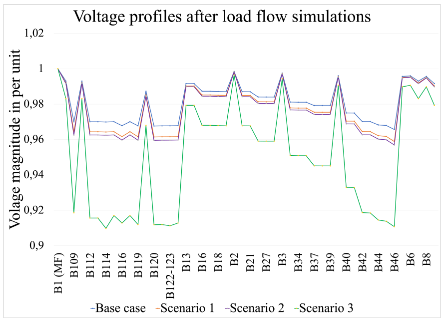

Figure 4: Voltage profiles for the different scenarios.

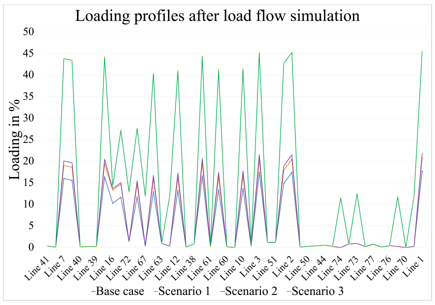

Figure 5: Loading for all the lines for the different scenarios.

Scenario 0: As can be seen from the legend in Figure 6 the load flow simulations show good system performance. The voltage level is within acceptable limits, indicating that the network is well balanced and the equipment is functioning correctly. Additionally, the loading is within the acceptable range, indicating that there is sufficient capacity to meet the power demands of the system without overloading or overstressing the equipment. These results suggest that the network model is operating efficiently and is capable of handling peak loads without compromising the reliability or stability of the system.

Scenario 1: Figure 7 reveals a notable area highlighted in light blue that is of critical importance. This area comprises buses 42-46 on the branch and the radials emanating from it. Fortunately, none of the buses within this critical zone exhibit voltage magnitudes below the minimum level of 0.94pu, indicating that the system is functioning as expected. The corresponding parameters listed in Table III show a 50% increase in total losses when compared to the base case. It is also evident from Figure 5 that the loading of the lines is higher than compare to base case.

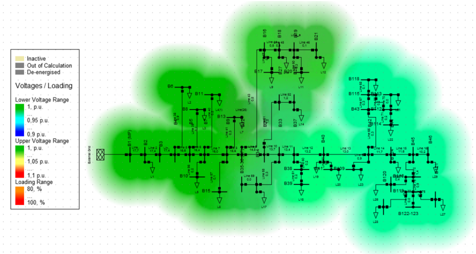

Figure 6: Simulation result for base case scenario.

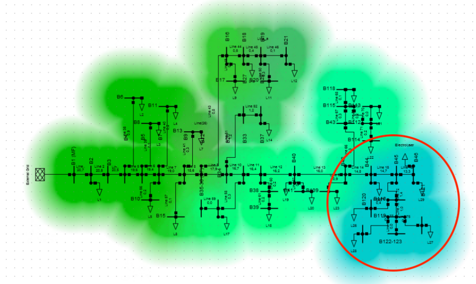

Figure 7: Simulation result for base Scenario 1 where the water electrolyser is connected at the end of the network.

Scenario 2: Figure 8 indicates an expansion of the critical area, depicted in light blue. Meanwhile, Figure 4 shows that although the voltage profile has decreased compared to both the Base Case and Scenario 1, it remains within acceptable levels (0.94-1.06pu). However, there has been a 68.8% increase in losses compared to the Base Case. Figure 5 reveals that the highest line loading is approximately 21%, suggesting that the network can accommodate such a load.

Scenario 3: Shown in Figure 4, the voltage exceeds the acceptable limit, indicating instability within the system. As a result, the scenario 3 is not technically feasible. In addition, Table III reveals a significant increase in total losses compared to the Base Case. Thus, connecting three FCSs or two FCPs is not a viable option. Further analysis of the system may be necessary to ensure stable and efficient operation.

VI. CONCLUSION

Hydrogen play an important role in the transformation of power system towards electrification and operational flexibility. This work address distribution grid capacity challenge using hydrogen technology. Based on the proposed model, running various scenarios, it is possible to incorporate an electrolyser as a source of flexibility and estimate its impact on the distribution network. The results of the scenarios indicate that the system can effectively handle the implementation of the electrolyser even under maximum loading conditions. It also exhibits flexibility possibilities, as evidenced by the stable voltage and loading of the lines. Moreover, the study presents additional business prospects for the Lofoten region, as well as flexiblity solutions tested with maximum loading for the electrolyser. However, the instability observed in the last scenario limits the flexibility possibilities. Building upon the model presented in this paper, future research can leverage it as a foundation to develop a real network model with real data. Nonetheless, the electrolyser can be utilized alone for flexibility purposes or integrated with FCSs. These findings highlight the potential of the electrolyser technology in terms of flexibility in the Lofoten area, creating potential of flexibility services for system services to be provided to transmission and distribution system operators, to allow safe and reliable grid operations. From the various options currently investigated, electric-hydrogen technology demonstrating great potential in terms of lower energy costs for consumers/prosumers, lower emissions, and improving reliability and security of supply.

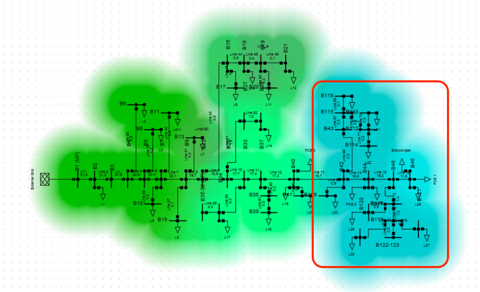

Figure 8: Simulation result for base Scenario 2 where 3 Fast-charging stations (FCS) is connected in the critical bus area.

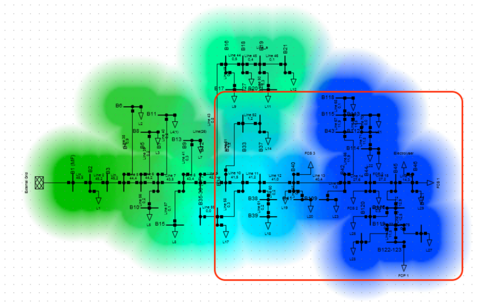

Figure 9: Simulation result for base Scenario 2 where 3 Fast-charging stations (FCS) and 2 Ferry charging points is connected in the critical bus area.

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