Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Economics and Management
NTNU Business School

Martha Utengen & Vebjørn Weldingh Nilsen

Leveraging Grid Efficiency Through Dynamic Line Rating and N-0.9 Operations

A Case Study for Reducing Costs Related to Special Regulation

Master's thesis in Economics and Business Administration
Supervisor: Ranik Raaen Wahlstrøm
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Abstract

The costs associated with Special Regulation (SR) for Statnett have significantly increased due to rising energy demands. This master's thesis investigates the potential of Dynamic Line Rating (DLR) and a deviation from the standard N-1 grid reliability criteria (termed N-0.9) to reduce these costs. The study addresses three research questions: historical efficiency, projected future savings, and exploring an alternative grid management strategy (N-0.9)

Utilizing real-world data from two power lines in a bottleneck-constrained area, we analyzed a Baseline Scenario and three future scenarios — each reflecting different levels of increased energy demand (20% increased Power Flow, 10% and 20% Fixed Gains). The analysis compared the potential savings from operating the lines with DLR against the traditional Static Line Rating (SLR), measuring the savings in percentage, Megawatt-hours (MWh), and Norwegian Kroner (NOK).

In the Baseline Scenario, DLR enabled a 20% capacity gain, reducing SR costs by 14.79 million NOK, or 67.31% of the 21.97 million NOK spent. Although savings in future scenarios were slightly less, they were still substantial: 53.38% in the 20% increased Power Flow scenario, 63.14% in the 10% Fixed Gain scenario, and 59.72% in the 20% Fixed Gain scenario. These results demonstrate that although DLR's impact on SR costs diminishes as power levels increase, it still offers significant potential for cost reductions.

The savings for the alternative grid management strategy, N-0.9, were also noteworthy. In the Baseline Scenario, operating with DLR and N-0.9, the reduction in SR was 100%. Even with SLR, we achieved a 77.4% reduction. With the N-0.9, combined with DLR, it would be possible to achieve a 38% increase in power flow while maintaining SR costs close to today's levels.

These findings affirm the substantial economic and operational benefits of adopting advanced grid management strategies like DLR and N-0.9, especially under scenarios of increased energy demand. This research provides a solid foundation for future strategic decisions aimed at enhancing the efficiency and sustainability of grid management in the face of rising energy challenges.

Sammendrag

Statnett sine kostnader knyttet til spesialregulering (SR) har økt betraktelig grunnet økende energibehov. Denne masteroppgaven undersøker mulighetene til Dynamic Line Rating (DLR) og et alternativ til sikkerhetskriteriet N-1 (kalt N-0.9) for å redusere disse kostnadene. Studien tar for seg tre forskningsspørsmål: historisk effektivitet, estimerte fremtidige besparelser og utforsking av alternativ nettstyringsstrategi (N-0.9).

Ved å bruke reell data fra to kraftlinjer i et område med flaskehalser, analyserte vi et grunnscenario og tre fremtidige scenarier — der hvert representerer ulike nivå av økt energibehov (20% økt energiflyt, 10% og 20% fast tillegg). Analysen sammenlignet potensielle besparelser ved å operere linjene med DLR mot den tradisjonelle Static Line Rating (SLR), og målte besparelsene i prosent, megawatt-timer (MWh), og norske kroner (NOK).

I grunnscenarioet muliggjorde DLR en kapasitetsøkning på 20%, noe som reduserte SR-kostnadene med 14,79 millioner NOK, eller 67,31% av de 21,97 millioner NOK som ble brukt. Selv om besparelsene for de fremtidige scenariene var noe mindre, var de fortsatt betydelige: 53,38% i 20% økt energiflyt scenarioet, 63,14% i 10% fast tillegg scenario, og 59,72% i 20% fast tillegg scenario. Disse resultatene viser at selv om DLRs innvirkning på SR-kostnader avtar når energinivåene øker, er det fortsatt vesentlig potensial for kostnadsreduksjoner.

Besparelsene for den alternative nettstyringsstrategien, N-0.9, var også betydningsfulle. I grunnscenarioet, ved bruk av både DLR og N-0.9-strategien, var reduksjonen i SR 100%. Med N-0.9 og SLR oppnådde vi en reduksjon på 77,4%. N-0.9 kombinert med DLR ville gjøre det mulig å oppnå en økning på 38% i energiflyt samtidig som man holder SR-kostnadene nær dagens nivåer.

Disse funnene bekrefter de økonomiske og driftsmessige fordelene ved å implementere nettstyringsstrategier som DLR og N-0.9, spesielt under scenarier med økt energibehov. Denne oppgaven gir et grunnlag for forbedrede beslutninger rettet mot effektivisering og bærekraftig utvikling av nett, i møte med stigende energiutfordringer.

Preface

This thesis is the final part of our Master of Science degree in Economics and Business Administration, with a major in Business Analytics. We would like to express our gratitude to our supervisor, Ranik Raaen Wahlstrøm, for his guidance and knowledge. We would also like to thank Heimdall Power for providing valuable information about the DLR technology, and the anonymous DSO for sharing information about their networks and the data they provided.

We take full responsibility for the content of this thesis.

Trondheim, 2024

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List of Abbreviations

CIGRE Conseil International des Grands Réseaux Electriques
DLR Dynamic Line Rating
DSO Distribution System Operators
IoT Internet of Things
OHL Overhead Lines
SLR Static Line Rating
SR Special Regulation
TSO Transmission System Operator

1 Introduction

Actualization

Norway's electrification efforts, aimed at reducing CO2 emissions and fostering new green industrial production, are significantly increasing the country's power consumption (Christiansen et al., 2023). This surge necessitates substantial new power generation. According to Statnett, Norway's Transmission System Operator (TSO), there is an anticipated increase in power consumption of 20% by 2030, potentially escalating to 85% by 2050 (Christiansen et al., 2023). These projections underline the critical need for sustainable and resilient energy solutions to support the growing demand. Furthermore, the infrastructure required to sustain such growth is extensive, necessitating long-term investments. Statnett projects that between 100-150 billion NOK will be needed over the next decade to improve the grid's capacity and reliability, reduce congestion, and enhance safety (Statnett, 2023). This underlines the urgency of grid upgrades to keep pace with the ambitious targets for a low-carbon future.

The traditional approach to mitigating grid congestion involves costly grid upgrades. Historically, power grids were designed for centralized power generation from a few large plants, necessitating substantial transmission capacity (Brunekreeft et al., 2022). While grid expansion can accommodate higher energy demands, these upgrades are typically expensive and time-consuming. However, the future may not require such extensive infrastructure due to the rise of more localized and flexible energy production methods (SINTEF, 2020).

Dynamic Line Rating (DLR) offers a strategic solution to grid congestion by maximizing existing grid capacity and reducing congestion by revealing additional capacity within safe operational limits (Dupin and Michiorri, 2017). By providing real-time data on the actual capacity of power lines, DLR helps avoid unnecessary and costly network expansions. It accurately determines the current carrying capacity based on real-time weather conditions.

Another approach to minimizing reserve capacity in the current grid is using probabilistic contingency methods instead of the conservative and traditional N-1 criterion (SINTEF, 2019). This approach can free up more capacity in the existing grid during peak congestion hours by deviating from the N-1 criterion for 10% of the operating time, referred to as N-0.9 operation.

This thesis explores the impact of DLR and N-0.9 operations, specifically focusing on their economic effects on congestion costs, particularly redispatching, known as "Special Regulation" (SR) by Statnett. In 2022, the cost of SR in Norway reached a record high of 527 million NOK, more than doubling from the previous year (Statnett SF, 2022). With persistent high energy prices and rising energy demands, these costs are likely to escalate further if proactive measures are not implemented within the power grid.

1.1 Research Questions

Based on this actualization, we examine the potential cost savings associated with SR by leveraging DLR technology and an N-0.9 operation. The investigation is structured around three research questions:

1. **Historical Efficiency:** To what extent could SR costs have been mitigated historically with the application of DLR technology?
2. **Future Savings:** What potential cost savings can be achieved through the implementation of DLR in response to projected increases in energy demand?
3. **Alternative Grid Management:** How does adopting a modified grid management strategy, specifically implementing an N-0.9 operation, affect grid operations?

Our research aims to evaluate the benefits of DLR technology. By analyzing historical data, we will assess DLR's efficiency in mitigating unnecessary grid operations and explore its potential for improving grid management efficiency. Additionally, we will investigate the impact of grid management adjustments, implementing an N-0.9 criterion, on managing peak loads and reducing congestion costs. This analysis will encompass both retrospective and prospective scenarios, highlighting how DLR and an alternative to N-1 can significantly diminish SR expenses and support more cost-effective energy distribution.

1.1.1 Study Approach

To answer the research questions laid out in this thesis, we have established collaborations with key industry partners: Heimdall Power, which provides DLR Neurons solution, and a *Unnamed Distribution System Operator in NO4 - from now on referred to as 'UDSO-NO4'*, who has opted to remain anonymous. UDSO-NO4 has integrated Heimdall Power's DLR solution within their network, enabling access to precise data on line capacity. Our analysis centers on a case study of a bottleneck-constrained area managed by UDSO-NO4.

UDSO-NO4 provided us with a dataset, which we utilized to analyze the financial implications of SR under traditional grid capacity calculations versus those calculated from DLR. This study helps identify potential cost efficiencies achievable through the adoption of DLR.

Additionally, we included projections from Statnett's 2023 report on future energy consumption trends, extending up to 2050. Our analysis focused on the data up to 2030 (Christiansen et al., 2023). These projections were instrumental in developing future scenarios that allowed us to examine the implications of increased energy demands on grid management and SR costs. This forward-looking analysis aims to understand how DLR and deviating from the N-1 criterion can contribute to more sustainable and cost-effective grid operations in the face of rising energy requirements.

1.1.2 Contributions to Industry and Research

In this master's thesis, we aim to explore and address a problem that has not been tackled previously. While previous research has outlined the general benefits of DLR, our study is unique in its specific research questions and focus. We hope this investigation will advance further research within this field and provide valuable insights that can benefit the industry. By utilizing real-world data and analyzing a concrete case, we aspire to make a substantial and meaningful contribution to the existing body of knowledge on DLR applications and alternative grid management.

1.2 Thesis Structure

Chapter 2 offers an overview of the theoretical framework underpinning the study and reviews previous literature, identifying gaps addressed by this research. Chapter 3 outlines the methodologies used to explore the research questions, detailing the data collection and analysis processes. Chapter 4 presents and thoroughly discusses the results of the case study, examining their real-world applicability and critiquing the study's limitations. Chapter 5 concludes the thesis by answering the research questions and suggesting directions for future research.

2 Theoretical Background

This chapter lays the groundwork for understanding important concepts and mechanisms crucial to our thesis. It provides a detailed examination of the Norwegian energy market, highlighting its structure, regulatory framework, and market dynamics. Additionally, it explores the physical principles of electrical engineering relevant to our research, focusing on the behavior of electric current in power lines and the methods for assessing line capacity through Static Line Rating (SLR) and Dynamic Line Rating (DLR). It also explains the principle N-1 and how to deviate from this by implementing N-0.9 instead. Lastly, it includes a section on previous research to provide context for our study within the existing body of knowledge.

2.1 Electricity Distribution in Norway

The energy sector in Norway covers all aspects of energy production, trade, and distribution to end users (Energifakta Norge, 2024b). Power generation is the main component of this system, which is organized within a power grid to ensure the distribution of energy across the country.

2.1.1 Power Grid Levels

The power grid is divided into three levels (NVE, 2024a):

At the highest level, we find the **transmission grid**. This nationwide network, operating at voltage levels between 300 and 420 kV, connects large power producers with consumers and also integrates international connections (Energifakta Norge, 2024c). The transmission grid ensures that electricity can be transported over long distances from production sites to areas of consumption (NVE, 2024a).

One level below lies the **regional grid**, which acts as a link between the transmission grid and the distribution grid (Energifakta Norge, 2024c). This network operates at 33 and 132 kV voltage levels and often includes radials for production and consumption at higher voltage levels. The role of the regional grid is to distribute power more locally and ensure that the flow of energy reaches various parts of the country (NVE, 2024a).

At the third and lowest level, we have the **distribution grid**, which is responsible for the final stage of electricity supply to end users (Energifakta Norge, 2024c). This network handles low-voltage (400 V and 230 V) and high-voltage (over 1 kV) connections, and it directly supplies electricity to households and small businesses (NVE, 2024a).

2.1.2 Electricity Price Zones

Bottlenecks in the Power Grid

Bottlenecks in the power grid occur when the capacity to transmit electrical power is limited, often due to physical constraints or safety measures that prevent overheating and damage to the infrastructure (Federal Ministry for Economic Affairs and Climate, 2018). Each transmission line has a maximum capacity; exceeding this threshold results in a bottleneck. These are typically triggered by disparities between regions with high electricity production and those with high demand, especially when the connecting transmission lines lack sufficient capacity (Statnett, 2022). While congestion and bottlenecks are obstacles to the operation, they also give clear signals to where the grid lacks capacity, making it clear where it is the most urgent to take capacity measures (Brunekreeft et al., 2022).

The occurrence of bottlenecks brings several operational and economic challenges. Excess demand or production forces the grid to reroute electricity, leading to inefficiencies and higher operational costs as power takes fewer direct paths or uses underutilized lines (Statnett, 2022). Economically, bottlenecks can create price disparities across different regions, as areas affected by bottleneck congestion may have to depend on costlier local power sources or emergency reserves. Unmanaged bottlenecks can compromise grid reliability, potentially causing blackouts, particularly in regions lacking alternative transmission routes (Statnett, 2022).

Electricity is generated in different parts of the country, and it needs to be transmitted over a long distance to meet the demand in different regions. However, the production and consumption areas don't always align with each other, leading to transmission challenges that can result in electrical surpluses or shortages (Statnett, 2022).

The national transmission grid has a limited capacity to handle large volumes of electricity, which creates bottlenecks in the distribution process. These bottlenecks influence the price of electricity and create distinct price zones across the country (Statnett, 2022). The price zones for Norway are displayed in Table 2.1. These zones have different electricity prices, depending on the location, due to the geographical and infrastructural constraints of the transmission grid, particularly where bottlenecks are most pronounced.

Table 2.1: Electricity Price Zones in Norway

Price Area	Region
NO1	Eastern Norway
NO2	Southern Norway
NO3	Central Norway
NO4	Northern Norway
NO5	Western Norway

2.1.3 Administrative Organization of the Power Grid

In Europe, the organization of the power grid is divided into two principal categories: **Transmission System Operators** (TSOs) and **Distribution System Operators** (DSOs) (gridX, 2024). A TSO owns and manages the transmission grid, ensuring efficient and reliable electricity transmission from generation sites through the power grid to local or regional distribution operators (gridX, 2024). In Norway, Statnett serves as the TSO (Energifakta Norge, 2024c). A DSO is responsible for operating, managing, and sometimes owning the distribution and regional networks (gridX, 2024). In Norway, various network companies perform these functions. Municipalities own many of these DSOs fully or partially (Energifakta Norge, 2024c).

Statnett's role as the TSO is governed by the *"Forskrift om systemansvaret i kraftsystemet"*, which aims to ensure an efficient electricity market and satisfactory quality of power delivery (Forskrift om systemansvaret i kraftsystemet, 2002). The regulation mandates that the TSO is exercised socially and rationally, considering both public and private interests affected. Further responsibilities include managing frequency regulation, ensuring instantaneous balance in the power system at all times, and developing market solutions that contribute to the effective development and utilization of the power system (Forskrift om systemansvaret i kraftsystemet, 2002).

In Norway, the DSOs and TSOs are legally required to provide all consumers with a grid connection (NVE, 2018). This obligation involves planning, applying for necessary licenses, and investing in new capacity. However, they are only mandated to undertake these responsibilities if the consumer covers the connection charge and grid tariffs. This process can be time-consuming.

Upgrades to Avoid Congestion

In Norway, managing bottleneck congestion is critical to ensure that the energy supply is stable and reliable. The responsibility of upgrading the grid to avoid bottlenecks lies with the network operator, who can be either TSOs or DSOs based on the type of line and is achieved through network pricing Nakstad et al., 2022. Several measures can be taken to manage power line congestion, including upgrades to the network, higher line clearance, or grid-enhancing technologies such as DLR.

2.1.4 The Electricity Market

The wholesale electricity market in Norway serves an important function in the energy system. Its primary role is to ensure efficient utilization of resources and stability in power supply (Energifakta Norge, 2024a). This market is composed of three segments - **the day-ahead market, the intraday market**, and **the balancing market**. These segments work together to establish prices and balance the supply and demand of electricity.

The day-ahead market is the main trading platform for electricity in the Nordic region, and it operates on the Nord Pool power exchange (Energifakta Norge, 2024a). This market facilitates trading for power delivery hourly for the following day. Market participants, including power producers, brokers, and large industrial consumers, submit their buy and sell bids between 08:00 and 12:00. Before 10:00, transmission capacities are allocated by the TSO to different bidding areas, and the auction concludes at 12:00 . Prices for each hour of the next day are determined based on supply, demand, and available transmission capacity.

After the day-ahead market closes, **the intraday market** takes over. It operates until one hour before the electricity is needed (NVE, 2022). This market allows participants to adjust their positions based on changes in production or consumption that were not anticipated during the day-ahead market. Trading occurs continuously, giving participants the flexibility to handle short-notice fluctuations in demand and supply.

The balancing market is essential for maintaining a continuously balanced power system, where production and consumption must be in perfect equilibrium (Energifakta Norge, 2024a). This market becomes active in the last hour before the electricity is used and during the actual operating hour. The TSO operates in this market to buy or sell flexibility from power plants and large industrial consumers. This ensures that electricity production matches consumption at all times and immediately responds to any imbalances in the system.

If the balancing market is to be utilized, all producers and consumers submit bids, similar to the day-ahead market (Personal Communication with Statnett, May 2, 2024). The bids are compiled into a common Nordic price list and activated based on price priority, ensuring that the most cost-effective regulatory resource is used first. Just as in the day-ahead market, the price in the balancing market will be the same across two bidding areas if there are no bottlenecks between the areas.

Special Regulation: the Redispatch Principal

Special Regulation (SR) involves making adjustments that are applied outside the usual price order in the balancing market (Statnett SF, 2022). Bids used to correct imbalances within the system are classified as standard regulations, while bids that concern redispatching, fault scenarios, or serve other unique purposes are termed SRs. The costs associated with these SRs are borne by the TSO, while standard regulations are part of the settlement process among the market participants.

This study focuses on the type of SR called redispatching. During this process, the network operator checks whether energy feed-ins and withdrawals from the market are feasible on the grid (Brunekreeft et al., 2022). If a bottleneck constricts some parts of the network, the network operator must address this problem by changing the geographic locations of energy production or consumption. The cost associated with SR is called "Special Regulation Costs" for all types of SR. Therefore, even though we are looking at the specific cost created by redispatching, we will refer to it as SR costs from now on.

Special Regulation: Price

To understand the pricing mechanism of SR, we will examine a simplified electrical network model to grasp the dynamics of power distribution under capacity constraints (Brunekreeft et al., 2022). Consider a network comprising two nodes, A and B, connected by a transmission line with a capacity of 500 MW, shown in Figure 2.1. Node A has a generator capable of producing 1000 MW, while node B has a transmission line that can deliver 1000 MW. Both nodes are located in the same price zone, and end customers pay a fixed price for the electricity they consume. The generator's marginal production cost is 80 EUR/MWh, while the transmission line's marginal cost is 50 EUR/MWh.

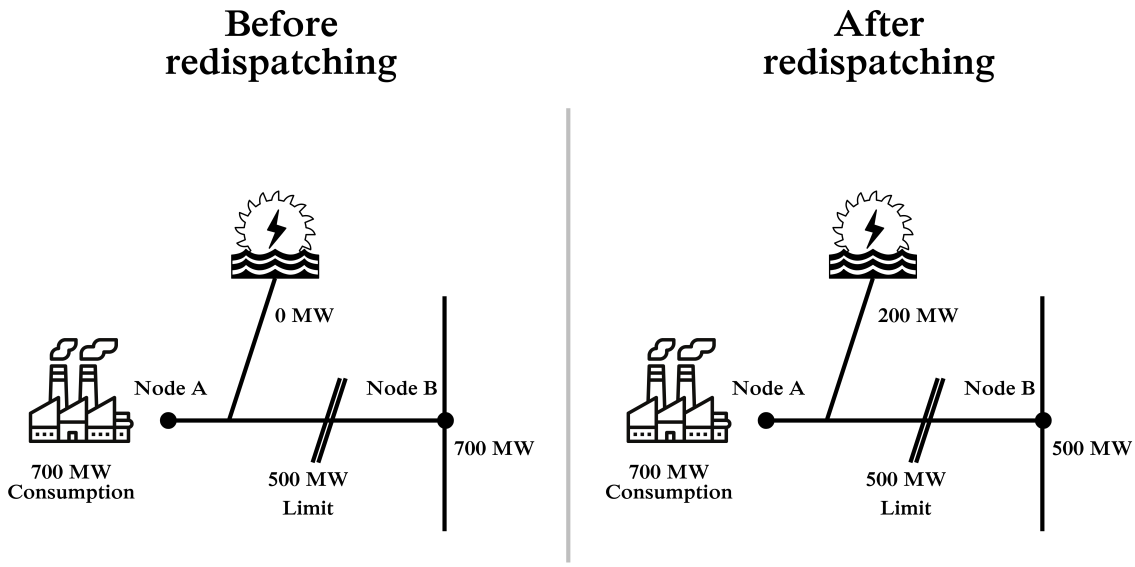

Figure 2.1: Principle of Redispatch Cost

Figure inspired by Brunekreeft et al. (2022)

Suppose we add a load of 700 MW at node A. If there were no constraints on the line between nodes A and B, all the energy would come from the cheaper transmission line. However, due to the constraint on the transmission line, the network operator must buy 200 MW from the generator at node A (upwards redispatch) and reduce the generation connected to the transmission line by 200 MW (downwards redispatch)(Brunekreeft et al., 2022).

2.1.5 Network Pricing

Network pricing serves the primary objective of financing the infrastructure required for efficient transmission and distribution of electricity (Brunekreeft et al., 2022). Since network operators function as monopolists, their pricing strategies and revenue levels are regulated to ensure that they do not exploit their position. This regulation helps maintain a balance where operators can recover the costs necessary for maintaining and expanding the network without imposing excessive charges on consumers.

Ideally, the price for using the network should equal its marginal cost, which is the cost of supplying electricity for one additional unit through the network (Brunekreeft et al., 2022). This approach, known as marginal cost pricing, is ideal for ensuring allocative efficiency. However, due to the high fixed costs and low marginal costs characteristic of electricity networks, relying solely on marginal cost pricing would not allow network operators to cover all their costs. This necessitates the inclusion of additional charges to ensure network services' financial viability and sustainability.

More sophisticated models, such as Ramsey and peak-load pricing, have been developed to address the shortcomings of marginal cost pricing (Brunekreeft et al., 2022). Ramsey pricing considers the price elasticity of demand, charging users based on how sensitive they are to price changes. This method aims to maximize welfare while covering the network's total costs. On the other hand, peak-load pricing addresses the variations in demand and network usage, setting different prices for peak and off-peak periods to manage the load and avoid unnecessary capacity expansion.

Power plants have traditionally been built on a large scale and connected to high-voltage lines (Brunekreeft et al., 2022). However, the congestion cost of these power plants is solely the responsibility of the TSOs, even if the lines are owned by local DSOs. The TSOs pay the price for both up and down redispatching. As a result of the increasing production of renewable energy and electrification of society, there is more congestion in the network, which makes redispatching a higher cost for the TSOs. The problem is compounded by the fact that the TSOs have to bear a high socio-economic cost for the congestion of the DSOs' network. This means that the DSOs have no incentive to deal with the congestion problems, and the cost for the TSOs becomes a part of the network cost, which ultimately consumers have to pay.

The network companies themselves set the prices for network usage, but these prices are subject to regulation by the Regulatory Authority for Energy (RME) in Norway (NVE, 2024b). The RME ensures that the revenues the network company collects through network pricing do not exceed what they are legally entitled to demand from their customers. This measure ensures that the network companies operate efficiently while developing and maintaining the network in a cost-effective manner.

2.2 Engineering Principles and Capacity Calculation

2.2.1 Thermal Limitations and Ampacity of Overhead Lines

Overhead lines (OHL) are electrical power lines above ground, typically on towers or poles, to transport electricity over long distances (Rax Industry, 2021). They have a current-carrying capacity, known as ampacity (Dupin and Michiorri, 2017). The ampacity is limited due to various safety factors. Two primary concerns are network stability and the thermal rating of the conductors, with the latter often being the most restrictive.

This restriction is primarily due to the Joule effect, or Joule heating, where resistance in the conductors causes electrical energy loss that generates heat (Dupin and Michiorri, 2017). When electric current flows through a conductor, the resistance inherent to the material transforms some energy into heat. External factors like solar radiation and environmental conditions also contribute to conductor heating. This excess heat can cause the conductive material to anneal, weakening it and increasing resistance.

Additionally, thermal expansion makes conductors more flexible, increasing sag and bringing them closer to the ground, posing safety risks and elevating outage probability (Dupin and Michiorri, 2017). Hence, the maximal thermal capacity is dependent on the clearance of the ground. Higher resistance further accelerates the Joule effect, increasing energy loss and making grid operation more costly.

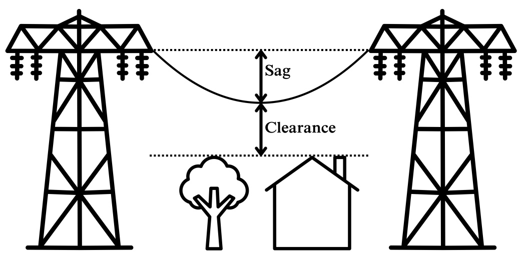

Figure 2.2: The Sag of the Line Given the Thermal Heating

Figure inspired by Dupin and Michiorri (2017)

2.2.2 Static Line Rating and Dynamic Line Rating

The thermal capacity of OHLs is calculated based on weather conditions, line load, and conductor temperature (Szabó and Németh, 2024). These variables determine the capacity of the lines. The heating and cooling of the environmental parameters keep the temperature of the conductors in balance. One way of calculating the capacity is with the CIGRE standard. Inputs consist of wind speed, wind angle, environmental temperature, conductor temperature, solar radiation, and the physical limits and dimensions of the conductor. The effects are shown in Figure 2.3, with red heating the line while blue cools the line.

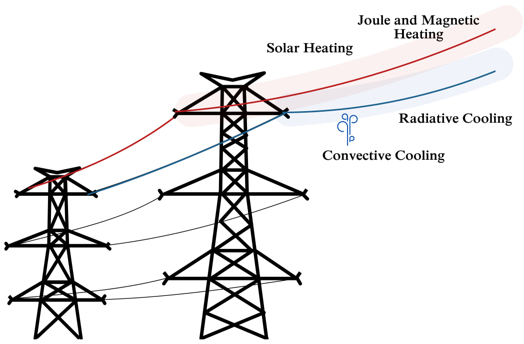

Figure 2.3: Factors Affecting the Thermal Rating of the Lines

Figure inspired by Heimdall Power (2022)

Traditionally, grid operators have used static weather parameters to determine the ampacity of the conductors. Hence the name Static Line Rating (SLR). Currently, Norwegian power grids primarily rely on **SLR** (Personal communication with UDSO-NO4, March 6, 2024). This method assumes a static wind speed of $0.5m/s$ and solar radiation of $500W \cdot m^{-2}$, which are quite conservative (Szabó and Németh, 2024). As a result, the static model often underestimates the cooling effects that occur during colder temperatures and higher wind speeds that blow at a 90-degree angle to the lines. Consequently, this leads to an underestimation of the thermal capacity of the transmission line.

DLR addresses these limitations by accounting for forecasted and real-time weather conditions, providing an accurate assessment of the line's thermal capacity (Szabó and Németh, 2024). The DLR methodology employs the same formulas as SLR but updates the parameters dynamically to reflect current weather conditions. This approach reveals unused capacity and ensures safety by mitigating the risk of lines sagging dangerously low.

2.2.3 Heimdall Power - DLR Neurons

Heimdall Power provides a DLR device called The Neuron (Heimdall Power, 2024c). The Neuron is a spherical IoT device mounted on OHLs and equipped with multiple sensors to collect operational and environmental data. The device applies an interpretation of the CIGRE standard for thermal rating, which allows for the delivery of an optimized DLR for the power system in real-time(Heimdall Power, 2022). This enhances grid operators' ability to safely and efficiently maximize their existing grid infrastructure.

Heimdall Power's solution also includes a forecasting feature, which uses machine learning to compare predicted capacity with actual measurements and improve DLR forecasts (Heimdall Power, 2024a). This feature allows for a more accurate prediction of the actual capacity of the power infrastructure, further enhancing the grid operators' ability to manage their existing grid infrastructure effectively. Overall, Heimdall Power's solution provides a comprehensive and effective approach to managing the DLR capacity of conductors in bottleneck areas, improving power infrastructure management's efficiency and safety.

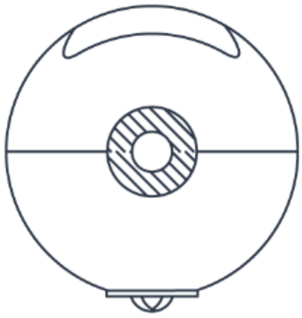

Figure 2.4: Neurons Mounted on the Power Grid

Figure from Heimdall Power (2024d)

2.2.4 Power Grid Security and N-1 Principle

The security measures of a power grid refer to its ability to operate within a wide range of configurations that ensure no equipment is damaged and no load is interrupted (von Meier, 2006). A secure power system is capable of handling emergency situations such as transmission line failures or unexpected generator shutdowns. In such scenarios, the power system should be able to transition to a new configuration by redistributing the load and ensuring that the grid users remain unaffected.

When the system operates under a higher load, it becomes harder to maintain security (von Meier, 2006). We can break this down into two parts: the even flow of energy and transmission capacity. In our paper, we will focus on transmission capacity.

Reserve capacity is required to ensure that the power grid can handle unexpected situations (von Meier, 2006). One common approach to addressing this issue is to implement a concept called "Normal minus One" or N-1. This means the power system should still function properly even after one contingency event, such as losing a major power line.

In practice, this means that if two power lines have different capacities — 650 amperes and 625 amperes, respectively — the total power transmitted cannot exceed 625 amperes (von Meier, 2006). This is because, in the worst-case scenario, the line with the lower capacity must carry the entire load.

N-0.9: Deviating from the N-1 Criteria

The N-1 criterion has been a standard in European power systems for many years. With the growing uncertainty in power generation due to the increased use of renewable energy sources, alongside changes in consumption and energy storage, the power grid operation needs more socioeconomically efficient (Jordanger et al., 2016). N-1 operates the grid with a lot of reserve capacity, making it robust against errors on the net. However, upgrading the grid to meet the increased capacity demand is costly. This expense is compared to the potential risks of deviating from the N-1 criteria, which would result in a slightly more error-prone system.

To enhance grid management, the GARPUR project, *"an EU-funded consortium of transmission system operators (TSOs) and R&D providers, developed and applied a new approach to the development and operation of the European electricity grid"* (European Commission, 2018). To create an effective socioeconomic model, it is essential to accurately cost grid errors while making precise predictions about them, a challenging task. GARPUR has developed models that take these factors into account. Ovaere and Proost (2018) concluded in their paper that a probabilistic approach is preferable as the N-1 criteria are sub-optimal for optimal grid reliability.

The future grid will need to be developed in a socioeconomic efficient manner (Nakstad et al., 2022). The N-1 criteria are not the most socioeconomic way to do this, and as of 2015, it is not a criteria that needs to be held in Norway (Nakstad et al., 2022). "Stømnettutvalget" considers greater utilization of "Tilknytning med vilkår om utkobling", conditional connection, to open more capacity without needing to upgrade the grid. This means having a power market where you can buy capacity on the grid without the N-1 guarantee for delivery at a lower price. This way, the consumer will not have access to the grid if one component is out of order. Aabø Power Consulting made a report in 2022, "Det Norske kraftsystemet i det grønne skiftet: Fra N-1 til N-0,9," suggesting to open up to operate the grid on N-0 for 10%

of the year, assuming that there are enough costumers in the condition connection grid (Alexandersson et al., 2022). We will, in this thesis, explore the cost savings in SR for operation on N-0.9. Here we have assumed that this is a feasible solution in the future and shows the potential cost savings from this measure.

2.3 Previous Work

Numerous studies have examined DLR technology, though relatively few have investigated its economic impacts. Despite the challenges in finding comprehensive analyses of DLR implementation, existing research highlights the technology's benefits through simulations.

Chapter 13, "Dynamic Line Rating," in the book Renewable Energy Forecasting: From Models to Applications (Dupin and Michiorri, 2017), identifies five key advantages unlocked by the additional transmission capacity that DLR provides:

- The improvement of the coupling between electricity markets.
- The reduction of wind power curtailment due to congestions.
- The reduction of redispatching due to curtailment.
- The delay of network reinforcements due to increased generation or loads.
- The improvement of reliability.

As discussed in Section 2.1.3, we focused on the economic benefits associated with SR costs. Renewable Energy Forecasting provides examples of studies illustrating these benefits. Khaki et al. (2010) calculated savings using DLR for economic dispatch on a simplified network consisting of three nodes: one load and two generators with different energy prices. The study found a 7% reduction in generation costs with DLR, while transmission losses increased by less than 1%.

Kazerooni et al. (2011) analyzed wind power integration at the Humber Estuary in Great Britain. By simulating network constraint costs using Latin Hypercube Sampling, the researchers measured the cost of redispatching fossil energy with and without DLR. They found a 52% reduction in constraint costs during winter. This simulation relied on historical weather data and prioritized wind energy, correlating increased DLR capacity with high wind generation.

Blumberg and Weber (2019) simulated redispatch volume and costs for Germany in 2020 using weather data from 2015. The best- and worst-case scenarios projected cost reductions of 32% and 38%, respectively, using DLR.

While operating the grid according to the N-1 principle ensures high security, it can result in missed opportunities. Several analyses have explored using grid capacity beyond N-1 for brief periods to avoid over-dimensioning and costly upgrades for occasional peak loads. For European Commission (2018), more probabilistic approaches to network security were considered, giving a socioeconomically cost benefit of about 25%; this was mostly considering upgrades of the grid. We have not found any research on the reduction of redispatching deviating from N-1.

These studies relied on weather, power flow, prices, and DLR capacity simulations. In contrast, our research employs real historical data for a descriptive analysis of a specific region in Norway. This is the first study of its kind, demonstrating real-world SR cost savings from DLR and N-0.9 operation in one Norwegian region.

3 Data and Research Design

In Chapter 2.2, "Engineering Principles and Capacity Calculation", we discussed how line capacity can be calculated both statically (SLR) and dynamically (DLR). SLR provides conservative estimates, while DLR offers updated, accurate values.

This chapter outlines the methods for calculating line capacity and describes the provided dataset, including its variables. It explains how we used this dataset to compute new variables. Additionally, it provides a mathematically detailed description of the parameters used in our analysis. The chapter also presents an argument for three different future scenarios. Lastly, we will present three future scenarios, discussing the selection of each and their reason for our study.

3.1 Calculating Capacity

The UDSO-N04 provided a dataset detailing SLR and DLR capacities for specific conductors for our case study. The UDSO-N04 utilized a standard SLR configuration with fixed parameters across all variables except temperature, which was adjusted based on the ambient conditions surrounding each conductor (Personal communication with UDSO-N04, March 3, 2024). The wind speed was set at $0.5m/s$ and solar radiation I_t, at $500W \cdot m^{-2}$. It is assumed that the framework aligning with CIGRE TB-601(Cigre Working Group B2.43, 2014) guidelines was employed. Additionally, we received data from Heimdall Power's sensors, which adhere to the same CIGRE TB-601 standard (Heimdall Power, 2022). This data provides real-time updates on conductor temperature, line sag, ambient temperature, and wind speed (Heimdall Power, 2024a). We can accurately determine the conductors' safe DLR current capacity by integrating this data with weather forecasts and grid modeling.

Neither Heimdall Power nor UDSO-N04 disclosed their specific computational methods; however, they confirmed that these are grounded in the CIGRE TB-601 principles.

We received post-calculation capacities, but the underlying framework remains consistent with the variables listed in Table 3.3 (Cigre Working Group B2.43, 2014). The equations provided in this section are also sourced from Cigre Working Group B2.43 (2014).

Table 3.1: Description of Variables in the Heat Transfer Equations

Variable	Description	Units
m	Mass per unit length; constant	$kg \cdot m^{-1}$
c	Specific heat capacity	$J \cdot kg^{-1} \cdot K^{-1}$
$\frac{dT_{av}}{dt}$	Rate of change of average temperature	$K \cdot s^{-1}$
P_j	Joule heating power	W
P_s	Solar heating power	W
P_c	Convective cooling power	W
P_r	Radiative cooling power	W
α_s	Solar absorptivity coefficient; varies between 0.2 and 0.9	*dimensionless*
I_T	Total solar irradiance	$W \cdot m^{-2}$
D	Diameter of the object; constant	m
I	Current through the conductor	A
R_{AC}	Alternating current resistance per unit length with skin effect	$\Omega \cdot m^{-1}$
σ_B	Stefan-Boltzmann constant; $5.6697 \cdot 10^{-8}$	$W \cdot m^{-2} \cdot K^{-4}$
ϵ_s	Emissivity of the surface; usually between 0.8 and 0.9	*dimensionless*
T_s	Surface temperature	$^{\circ}C$
T_a	Ambient temperature	$^{\circ}C$
T_f	Film temperature	$^{\circ}C$
λ_f	Thermal conductivity of the air	$W \cdot m^{-1} \cdot K^{-1}$
Nu	Nusselt number	*dimensionless*

The heat balance is given by the following equation:

$$m \cdot c \cdot \frac{dT_{av}}{dt} = P_j + P_s - P_c - P_r \tag{3.1}$$

To determine the maximal capacity of the conductor we want to have the conductor in thermal equilibrium at the maximum thermal capacity, hence setting $\frac{dT_{av}}{dt} = 0$, the equation becomes:

$$P_j + P_s = P_c + P_r \tag{3.2}$$

The heat generated from P_j and P_s must be of the same magnitude as the cooling from P_c and P_r

P_s represents the solar heating on the line and is calculated as:

$$P_s = \alpha_s \cdot I_T \cdot D \tag{3.3}$$

Joule heating, P_J, for AC conductors is given by:

$$P_J = I^2 \cdot R_{AC} \tag{3.4}$$

The resistance is dependent on the temperature, with higher temperatures giving higher resistance.

Radiative cooling is expressed with:

$$P_r = \pi \cdot D \cdot \sigma_B \cdot \varepsilon_s \cdot \left[(T_s + 273)^4 - (T_a + 273)^4\right] \tag{3.5}$$

Lastly, convective cooling is defined as:

$$P_c = \pi \cdot \lambda_f \cdot (T_s - T_a) \cdot Nu \tag{3.6}$$

Cigre Working Group B2.43 (2014) claims that in temperatures up to 300°C, the thermal conductivity of the air can be expressed as:

$$\lambda_f = 2.368 \cdot 10^{-2} + 7.231 \cdot 10^{-5} \cdot T_f - 2.763 \cdot 10^{-8} \cdot T_f^2 \tag{3.7}$$

where the film temperature (T_f) is assumed to be $T_f = 0.5 \cdot (T_s + T_a)$.

The Nu is dependent on wind speed and the angle between the OHL and the wind. The temperature, wind angle, and speed have a high effect on the cooling, as shown in Figure 3.1 on a high voltage "Drake" ACSR (conductor) for lower wind speeds. The example considers a conductor temperature of 100 °C and an ambient temperature of 40 °C. Although the conductor is designed for slightly higher voltages than those in our case study, it effectively illustrates the impact.

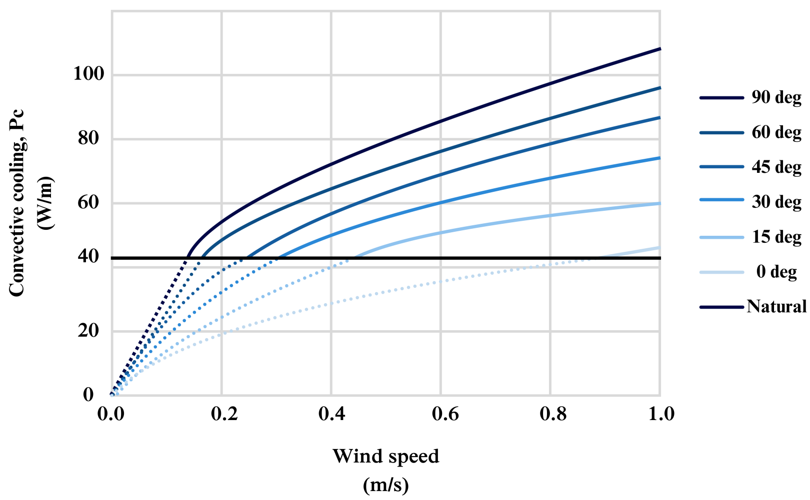

Figure 3.1: The Impact of Low Wind Speed and Different Angles on a Conductor

This example uses a "Drake" conductor at an ambient temperature of $40°C$ and conductor temperature of $100°C$, figure from Cigre Working Group B2.43, 2014.

Using these Equations (3.1-3.7), we can determine the maximum allowable electrical current (I) that does not exceed the conductor's maximum thermal rating.

Using Equation (3.4) and reallocating Equation (3.2) gives us the following expression for the current:

$$I = \sqrt{\frac{P_c + P_r - P_s}{R_{AC}}} \tag{3.8}$$

Equation (3.8) assumes a steady state at the maximal thermal capacity for the given conductor. However, this is a liberal assumption. Therefore, DLR calculation contains a lot of uncertainty and is served numerically. Sensitivity analysis from Cigre Working Group B2.43 (2014) shows an example of effects on higher wind speeds given a 80°C "Drake" conductor with 35°C ambient temperature. This is shown in Figure 3.2. As we can see, Convection heating is the most important cooler for the conductor, while Joule heating is the most important factor for heating. The dependency increases with wind speed. The figure use the optimal wind angle, 90°, on the conductor.

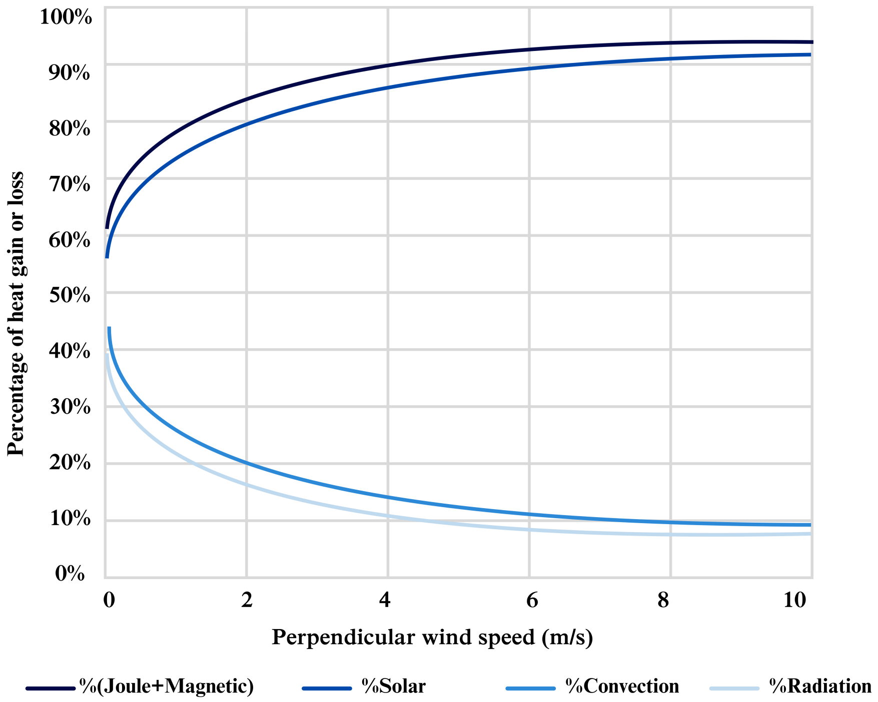

Figure 3.2: The Impact of Higher Wind Speed on a Conductor

Example for a "Drake" conductor at an ambient temperature of $40°C$ and conductor temperature of $100°C$. Convection and Radiation contribute to heat loss, while Joule + Magnetic and Solar heat up the conductor. Figure from Cigre Working Group B2.43, 2014.

As we want to be able to transfer as much energy as possible, we want the cooling to be as high as possible given a higher allowable current (I). Hence, low temperatures and high wind speed are favorable, as shown in Figure 3.8. This way, the temperature of conductors can only be high when convective cooling is highly effective. Because of this, convective cooling clearly affects the conductor temperature, along with the Joule heating, which determines the allowed current in the conductor.

3.2 Data Set

The dataset provided by UDSO-NO4 consists of data and calculations of the current capacity of the conductors from two 132 kV regional power lines connecting the transmission network to the region delimited by bottlenecks. The collection period extends from October 14, 2022, to January 11, 2024, and includes hourly measurements throughout this timeframe. SLR and DLR capacity in the dataset was computed by UDSO-NO4 and Heimdall Power.

Table 3.2 summarizes the variables contained in the dataset:

Table 3.2: Summary of Dataset Variables

Variable Name	**Description**
Timestamp	Hourly time stamp for each observation.
Line A - Current [A]	Scheduled current in amperes measured for Line A.
Line B - Current [A]	Scheduled current in amperes measured for Line B.
Total Current A+B [A]	Scheduled current in amperes for Line A and B.
Line A - SLR [A]	SLR capacity for Line A.
Line B - SLR [A]	SLR capacity for Line B.
Cut-set A+B - SLR [A]	Cut-set SLR capacity for Line A and B, the N-1 capacity.
Special Regulated Production [A]	Amount of SR in Ampere for the power grid
Line A - DLR [A]	Line capacity for Line A as measured by DLR neurons.
Line B - DLR [A]	Line capacity for Line B as measured by DLR neurons.
Cut-set A+B N-1 (DLR) [A]	Cut-set DLR capacity for Line A and B, the N-1 capacity.
Special Regulated Production DLR [A]	SR based on DLR measurements in Ampere.
Lost DLR Potential [A]	The potential capacity loss from not using DLR when computing special regulation

The dataset shows the planned current for each hour. If there were no SRs, it represents the actual current that passed through the lines. It also indicates the estimated capacity for the respective hours, calculated using SLR measurements.

The cut-set is determined based on the N-1 principle, where the total capacity of both lines is determined by the weakest line. N-1 is explained more in-depth in Section 2.2.4, "Power Grid Security and N-1 Principle".

Furthermore, the dataset indicates when special regulated production occurs. This happens when the planned current exceeds the SLR capacity.

SR for SLR operation is calculated based on this formula:

$$SR_{SLR_h} = TotCurrent_h - SLR_{capacity_h} \tag{3.9}$$

where:

- SR_{SLR_h}: Special Regulated Production [A] from the dataset
- $SLR_{capacity_h}$: Cut-set SLR capacity [A] for Line A and B from the dataset
- $TotCurrent_h$: Special Regulated Production [A] from the dataset.

The difference here represents the amount of SR.

DLR Against SLR capacity

Figure 3.3 shows the comparison of DLR for each hour in the dataset. The blue line represents DLR capacity, demonstrating a higher and more volatile trend than the gray line, representing SLR capacity. The variability in DLR capacity is due to its adaptability to dynamic conditions like temperature and wind, allowing it to operate at significantly higher capacity during favorable conditions. On the other hand, SLR maintains a stable but lower capacity throughout the period.

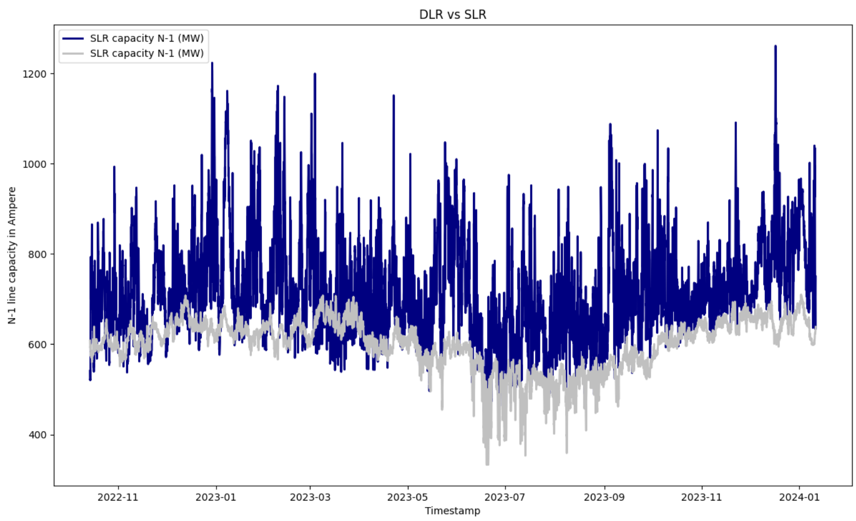

Figure 3.3: DLR Against SLR Capacity

When comparing DLR capacity with SLR capacity in percentage over time from our data, we observe that DLR exhibits higher capacity than SLR around 90% of the time while being lower approximately 10% of the time, as shown in Figure 3.4. The difference ranges from about 220% of the SLR capacity to about 85% of the SLR capacity. DLR capacity is lower than SLR capacity about 10% of the time.

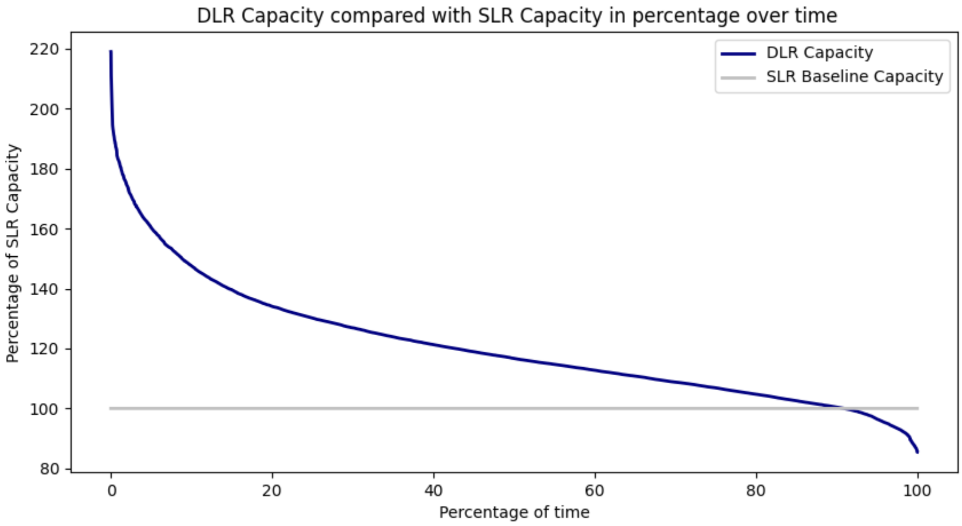

Figure 3.4: DLR Against SLR Capacity

Figure 3.4 shows that the static parameters used in the SLR calculation are often very conservative compared to the actual parameter values. This would typically be cloudy with higher wind speeds. In the hours where DLR gives lower capacity than SLR, the static parameters in the SLR calculation are too liberal. The wind is lower than $0.5m/s$, and the radiation I_t is higher than $500W \cdot m^{-2}$. It is important to make clear that DLR doesn't add any extra capacity to the grid. It only uses more information about the parameters from the CIGRE TB-601 calculation, giving more insight into the actual capacity of the conductor while still fulfilling the safety standards. As shown in Figure 3.4, it also reveals that the SLR overestimates the capacity for some time.

Added variable: Special Regulation using DLR measurements

To explore how the need for SR would appear if DLR values were used instead of SLR, an additional column titled "Special Regulated Production DLR [A]" was added, as shown in Table 3.2. This adjustment was made by identifying instances when the planned transmitted current exceeded the DLR calculations:

$$SR_{DLR_h} = SR_{SLR_h} + SLR_{capacity_h} - DLR_{capacity_h} \tag{3.10}$$

where:

- SR_{SLR_h}: Special Regulated Production [A] from the dataset
- $SLR_{capacity_h}$: Cut-set SLR capacity [A] for Line A and B from the dataset
- $DLR_{capacity_h}$: Cut-set DLR capacity [A] for Line A and B from the dataset.

The difference here represents the amount that would require SR if measurements were based on the DLR neuron measurements.

Added variable: Lost DLR Potential

We also calculated the potential losses in SR due to not using DLR when computing SR for each hour. Also included in Table 3.2.

$$DLR_{pot.gain_h} = SR_{SLR_h} - SR_{DLR_h} \tag{3.11}$$

where:

- SR_{SLR_h}: Special Regulated Production [A].
- SR_{DLR_h}: Special Regulated Production DLR [A].

The formula shows how the lost potential from not utilizing DLR varies depending on the amount of SR load (SR_{SLR_h}) and the additional capacity available through DLR (SR_{DLR_h}). It helps assess whether DLR can fully or partially replace SR needs and quantifies the capacity losses possible by utilizing DLR over SLR. If the DLR capacity were to be lower than the SLR capacity for a given hour where SR was needed, the potential gain would be negative.

3.2.1 Price Data

In order to determine the values and potential savings in numerical terms, we needed to gather additional information regarding pricing. We attempted to acquire the exact pricing data for a SR related to our dataset, but unfortunately, we could not obtain this information in time.

As an alternative, we calculated the total cost of SR for the whole of Norway (2022) and divided it by the total number of SR hours (2022) in Norway (measured in MW) to estimate the costs (Statnett SF, 2023). In this way, we obtained an hourly average price for SR.

$$\text{Average Hourly Price of SR} = \frac{\text{Total Cost of SR 2022}}{\text{Total MWh of SR 2022}} \tag{3.12}$$

$$= \frac{527\,\text{MNOK}}{1,212,000\,\text{MWh}} = 434.82\,\text{NOK} \tag{3.13}$$

We would have preferred to have the exact prices, but we consider this method sufficient for demonstrating savings.

To effectively combine our dataset, which was provided in amperes (A), with our pricing data, which was in megawatts (MW), we needed to convert the units. Therefore, we converted the data from the dataset to megawatts (MW).

Since the power lines operate within a three-phase system, we employed the following equation for conversion (von Meier, 2006):

$$P_{\text{MW}} = \frac{\sqrt{3} \cdot V \cdot I \cdot PF}{10^6} \tag{3.14}$$

In Equation (3.14), P_{MW} denotes the power in megawatts, V is the line voltage, and I represents the current. The factor $\sqrt{3}$ is included to account for the three-phase nature of the electrical system. In our case, the voltage for the conductors is specified as 132 kV, and we assumed a Power Factor PF of 1 as previous research has done (Glaum and Hofmann, 2023). We use MW as the prices are given in NOK/MWh.

3.2.2 DLR Utilization Parameters

After analyzing the data based on our research questions, we aimed to examine the parameters in Table 3.3 to understand the impact of DLR on the necessity and cost of SR. We will analyze our original data, called the "Baseline Scenario" and the three future scenarios.

Parameter Name	Description	Units
hSR_{SLR}	Hours of Special Regulation (SLR)	*dimensionless*
$nh_{pos.DLR}$	Positive DLR Hours Count	*dimensionless*
$nh_{neg.DLR}$	Negative DLR Hours Count	*dimensionless*
SR_{SLR}	Total Special Regulation SLR	MWh
$CostSR_{SLR}$	Total Special Regulation Cost SLR	NOK
SR_{DLR}	Total Special Regulation DLR	MWh
$CostSR_{DLR}$	Total Special Regulation Cost DLR	NOK
$SR_{cut}DLR$	Cut in Special Regulation with DLR	NOK
DLR_{gain}	Total DLR Gain	MWh
DLR_{save}	Total DLR Cost Saving	MWh
$hDLR_{cov}$	Hourly DLR Coverage	%

Table 3.3: Summary of Parameters

The parameters used to calculate the variables in Table 3.3 are given in Table 3.4.

Variable	Description	Units
nh	number of hours	*dimensionless*
h	given hour in the data	*dimensionless*
SR_{SLR_h}	Special Regulation with SLR for given hour	MW
SR_{DLR_h}	Special Regulation with DLR for given hour	MW
P_h	Price of special regulation for given hour in	$NOK \cdot MWh^{-1}$

Table 3.4: Summary of Variables

The purpose of the formulas using hourly measurements is to determine the SR price for each hour accurately. We developed this in the hope of obtaining the correct prices in a timely manner, as outlined in Section 3.2.1. However, this goal was not achieved.

Hours of Special Regulation ($nhSR_{SLR}$)

Number of hours where SR was needed:

$$nhSR_{SLR} = \sum_{h=1}^{nh} \begin{cases} 1 & SR_{SLR_h} > 0 \\ 0 & SR_{SLR_h} \leq 0 \end{cases} \tag{3.15}$$

Number of hours where the need for SR is higher with SLR than DLR ($nh_{pos.DLR}$):

$$nh_{pos.DLR} = \sum_{h=1}^{nh} \begin{cases} 1 & SR_{DLR_h} < SR_{SLR_h} \\ 0 & SR_{DLR_h} \geq SR_{SLR_h} \end{cases} \tag{3.16}$$

Number of hours where the need for SR is higher with DLR than SLR $nh_{neg.DLR}$:

$$nh_{neg.DLR} = \sum_{h=1}^{nh} \begin{cases} 1 & SR_{DLR_h} > SR_{SLR_h} \\ 0 & SR_{DLR_h} \leq SR_{SLR_h} \end{cases} \tag{3.17}$$

These three parameters indicate how frequently SR is required when using SLR, which is especially useful when analyzing different changes in power consumption.

Total Special Regulation SLR in MWh ($SR_{SLR.MWh}$)

$$SR_{SLR.MWh} = \sum_{h=1}^{n_h} SR_{SLR_h} \tag{3.18}$$

Totaling up the SR_{SLR} for each hour in the dataset. This gives the total amount of SR for our dataset.

Total Special Regulation Cost SLR in NOK ($CostSR_{SLR}$)

$$CostSR_{SLR} = \sum_{h=1}^{n_h} SR_{SLR_h} \cdot P_h \tag{3.19}$$

Summing the product of the SR_{SLR} for each hour with its corresponding price (P_h) as the price varies hour by hour. We have used the same price for each hour as we were unable to obtain the prices during our work, but the principle stays the same.

Total Special Regulation DLR MWh(SR_{DLR})

$$SR_{DLR} = \sum_{h=1}^{n_h} SR_{DLR_h} \tag{3.20}$$

Using the same Equation (3.18), but with the SR given use of DLR.

Total Special Regulation Cost DLR in NOK ($CostSR_{SLR}$)

$$CostSR_{DLR} = \sum_{h=1}^{n_h} SR_{DLR_h} \cdot P_h \tag{3.21}$$

Using the same Equation (3.19), the price per MWh for each hour would be the same as the SR given the use of DLR.

Cut in Special Regulation with DLR in % ($SR_{cut}DLR$)

$$SR_{cut}DLR = \frac{\sum_{h=1}^{n_h} DLR_{pot.gain}}{\sum_{h=1}^{nh} SR_{SLR_h}} \tag{3.22}$$

This metric measures the percentage of SR that could have been avoided by using DLR data instead of SLR. It does so by comparing the total potential avoidance of SR using DLR compared to the total amount of SR operating with SLR

where:

- $\sum_{h=1}^{nh} DLR_h$: This summation calculates the total load the DLR system manages for all hours in the dataset. Here, DLR_h represents the load handled by DLR during hour h.
- $\sum_{h=h}^{nh} SR_h$: This summation calculates the total requirement for SR across the relevant hours, Here, SR_h represents the load handled by SR during hour h.
- If $SR_{cut}DLR$ is high, it means that the DLR could cover a significant portion of the SR load.
- This ratio helps quantify the effectiveness of the DLR operation in reducing the need for traditional regulation methods.

Total cost cut in SR cost using DLR in NOK ($SR_{cut.NOK}$)

$$DLR_{cost.save} = \sum_{h=1}^{n_h} DLRgain_h * P_h \tag{3.23}$$

This formula calculates the total monetary savings by multiplying the DLR gain ($DLRgain_h$) by the price per MWh (P_h) for each hour (h), and then summing these hourly savings across the given time range. The result is the total cost savings in NOK that could be achieved using DLR instead of SLR to manage SR requirements.

Average Hourly cut in SR using DLR ($hourlySR_{cut\%}$)

$$hourlySR_{cut\%} = \frac{\sum_{h=1}^{nh} \frac{DLR_h}{SR_h}}{n_h}, h \in H : SR_{SLR} > 0 \lor SR_{DLR} > 0 \tag{3.24}$$

This metric measures the average effectiveness of DLR in reducing the need for SR in percent, excluding hours when no regulation is required. It gives insights into how consistently DLR meets capacity requirements relative to SLR. This way, high peaks in SR do not affect the result as much.

- $\sum_{h=1}^{nh}$: The summation notation, which adds up the effectiveness ratios across all hours.
- $h \in H : SR_{SLR} > 0 \vee SR_{DLR} > 0$: Indicates that only hours where SR was required are included.

3.3 Scenario Development for Future Savings

In order to expand our research and investigate the potential future developments of DLR, we analyzed various scenarios and simulated the effects of DLR on them. Our objective was to test three different grid congestion scenarios in the year 2030, based on the report outlined in Section 1.1.1.

We consulted with the UDSO-NO4 and discovered that the congestion in the area we examined was caused by energy consumption rather than production (Personal Communication with UDSO-NO4, May 5, 2024). This suggests that an increase in congestion will likely coincide with a rise in consumption. We are currently using the 20.3% growth, referred to as 20% from now, provided by Christiansen et al. (2023), but we need to understand what this increase would look like for 2030. To test this, we conducted three scenarios:

1. We scaled up the power flow from our data by 20,3%, assuming that new energy consumption patterns will follow the same trends in 2030 as in 2023. Here, we scaled the current for each hour with 1.203 like this:

$$\text{20\% current gain} = TotCurrent_h \cdot 1.203 \tag{3.25}$$

   We changed the Total Current A+B [A] with the multiplied data and did the same analysis on the provided data. We call this 20% Increased Power Flow.

2. We conducted a second case assuming that future energy consumption in 2030 will not necessarily follow the same patterns as current consumption in 2023. Since most existing energy consumption is primarily for heating, the green transition will electrify processes that may not follow these existing consumption trends. To account for this, we totaled the power flow in our data, increased it by 10%, and then divided it by the number of data points (hours). This was added as a Fixed Gain for each timestamp. We call this 10% Fixed Gain

3. The same procedure was done for a Fixed Gain of 20%. Called 20% Fixed Gain.

The method was the same for both of the scenarios for the latter case. We took the total amount of current over all the data and divided it by the number of hours to find the average hourly current.

$$Avg.Current = \frac{\sum_{h=1}^{nh} \cdot TotCurrent_h}{nh} \tag{3.26}$$

Then we found the percentage we wanted to add to the baseline and added it to each hour of $TotCurrent$

$$\%\text{gain current baseline} = TotCurrent_h + (Avg.Current \cdot \%gain) \tag{3.27}$$

We altered Total Current A+B [A] for the analysis and performed the same analysis on the provided data.

3.3.1 N-0.9 Operation

To further explore the potential evolution of the SR costs, we will conduct additional testing with the N-0.9 concept. This approach was suggested by Alexandersson et al. (2022). In this scenario, we allow the grid in the case study to operate with the total capacity of both lines for 10% of the time, meaning it does not operate with the N-1 standard. Alexandersson et al. (2022) suggested that this would be feasible for 10% of the time. Our data assumes that one can utilize the DLR capacity on both lines for hours with the top 10% highest SR_{DLR_h} value.

The N-0 capacity for these hours is then:

$$N - 0_{capapciy_h} = DLR_{capacity_h} LineA + DLR_{capacity_h} LineB \tag{3.28}$$

Here we use the N-0 capacity instead of the $DLR_{capacity_h}$ for the hours within the 90% quantile.

4 Findings and Interpretations

This chapter presents and interprets our study's findings, offering a continuous analysis intertwined with relevant discussions throughout its structure. First, we will examine the Baseline Scenario, detailing how it unfolded under the established parameters. Next, we will compare the three projected future scenarios, highlighting their differences and deviations from each other and the Baseline Scenario. Afterward, we will explore the data after adopting the N-0.9 concept. The chapter will conclude by acknowledging the study's limitations and providing context for the interpretation of our findings.

4.1 Capacity Gain Using DLR

To start our analysis, we calculated the additional capacity DLR could provide for our Baseline Scenario. This calculation amounted to:

DLR gain	20.02 %

Table 4.1: DLR Gain

Using DLR instead of SLR indicates the potential to operate the lines 20% more without risking failure, although the maximum capacity remains unchanged. Heimdall Power reports that the DLR neurons provide a 30% increase in capacity Heimdall Power, 2024b. Our findings are slightly lower than this. This difference could be attributed to our comparison with an SLR measurement that is not purely static. UDSO-NO4 accounts for temperature variances in the SLR measurements, which may explain why our calculated gain is on the lower end, mentioned in Section 3.1.

Further, we examined how this spreads out over the year for each month, illustrated in Figure 4.1. The SLR capacity is generally lower in the warmer summer months and higher in the colder months, indicating the temperature considered. The difference between DLR and SLR does not follow a clear pattern, possibly due to less seasonal-dependent behavior, such as clouds and wind, which can either dampen or accelerate the differences for each month, as only DLR considers the change of these parameters. For example, in March 2023, the DLR gain was at its lowest percentage, benefiting by 7.9%, while in September 2023, the gain was at its highest percentage, with a benefit of 31.7%.

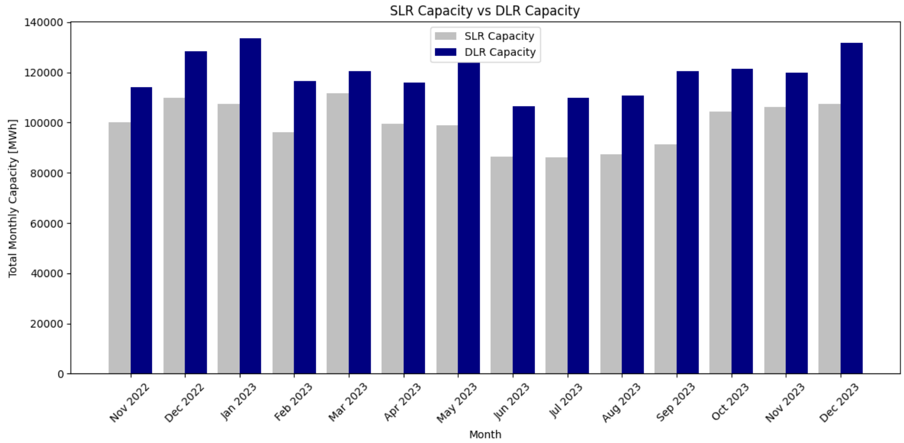

Figure 4.1: Total Monthly Capacity DLR Against SLR

4.2 Evaluating Baseline Scenario Parameters

As described in Section 3.2.2, the data were measured on 10 different parameters. Here, we visualized the level of SR required by DLR and SLR measurements, shown in Figure 4.2.

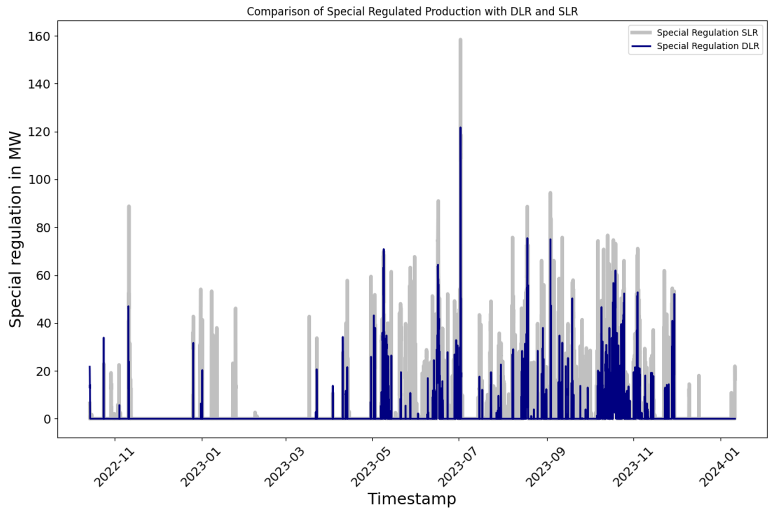

Figure 4.2: DLR Against SLR Special Regulation.

The grey bars depict the amount of SR necessary to operate on SLR capacity, while the blue bars represent the potential amount needed with DLR capacity. Generally, SLR requires more SR than DLR. A grey bar without a corresponding blue bar indicates a period when DLR-based SR was not necessary at all.

Table 4.2 summarizes the results obtained from the various parameters.

Parameter	**Value**
Hours of SR (SLR)	2220
Positive DLR Hours Count	2161
Negative DLR Hours Count	59
Total SR SLR (GWh)	50.52
Total SR Cost SLR (MNOK)	21.97
Cut in SR with DLR (%)	67.31 %
Total DLR Gain (GW)	34.00
Total SR Cost DLR (MNOK)	7.18
Total DLR Cost Saving (MNOK)	14.79
Hourly DLR Coverage (%)	75.04 %

Table 4.2: Parameter Results - Baseline Scenario

Table 4.2 shows a total of 2220 hours of SR operating with SLR. They also indicated that DLR could have a positive impact by utilizing more capacity, reducing the need for SR, resulting in 2161 hours of "Positive Count." However, there are also 59 hours where DLR required more SR than SLR, indicated as the "Negative Count".

The total SR operating with SLR is 50.52 GWh, with associated costs of 21.97 MNOK. This highlights the potential savings with DLR, estimating that 67.31% of the SR could be avoided with DLR operation of the grid. This change would result in a cost reduction of 14.79 MNOK and a capacity gain of 34.00 GWh.

In comparison, the total SR cost, operating on DLR capacity for the entire period, amounts to 7.18 MNOK. This indicates that Statnett spent nearly 15 MNOK in excess on SR out of a total of almost 21 MNOK. This highlights the cost-saving potential of using DLR and the efficiency gains that can be achieved by leveraging this technology.

4.2.1 Monthly Baseline Scenario Savings

To further investigate the potential SR savings through the use of DLR, we examined the data for each month.

Figure 4.3 shows the variations in the *Total SR Cost SLR* and the *Total SR Savings DLR* throughout the year, with costs ranging from very low in December to April, and peaking in the summer months. This indicates the influence of temperature on SLR, and avoiding a lot of SR in the winter.

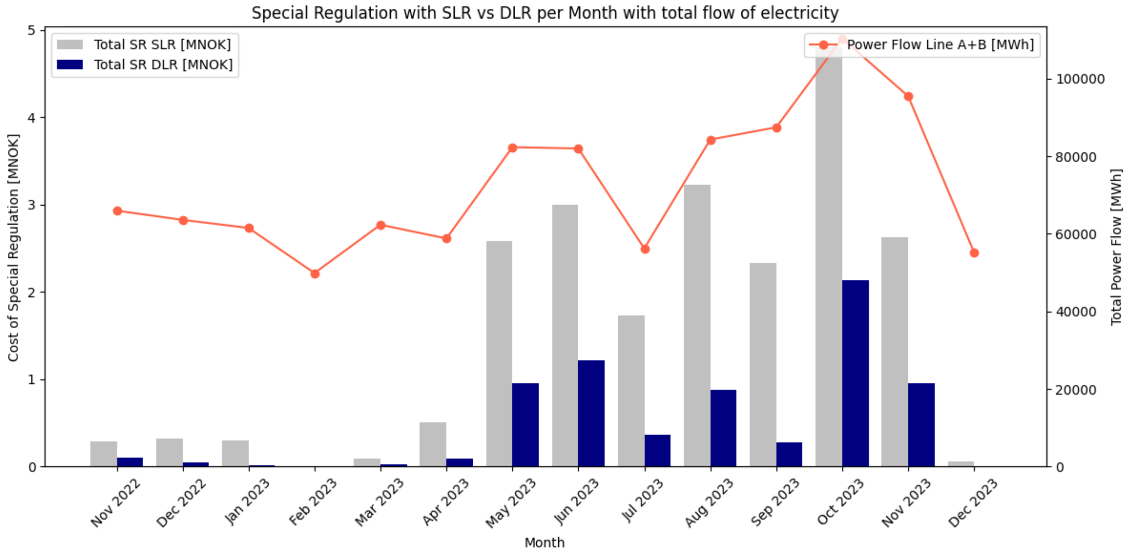

Figure 4.3: DLR Against SLR Special Regulation.

The demand for SR during the summer and fall months is not entirely unexpected. This demand is influenced by electricity prices, the level of water in reservoirs, and the value of water. When water is highly valued but electricity prices are low, major reservoir power plants conserve water and reduce production (Personal communication with UDSO-NO4, May 3, 2024). As a result, SR is needed to avoid bottlenecks and maintain stability in the power system.

The cost of SR could also be compared to the power flow over the months. As seen in Figure 4.3, the months with a high need for power, e.g., September, October, and November 2023, need the most SR. Signaling that it is the higher peaks that lead to higher needs of SR. We could also see that the months with the highest difference in SLR and DLR capacity from Figure 4.1 had a great difference in SR cost with SLR and DLR. An example of this is September 2023.

4.2.2 Upscaling to the Whole of Norway

Assuming that the *DLR gain* we observed remained constant over time, consistently offers a 20% increase in capacity (from 4.1). From this, we could also assume the *Cut in SR with DLR* 67.31% is consistent (from 4.2). These figures can be used to project potential savings on a national scale.

The specific location under study contributed 21 MNOK to the national SR expenditure, accounting for approximately 4% of the total, which amounted to 527 MNOK in 2022 (see Section3.2.1). This total expenditure includes all instances of SR (Statnett SF, 2022). Focusing solely on SR costs by *"Intact network, overload"* and excluding costs related to Revisions, Errors/Outages, and Other factors, the associated SR costs are estimated at 340 MNOK. By applying the observed reduction potential of DLR (67.31%), we can conservatively estimate the savings nationwide.

We then receive a *Total Savings: Intact network, overload* of 228.85 MNOK. If based on all the SR costs, the figure would be 354.72 MNOK.

The figures provided are only estimates and may be subject to change due to various factors and energy peaks. However, the main point is to demonstrate the potential savings possible by using DLR to optimize line usage more effectively.

These are incredibly large amounts to save. By utilizing the network with DLR measurements, we can optimize capacity and significantly reduce costs associated with SR. This demonstrates the substantial economic benefits of implementing DLR systems on a national scale.

4.3 Evaluating Parameters for the Different Scenarios

The Capacity Gain (from Table 4.1) with DLR will be equal for all scenarios in our case study, as only the power flow changes for each scenario. Table 4.3 shows the parameter results from each of the scenarios.

Parameter	**Baseline Scenario**	**20% Increased Power Flow**	**10% Fixed Gain**	**20% Fixed Gain**
Hours of SR (SLR)	2220	3860	2947	3714
Positive DLR Hours Count	2161	3749	2866	3611
Negative DLR Hours Count	59	111	81	103
Total SR SLR (GWh)	50.52	140.67	76.53	109.43
Total SR Cost SLR (MNOK)	21.97	61.18	33.28	47.58
Cut in SR with DLR (%)	67.31%	53.38%	63.14%	59.72%
Total DLR Gain (GWh)	34.00	75.01	48.32	65.35
Total SR Cost DLR (MNOK)	7.18	28.52	12.27	19.17
Total DLR Cost Saving (MNOK)	14.79	32.65	21.01	28.42
Hourly DLR Coverage (%)	75.04%	65.61%	73.12%	69.18%

Table 4.3: Parameter Results - Across Scenarios

We noted that a 20% increase in Power Flow and a 20% Fixed Gain resulted in a similar number of hours requiring SR. However, with SLR, the Power Flow requires approximately 30 GWh more in SR, leading to nearly 14 MNOK in additional SR costs. Furthermore, the potential savings will vary by approximately 6% more for 20% Fixed Gain. The daily coverage differs by only 3.5% more for 20 % Fixed Gain. All these numbers and differences between Power Flow and Fixed Gain highlight that the peaks in consumption primarily drive the need for SR, which is more evident in the Power Flow scenario. This is also shown by the SR cost calculated to be 28.52 million NOK for Power Flow, higher than the 19.17 million NOK for the Fixed Gain.

Additionally, we discovered that a 10% Fixed Gain produces the most effective results in reducing SR, resulting in a 63.14% reduction. This reduction is higher than in the other scenarios but slightly lower than the Baseline Scenario. This suggests that the decrease in SR lessens as the flow and current gain increase.

The analysis indicates that grid operators could potentially handle a 20% Fixed Gain while maintaining performance close to today's levels. This effect is significant when compared to the Baseline Scenario, with the DLR effect decreasing by only 8 percentage points in terms of SR. These findings highlight the power system's ability to adapt to increased energy consumption. In this case, the cost of not using DLR today is the same as *Total DLR Cost Saving* for each scenario.

The cost of the SR is quite sensitive to higher energy consumption. However, reducing the SR cost is just one isolated economic benefit of the DLR solution. This can be further weighed against the net present value of delaying investment in the grid and the gain in information about the future power system developed over time.

4.4 Operating With N-0.9

Baseline Scenario

The dataset consists of 10,897 data points. This means that by operating on N-0.9, we can have 1089 hours of operation on N-0 capacity, allowing the grid to operate at full capacity on both power lines. For the Baseline Scenario, there were 950 hours where SR was needed after utilizing DLR. This is visualized in Figure A.3. During these hours, we should avoid using SR unless its value is more than double the N-1 DLR capacity. This is because we now operate on N-0 for these hours. Figure 4.4 shows that all the SR in our data from October 2023 to January 2024 could be avoided using the less rigid grid operational constraints of N-0.9 and DLR. This demonstrates cost-effective congestion measures that may avoid grid upgrades.

Table 4.4 illustrates that by adopting N-0.9 and DLR, all SR costs can potentially be eliminated. The table also presents the impact of implementing N-0.9 without DLR. Specifically, the data in the N-0.9 SLR column reveals that during the 10% of hours with the highest SR demand, 77.4% of the total 50.5 GWh and 22.0 MNOK are accounted for, corresponding to a 77.4% reduction in SR by utilizing N-0.9. This demonstrates that deviating from the strict N-1 grid operation policy offers substantial opportunities for cost savings, as highlighted by the results from the N-0.9 operational strategy.

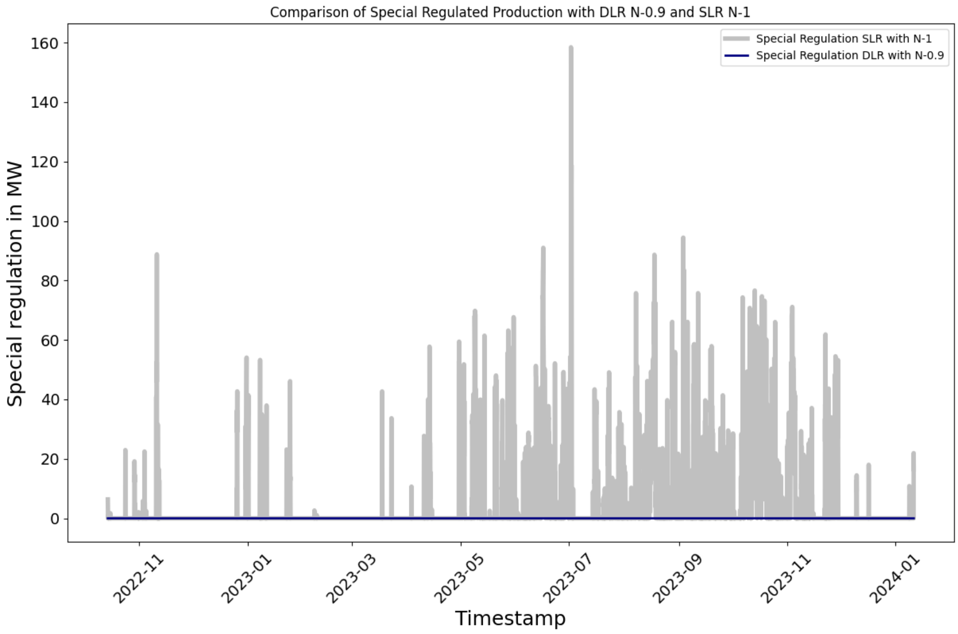

Figure 4.4: Baseline Scenario With N-0.9

Parameter	Value with SLR	Value with DLR
Hours of SR (SLR)	2220	2220
Positive DLR Hours Count	1089	2161
Negative DLR Hours Count	0	59
Total SR SLR N-1 (GWh)	50.52	
Total SR Cost SLR N-1(MNOK)	21.97	
Cut in SR with N-0.9	77.40%	100%
Total N-0.9 Gain (GWh)	39.10	50.52
Total N-0.9 Cost Saving (MNOK)	17.00	21.97
Total N-0.9 SR Cost (MNOK)	4.97	0.00
Hourly N-0.9 Coverage	49.0%	100%

Table 4.4: Parameter Results - Baseline Scenario

In this scenario, we considered a perfect N-0.9 operation in which the system operates under N-0 conditions during the top 10% of hours with the highest congestion. Practically, it would be challenging to predict precisely which hours would fall into this 90% quantile during real-time operations. However, this theoretical model highlights the significant potential of such an approach in reducing congestion and optimizing grid performance.

20% Increase in Power Flow

Since the scenario with a 20% increase in Power Flow yielded the poorest results in the evaluations detailed in Section 4.3, we continued our calculations with this scenario to avoid overestimating our results.

In this case, SR is required for 2,146 hours with DLR, as depicted in Table A.1. This indicates that even after operating under N-0 conditions for 1,089 hours, there are still 1,057 hours where SR is necessary while using DLR. The impact of operating at peak times under N-0 is evident in Figure 4.5, where we see that only moderate SR is needed for the remaining 1,089 hours.

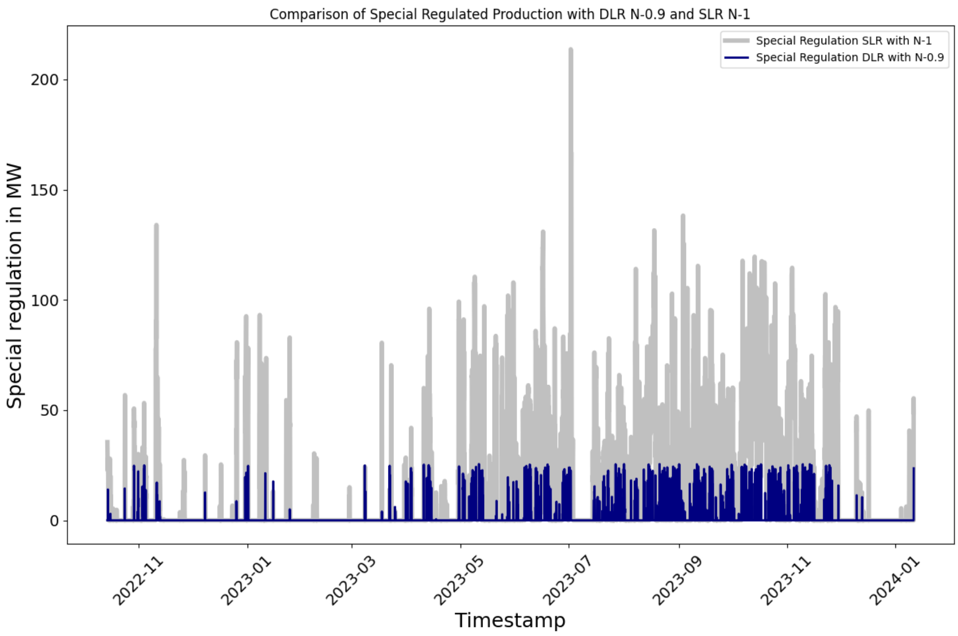

Figure 4.5: 20% Increased Power Flow With N-0.9

Table 4.5 reveals that by using N-0.9 and DLR, 90.59% of the SR, corresponding to 140.7 GWh and 61.18 MNOK, could be avoided. The cost associated with SR would then be reduced to 5.75 million, which is lower than the 7.18 million incurred under the Baseline Scenario referenced in Section 4.2. This cost is significantly less than the 28.52 million required when operating at a 20% increased Power Flow with DLR and an N-1 policy, as noted in Section 4.3. When operating with N-0.9 and SLR, the reduction in SR is 53.7%, with an associated cost of 28.33 MNOK, which aligns with the costs observed when using DLR under similar conditions in Section 4.3. This further underscores the substantial impact of the N-0.9 operation in mitigating high SR peaks. The cut in SR (90.59%) is higher than the hourly cut in SR of 87.55%, in contrast to the DLR N-1 operation, where the hourly cut in SR was higher than the total cut in SR. This is because the N-0.9 operation removes the highest peaks.

Parameter	Value with SLR	Value with DLR
Hours of SR (SLR N-1)	3860	
Positive N-0.9 Hours Count	1090	3823
Negative N-0.9 Hours Count	0	37
Total SR SLR N-1 (GWh)	140.69	
Total SR Cost SLR N-1 (MNOK)	61,18	
Cut in SR with DLR (%)	53.7%	90.59%
Total N-0.9 Gain (GWh)	75.55	127.45
Total N-0.9 Cost Saving (GWh)	32.85	55.42
Total N-0.9 SR Cost (MNOK)	28.33	5.75
Hourly N-0.9 Coverage (%)	28.15%	87.55%

Table 4.5: Parameter Results - 20% Increased Power Flow

Implementing N-0.9 alongside DLR could potentially avoid 90% of SR by 2030 without necessitating grid upgrades. This strategy offers significant advantages, especially considering the high costs and lengthy lead times associated with constructing new power grids. Additionally, employing SLR in this context accentuates the cost-effectiveness of adapting existing infrastructure in an era of uncertain future grid demands.

Power Flow Equal to Today's Cost

Through experimenting with various scaling factors for Power Flow, we found that a 38% increase in capacity using N-0.9 and DLR yielded SR costs comparable to the Baseline Scenario with N-1 and SLR, as detailed in Section 4.2. Table 4.6 indicates that the cost of operating under N-0.9 with DLR is 22.21 MNOK, nearly matching the 21.97 MNOK for the Baseline Scenario with SLR and N-1. Figure 4.6 displays the hourly distribution of MWs of SR, showing a total of 4893 hours requiring SR under N-1 and SLR conditions. Although N-0.9 with DLR effectively reduces many high SR peaks, the grid still experiences frequent congestion.

In Table 4.6, we observe that the SR cost for operating under SLR with N-1 is significantly high at 106.83 MNOK. When scaling up the flow by 38%, the SR cost for SLR N-0.9 operation decreases, but only by 43.40%, resulting in a cost of 60.46 MNOK. This suggests that, at this increased flow rate, high peaks are no longer the primary drivers of SR costs, indicating a shift in the cost-contributing factors under these conditions.

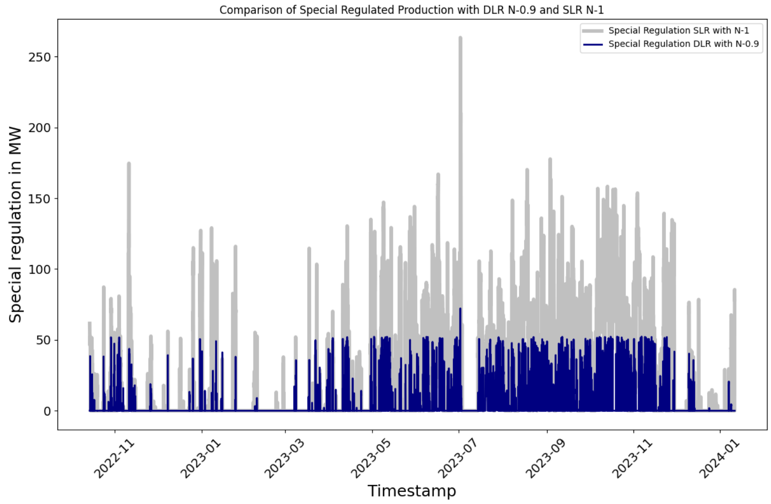

Figure 4.6: 38% Increased Power Flow with N-0.9

Parameter	Value with SLR	Value with DLR
Hours of SR (SLR N-1)	4893	
Positive N-0.9 Hours Count	1089	4797
Negative N-0.9 Hours Count	0	96
Total SR SLR N-1 (GWh)	245.70	
Total SR Cost SLR N-1 (MNOK)	106.83	
Cut in SR with DLR (%)	43.40%	79.23%
Total N-0.9 Gain (GWh)	106.64	194.66
Total N-0.9 Cost Saving (MNOK)	46.37	84.64
Total N-0.9 SR Cost (MNOK)	60.46	22.19
Hourly N-0.9 Coverage (%)	22.06%	75.49%

Table 4.6: Parameter Results - 36% Increased Power Flow

Although the cost of SR under N-0.9 with DLR would be roughly equivalent to current levels, SR would be required more frequently, leading to a more uniform cost distribution, as illustrated in Figure 4.6. This indicates that grid upgrades could be advantageous. Nevertheless, a 38% increase in power flow represents a substantial change, and given the uncertainties surrounding future power flows and grid operations, it demonstrates that the grid possesses significant capacity before SR costs exceed today's levels with the adoption of N-0.9 and DLR. This insight is crucial for future grid management and cost evaluations, enabling informed investment decisions and facilitating beneficial socioeconomic outcomes.

4.5 Limitations of the Study

This study encounters several limitations. Firstly, the accurate pricing data associated with SR was unavailable, necessitating the creation of a proxy number. Although we assume this number to be representative, it remains an assumption. Additionally, the number recorded in 2022, which we used for our calculations, was record high. When considering scaling our findings from our specific region to the entirety of Norway, we lack insights into how SR manifests across the different price zones (see Table 2.1) and the underlying factors influencing peaks, such as those caused by redispatching, which our study focused on.

The model employed is probabilistic, adding an element of uncertainty to the predictions and outcomes.

4.5.1 Real-World Application

In terms of real-world application, the primary challenge lies in maintaining continuous control over the DLR data. Our discussions have not addressed the logistics of how resources would be managed or how such a system could be implemented in reality.

Using the N-0.9 principle, we selected hours with the highest consumption peaks based on historical data. In practice, predicting which 10% of hours in a year will experience the highest peaks is challenging. This could potentially be simulated using machine learning algorithms to analyze variables historically associated with high peaks. However, implementing the N-0 solution when these conditions occur cannot be perfectly accurate.

Moreover, the hours with the highest peaks may not be suitable for N-0 operation due to extreme conditions such as snowstorms or extreme weather, which might compromise safety. Additionally, it remains uncertain whether there will be sufficient consumer demand for electricity under non-N-1 operating conditions who are willing to accept the associated risks.

We have only calculated potential savings without considering the costs of implementation or the expenses related to network losses.

4.6 Regarding Previous Literature

Most literature on DLR and alternatives to the N-1 standard relies on simulations of both DLR and dispatching, making direct comparisons with this thesis challenging. In Section 2.3, we review research on dispatch costs, and our findings indicate a more significant impact of DLR on redispatch than previously reported. However, comparisons are difficult due to the many factors influencing DLR's effectiveness.

We believe that our study, grounded in descriptive data and precise measures from Heimdall Power's technology, offers an accurate contribution to existing research.

As for deviations from the N-1 criteria, no prior research specifically addressing SR costs was found. Previous studies primarily focus on integrating renewable energy sources and grid upgrades. Our approach to implementing N-0.9 grid operation, inspired by the recommendation from Alexandersson et al. (2022), presents an innovative yet straightforward solution that leverages descriptive data for robust and clear outcomes. Nonetheless, comparing this method with earlier studies remains challenging due to its unorthodox nature.

The primary goal of this study is to generate interest and motivation for further exploration in this field. It is the first study of its kind to examine this type of case on descriptive data. Despite its limitations, the potential for substantial cost savings is clear. We hope that our findings will inspire additional research and improved use of the network, benefiting both the industry and academic research.

5 Conclusion

This thesis has examined the impact and potential of DLR technology on Norway's power grid, particularly focusing on its ability to reduce SR costs, which have reached record highs in recent years. Driven by Norway's escalating energy demands, this investigation was structured around three research questions: evaluating historical efficiency, projecting future savings, and exploring the alternative grid management strategy N-0.9.

DLR offers a more efficient alternative for utilizing existing grid capacity. Although DLR does not increase the grid's physical capacity, it enhances the ability to operate on higher levels. This technology reduces the need for traditional grid upgrades by optimizing the use of current grid capacities without compromising on grid security

We observed that DLR achieved a capacity gain of 20% in terms of historical efficiency. Had UDSO-NO4 utilized DLR instead of SLR, the costs associated with SR could have been reduced by 14.79 million NOK, representing 67.31% of the total 21.97 million NOK spent by Statnett in the time period. When scaling this up to the whole of Norway, the savings could be conservatively 228.85 million NOK.

From the future scenarios, both the 20% Power Flow increase and the 20% Fixed Gain exhibited similar frequencies of SR. However, the Fixed Gain scenario achieved greater SR cost savings compared to the Power Flow scenario. This suggests that the peak loads predominantly drive the need for SR, which are more pronounced in the Power Flow scenario. The 10% Fixed Gain scenario yielded the most substantial savings, yet these were still lower than those observed in the Baseline Scenario, indicating a diminishing impact of DLR on SR as power levels increase. Nonetheless, significant savings are still achievable: 53.38% in the 20% increased Power Flow scenario, 63.14% in the 10% Fixed Gain scenario, and 59.72% in the 20% Fixed Gain scenario.

We observed significant results with the alternative grid management strategy, N-0.9. In the Baseline Scenario, using both DLR and N-0.9, the reduction in SR was 100%. Even with SLR, we achieved a 77.4% reduction. In scenarios with a 20% increase in Power Flow, the reduction in SR could reach 90.59%. The socioeconomic benefits of this approach are significant, particularly considering the lengthy lead times and high costs associated with grid upgrades in a market filled with uncertainties about the future of the grid.

By implementing N-0.9 alongside DLR, we managed to increase Power Flow by 38% while maintaining SR costs comparable to the Baseline Scenario operating with N-1 and SLR. This substantial upscaling reveals the grid's previously untapped capacity. Demonstrating that the grid can accommodate significant increases without surpassing current SR costs provides crucial insights for more efficient future grid management and strategic investment decisions.

With this master's thesis, we hope to have highlighted an area within the current system that holds the potential for significant savings, both now and in the future.

5.1 Future Work

As mentioned previously, we did not receive accurate prices for SR. It would have been preferable to perform calculations using the actual prices. If these become available, incorporating them into further research would be interesting.

Also, from Section 2.1.5, we highlighted that the TSO pays the redispatch cost in the SR even though the congestion happens in the DSO's network. The DSO does not have any incentive to upgrade the network, so the TSO avoids the cost of SR. The economic burden ultimately falls on the end customer, both private and corporate, as the SR costs are incorporated into their network charges. Therefore, the 14.79 million of NOK is paid by consumers but could have been avoided by leveraging DLR. A potentially interesting aspect for further research is this dynamic interaction between the TSO and the DSO.

The thesis has focused on a specific region and section of the grid. Future research should encompass larger geographical areas to provide a more thorough analysis. Additionally, the cost implications of DLR and alternative solutions, such as N-0.9, require further investigation.

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A Appendix

A.1 20% increase in Power Flow

Parameter	Value
Hours of SR (SLR)	3860
Hours of Special Regulation (DLR)	2146
Positive DLR Hours Count	3749
Negative DLR Hours Count	111
Total SR SLR (GWh)	140.69
Total SR Cost SLR (MNOK)	61.18
Cut in SR with DLR	53.38%
Total DLR Gain (GWh)	75.10
Total SR Cost DLR (MNOK)	28.53
Total DLR Cost Saving (MNOK)	32.65
Hourly DLR Coverage	65.61%

Table A.1: Parameter Results - 20% Increased Power Flow

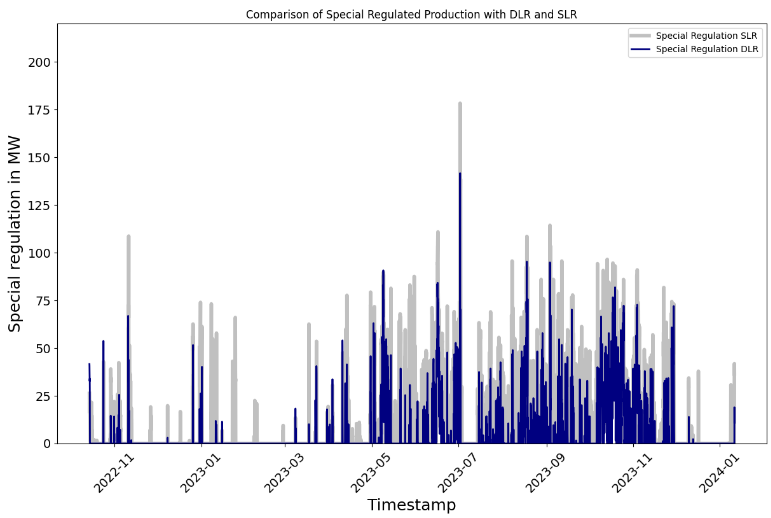

Figure A.1: 20% Increased Power Flow.

A.2 10% Fixed Gain

Parameter	Value
Hours of SR (SLR)	2947
Positive DLR Hours Count	2866
Negative DLR Hours Count	81
Total SR SLR (GWh)	76.53
Total SR Cost SLR (MNOK)	33.28
Cut in SR with DLR	63.14%
Total DLR Gain (GWh)	48.32
Total SR Cost (MNOK)	12.28
Total DLR Cost Saving (MNOK)	21.00
Hourly DLR Coverage	73.12%

Table A.2: Parameter Results - 10% Fixed Gain

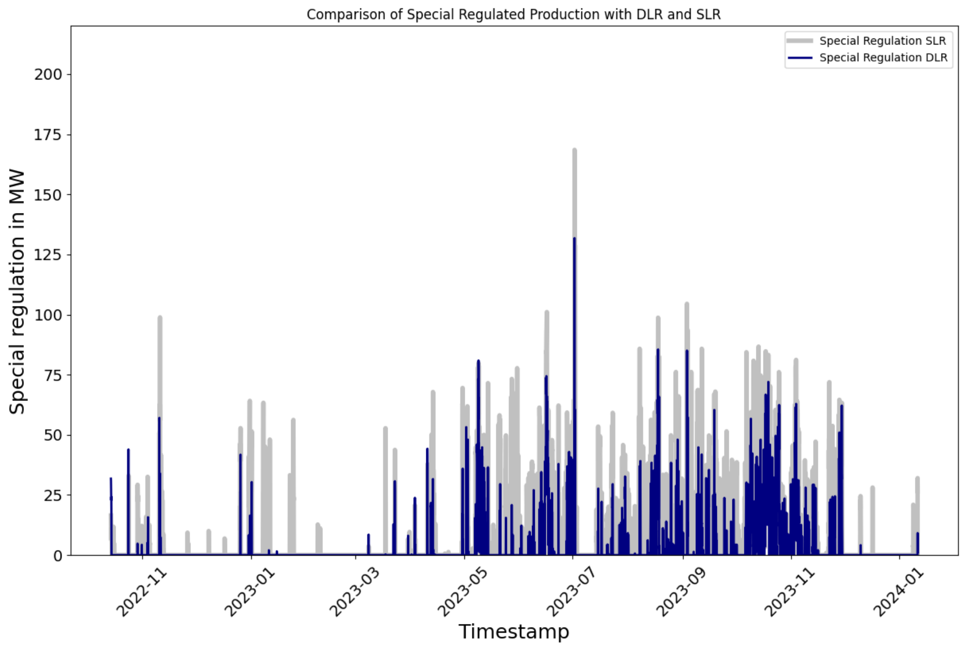

Figure A.2: 10% Fixed Gain.

A.3 20% Fixed Gain

Parameter	Value
Hours of Special Regulation (SLR)	3714
Positive DLR Hours Count	3611
Negative DLR Hours Count	103
Total SR SLR (GWh)	109.43
Total SR Cost SLR (MNOK)	47.58
Cut in SR with DLR	59.72%
Total DLR Gain (GWh)	65.35
Total SR Cost DLR (MNOK)	19.16
Total DLR Cost Saving (MNOK)	28.42
Hourly DLR Coverage	69.18%

Table A.3: Parameter Results - 20% Fixed Gain

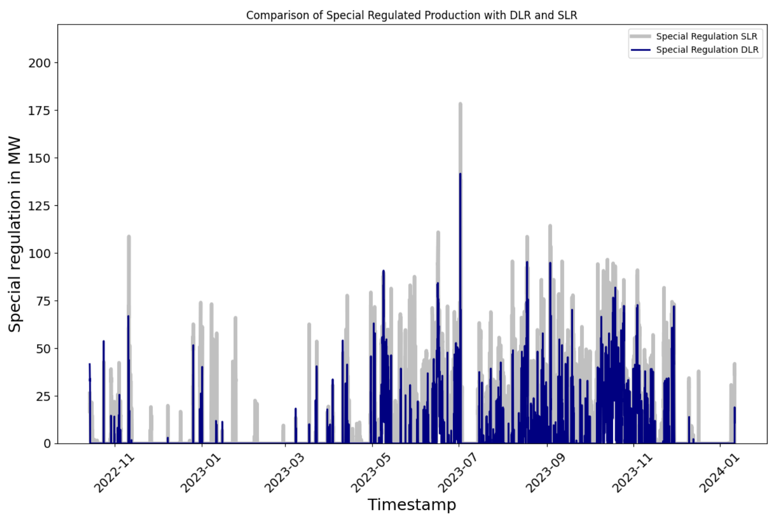

Figure A.3: 20% Fixed Gain.

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