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Case Study: Self-Interest for Microgrids in Providing Peak Shaving and Congestion Management Services

Master's thesis in Energy and Environmental Engineering
Supervisor: Gro Klæboe
Co-supervisor: Stine Fleischer Myhre
June 2021

Master's thesis

NTNU
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Abstract

Recent years have seen an increase in non-dispatchable energy resources and a changing power consumption pattern. With his trend expected to continue, DSOs[1] anticipate a rise of power congestion issues in transmission lines. Many points towards flexible resources being the most cost-efficient solution for addressing this issue. Flexible resources can be regarded as systems with controllable power production and/or consumption. Microgrids are an example of this.

The case study in this thesis regards a microgrid and the operation of its flexible resources. The objective of the case study is to determine if the existing Norwegian market model and regulations facilitates for the self-interest of market players in providing peak shaving and congestion management services. The self-interest lies in the economical gain from utilising storage systems for power trading that exploits price fluctuations. The thesis argues that a correlation between electricity prices and congestion tendencies in the local distribution grid makes power trading implicate congestion management. To prove this, several MPOPF[2] problems are formulated. These help in identifying in which areas the objectives of a microgrid owner and the DSO coincide.

The quantitative results from the simulation of the case study model suggest that there are economical incentives for storage system operators to provide peak shaving and congestion management services in a system where they are strictly motivated by *market-based drivers* [3]. It also indicates how implementing a nodal pricing model, compared to the existing zonal pricing model, would strengthen the correlation between electricity prices and congestion tendencies in the local distribution.

[1]Distribution System Operator

[2]Multi-Period Optimal Power Flow

[3]Refers to a market that establishes price signals which encourage a certain interaction.

Sammendrag

Det har de siste årene vært en økning i uregulerbar kraftproduksjon og et endret forbruksmønster hos sluttbruker. Analyser av den langsiktige utviklingen i kraftsystemet tilsier at denne utviklingen vil fortsette. Dette fører til at operatører av distribusjonsnett forventer en økning flaskehalsproblematikk. I denne sammenheng peker mange mot at fleksible ressurser er den mest kostnadseffektive løsningen. Fleksible ressurser er definert som systemer med regulerbar kraftproduksjon og/eller -forbruk. Mikronett er et eksempel på dette.

Case-studien i denne oppgaven tar for seg et mikronett og driften av dets fleksible ressurser. Målet med case-studien er å avgjøre om den eksisterende norske markedsmodellen og regelverket medfører en implisitt egeninteresse for markedsaktører i å tilby toppkuttingtjenester. Denne egeninteressen ligger i den økonomiske gevinsten ved å bruke lagringssystemer for krafthandel som utnytter prissvingninger. Oppgaven argumenterer for at en sammenheng mellom strømpriser og flaskehalstendenser i det lokale distribusjonsnettet gjør at krafthandel medfører flaskehalshåndtering. Som grunnlag for studien formuleres flere MPOPF[1]-problemer. Disse optimeringproblemene kan bidra til å identifisere på hvilke områder målene til en mikronett-eier og operatører av distribusjonsnett sammenfaller.

De kvantitative resultatene fra modellsimuleringen i case-studien antyder at det er økonomiske incentiver for eiere av lagringssystemer til å tilby toppkutting og flaskehalshåndtering i systemer hvor disse er utelukkende motivert av *markedsbaserte virkemidler*[2]. Resultatene indikerer også hvordan en innføring av nodeprising vil styrke sammenhengen mellom strømpriser og flaskehalstendenser i det lokale distribusjonsnettet sammenlignet med den eksisterende soneprissystem.

[1]Multi-Period Optimal Power Flow

[2]Refererer til markeder der det etableres prissignaler som fremmer et gitt bruksmønster.

Preface

This master's thesis was completed the spring of 2021 at the Department of Electric Power Engineering and concludes our education at the Norwegian University of Science and Technology, NTNU.

We address our sincerest gratitude to our supervisor, Gro Klæboe, and co-supervisor, Stine Fleischer Myhre, for your guidance and feedback. Your exceptional support and availability were highly appreciated. We are grateful for the productive and rewarding cooperation with you.

We would also like to thank Ph.D. candidate Per Aaslid for your insights.

Trondheim, June 2021

Elias Heimland　　　　Aasta Gran Andreassen

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Abbreviations

AC Alternating Current

BESS Battery Energy Storage System

DC Direct Current

DER Distributed Energy Resource

DOD Depth of Discharge

DOPF Dynamic Optimal Power Flow

DSO Distribution System Operator

EV Electric Vehicle

HESS Hydrogen Energy Storage System

IPOPT Interior Point Optimisation

MG Microgrid

MPOPF Multi-Period Optimal Power Flow

OPF Optimal Power Flow

PV Photovoltaic

SOC State of Charge

VER Variable Energy Resource

Chapter 1

Introduction

1.1 Context

The primary task of all distribution system operators (DSO) is the operation and development of perhaps the most important infrastructure in modern society - the distribution system. The last decades have seen a considerable increase in electricity demand and is expected to increase in years to come. Power market analyses estimate that the Norwegian electricity demand will rise to 163 TWh in 2040, an increase of 26 TWh from 2020 estimates [1]. This increase is in contrast to the expected decrease in electricity consumption of households and commercial buildings due to heightened energy efficiency of appliances [1]. The increase in electricity demand is mostly a result of the accelerated electrification of former non-renewable dependent appliances and installations - both in the private and corporate sector [1, 2].

As climate change and energy transition receive more and more attention, a shift towards an increased proportion of renewable non-dispatchable energy resources in the electricity market is expected. The Nordic electricity market has a 20% proportion of solar and wind power, as of 2020, which is expected to rise to 40% in 2040 [1]. With the decreased electricity market proportion of dispatchable electric energy, several challenges arise from the lack of controllability. In many cases, this will involve grid reinforcements or installation of flexible resources that can help maintain production/consumption balance and power quality [1].

The most promising technologies within flexible storage options are batteries and hydrogen storage units [1]. These technologies, in conjunction with smart control systems, constitute the most valuable resources for power systems with increased penetration of variable energy resources (VER) [1]. Wind and photovoltaic (PV) energy production units are inherently volatile and difficult to control, introducing the possibility that they can produce energy during low electricity demand periods or causing power flows that exceed rated limits of transmission lines. Areas with large amounts of VERs could consequently experience an increasing number of congestion events and will largely benefit from the installation of flexible storage options. DSOs could alternatively commit to investing in grid infrastructure. This investment can in many cases be excessive and only serve its purpose for a limited time during peak operational hours of the distribution grid. Deferring from these costs will therefore often be reasonable in situations where local energy storage is an option [3].

Microgrids are self-reliant energy systems. These grids are typically designed to be disconnected from the main distribution grid. They produce, store and consume electric power independently of the surrounding distribution grid. Microgrids could, however, prove to be more efficient when cooperating with the distribution grid. An ancillary service market will in many cases be beneficial for both the microgrid owner and the DSO. Microgrids can provide ancillary services such as voltage control, congestion management, and peak shaving to the distribution grid. As identified in the previous section, one of the most prevailing trends in the future distribution system is a growing penetration of variable energy sources which could indicate that the most urgent issue is congestion management and peak shaving.

In an ancillary service market there have to be incentives in place for either party to provide a service. By providing congestion management to the distribution grid the microgrid owner can be economically incentivised through direct reimbursements from the DSO. This thesis will, however, propose a model where the microgrid owner is indirectly incentivised towards providing ancillary services through the exploitation of market price fluctuations.

1.2 Objective

This thesis will investigate how the existing Norwegian market model and regulations facilitate for the self-interest of market players to provide peak shaving and congestion management services. By the self-interest of market players it is implied that the market players are incentivised to provide these services without the need for contracts with the DSO, but strictly motivated by market-based drivers.

Can the microgrid owner profit from providing congestion management and peak shaving without direct incentives from the DSO? How do the objectives of the microgrid owner and the DSO coincide? The case study, presented in Chapters 4 and 5, will conduct several multi-period optimal power flows (MPOPF) on a system that includes a microgrid and the surrounding distribution grid. The thesis will also aim at identifying factors that potentially inhibit or ratify the successful application of the operational strategies in the model to real-life systems. Are there other market pricing schemes and regulations that could encourage DSOs and owners of flexible resources to adopt these strategies?

The case study is based on Rye Microgrid. The microgrid has a wind turbine, a solar power plant, and storage units. The simulations will utilise measured power production and load data from the microgrid. The costs will be based on Elspot prices from NordPool. The optimisation models adopt a deterministic and nonlinear approach to the problems and constraints.

1.3 Outline

The report consists of eight chapters will the following content.

- Chapter 1 - Introduction
- Chapter 2 - Distribution Grid Operation: Current Status and Development
Provides motivational background for the proposed concept. Elaborates on future tendencies and the current situation of the Norwegian distribution grid. The main subjects are distribution grid development, power system flexibility, regulations, and market models.
- Chapter 3 - Multi-Period Optimal Power Flow: Theory and Applications
Gives a detailed background on the MPOPF and shows how this method is utilised in other studies.
- Chapter 4 - Rye Microgrid
Presents the technical overview of the case study object, Rye Microgrid. The majority of this chapter is information replicated and reused from the specialisation project written by the authors (unpublished work, referenced in [4]). This thesis overlaps with the specialisation project in terms of the case study object.
- Chapter 5 - General Methodology and Modeling
Describes the structure and specification of the system and mathematical model. Formulates the optimisation model.
- Chapter 6 - Results
Contains the main results from the simulations of the three cases and a sensitivity analysis of the battery size in one case.
- Chapter 7 - Discussion
Interprets and compares the case results and puts these into context with relation to the gradually changing power system and how market players are being incentivised.
- Chapter 8 - Conclusion
Summarises the main findings of the thesis.

Chapter 2

Distribution Grid Operation: Current Status and Development

With a growing focus on renewable energy sources, energy efficiency, and smart control systems, the composition and the operation of the electric grid is facing major changes. The evolution of the grid is central in the electrification of the society, which is required to attain the Norwegian goal to become a low emission society by 2050 [5]. New dynamics and challenges are present in many dimensions of the grid. Consumers, producers, and grid operators will have to adopt new technology, strategies, and habits. Future challenges and the solution to these will require a higher level of interaction and communication between grid users. The utilisation of power system flexibility and legislative standards will be defining for an efficient operation of the future grid. Section 2.1 will present future changes to power system units and trends, while also seeing the overall effect on the distribution grid. Section 2.2 will acknowledge these and examine the potential for employing them and existing systems as flexible resources. The extent of the efficiency and profitability in employing these is largely determined by laws, regulations, and the associated pricing scheme presented in Section 2.3.

2.1 System changes

Emerging technology, such as smart meters and accessible PV units, is increasingly available for users of the grid and can considerably affect power profile patterns. Additionally, an increase in distributed generation is expected, both as stand-alone systems and energy resources for prosumers or microgrids. In accordance with a developing end user and its characteristics, the DSO and distribution grid has to advance concurrently by evolving its strategy and end-goals.

2.1.1 Loads

The overall electricity demand in Norway is expected to grow in the coming years, mainly from the electrification of the oil sector, the transport sector, and new industries, such as data centres and hydrogen production [1]. With regards to the low- and medium-voltage distribution grid, the primary impact will arise from the electrification of transport, and smaller industries. This is in contrast to the decrease in demand from residential loads, which are becoming more energy-efficient [1].

New types of loads are emerging in the distribution grid with the electrification of the transport sector. Currently, 12% of the personal cars in Norway are electric, and the share is expected to grow further [6]. Electric vehicles (EV) pose as a challenging load for the DSO and could encourage grid upgrades as they operate at a large power outtake capacity, generally at a specific time of the day. EV has the potential to take a valuable part in peak shaving, as they can be shifted to charge during low demand periods by adopting a smart operation system [7]. The collective impact from end users that employs smart charging strategies could help alleviate issues imposed by the gradually increasing share of EVs in Norway.

A general trend is that the amount of power electronics is increasing in the network. Power electronics are used for the connection of DC components such as batteries and PV units, but also for regulating purposes associated with connecting wind turbines, or in control systems. Power electronics add harmonic components to the power and can worsen the power quality of the grid [8]. Mitigating for these effects is essential for the DSO - often a subject for ancillary services (see Section 2.2.3).

A typical load pattern for a Norwegian end user is high load during the day, especially around 8 am and 6 pm, and low during the night (based on the standard described in [9]). The general trend is that the load is high in winter due to electric heating, and lower during summer.

2.1.2 Distributed Generation and Energy Storage

Distributed energy generation is expected to grow in the coming years in Norway, mainly in small-scale hydropower stations, but also as wind turbines and solar panels [10]. This increase is a consequence of an evolving and more available technology. The evolution in smart grids and grid monitoring is also helping exploit the potential of smaller and local production.

With the increase of intermittent generation appliances, the power production can be unpredictable and variable. Storage systems will be an important part of containing this uncertainty. Various technologies allow for energy storage. Batteries are the most common as they are the most developed technology and readily available in the market. An advantage of batteries is the short response time [11]. Another emerging technology is hydrogen tanks. The response time is longer, and the efficiency is often lower. In contrast to battery energy storage, hydrogen has a considerable advantage in transportability and its higher energy density [12].

A growing part of the distributed generation originates from prosumers. Prosumers are grid users that act as small-scale power producers in addition to being a power consumer. This growth can be a consequence of increasing interest and knowledge of distributed generation and the profitability of installing them. It is also associated with the decrease in installation and unit cost, hence more available products and systems. In Norway, the expected growth within solar power is mainly through rooftops and integrated into roof panels [1].

2.1.3 Microgrids

A microgrid is a defined electrical network composed of loads and distributed energy resources (DERs) that acts as a single controllable entity [13]. Microgrids enable both off-grid and on-grid operation. A common strategy will be to maintain a distribution grid connection for the majority of the time. In the occurrence of a fault in the distribution grid that could inhibit normal operation in the microgrid, it can go off-grid and be self-reliant. When connected to the grid, the microgrid will provide power in periods of excess power.

A microgrid is often composed of renewable energy resources with unpredictable production. To account for imbalances in power demand and production, controllable units, such as storage systems and diesel generators, are installed. Energy storage is a valuable capability for the flexibility in the grid. It facilitates fully exploiting energy from intermittent resources by storing energy in periods of excess power and providing energy in periods of excess demand.

2.1.4 Distribution Grid

A lot of the overhead lines in the distribution grid in Norway are from the 70s and 80s [14]. In light of increasing electricity demand, older transmission lines can be considered as limiting for this development. To help control and monitor the condition of the distribution system several tools are employed. Among these are smart- and self-monitoring substations and smart-metering to surveil consumption patterns [5]. The value of these components lies predominantly in data collection.

Historically it has been common practice to excessively design the distribution grid, and a predict-and-provide process was employed when planning the network. This would often mean that the capacity of the grid corresponds to the worst-case scenario. Now, with the rapid deployment of distributed generation, the grid is developing towards a react-and-provide process [15]. This transition can be a difficult task for the grid operator but is enabled by increased availability of data and better operation algorithms.

2.1.5 Effect on Distribution Grid

Multiple future scenarios can be formulated on the basis of the aforementioned changes in the distribution grid. An example of such scenarios are presented in [5]. The four main scenarios for future distribution grid in 2030-2040 represents a variation of the combination of customer development and grid development and include:

- *Flexible and intelligent grid* - Digitalised grid and active users
- *Automated grid* - Digitalised grid and passive users
- *Grid as back-up* - Analog grid and active users
- *Business as usual* - Analog grid and passive users

The *flexible and intelligent grid* scenario is preferred. This scenario will employ a bidirectional flow of data between the end user and the DSO. It will largely depend on the mutual interaction on the operation of the distribution grid. The power system will have active end users and power appliances that adopt strategies that promote flexibility. The realisation of this scenario could prove to be resource-intensive and could be entirely contingent on how end users are being incentivised. This regards willingness to invest, costs and regulations [1].

2.2 Power System Flexibility

In this section, opportunities and challenges associated with power system flexibility and variability will be discussed. As identified in Section 2.1, the increasing penetration of intermittent energy resources introduces variability in the network. In order to balance and control this tendency, DSOs employ flexible solutions to ensure a rigid power system. The transition into a flexible power system requires a well-developed communication infrastructure, but also laws, regulations, and pricing schemes that enable it. Power system flexibility can be regarded as an ancillary service - a service provided by end users to the DSO.

2.2.1 Integrating Variable Energy Resources

Distributed production and flexible loads can be regarded as a value to the grid as they can contribute to better security of electricity supply in terms of energy availability, power capacity, reliability of supply, and power quality [16]. They provide local generation which minimises the line losses, are not affected by congested transmission lines, and can supply local power quality services to the distribution grid.

When connecting distributed generation in the distribution grid, several measures have to be taken. The line capacity and the thermal limits in the grid have to be held, as well as keeping the power balance stable [10]. The market framework and agreements must align themselves with the objective of the prosumer and the DSO. New prosumers in the grid must be properly integrated. Being a relatively new actor, prosumers are subjugated to limiting laws and regulations, and it can therefore be difficult for them to take an active part in the distribution grid. The grid operator must set premises for connecting these to the grid without compromising the functioning of the grid and the interests of the actors. The market regulations will largely dictate how the distribution grids of the future will be. The biggest barrier facing these projects is the lack of a well-defined business model since there are generally no existing markets or other standardised commercial arrangements in place for the services provided by local energy communities [17].

There is also a potential risk in introducing intermittent resources. The grid will be more vulnerable as a result of its dependency on probabilistic forecasts and trends, thus relying on accurate communication systems [18].

2.2.2 Data Availability

As indicated in the previous section, network flexibility is reliant on reliable information about grid operational status. Smart meters are one of many appliances that provide insight into this. To ensure the stability of the grid, several metrics and variables must be analysed. The increased deployment of storage systems in the network in combination with a more digitalised grid, such as smart metering, will enable end users to respond to local price signals and other control signals [19]. DSOs are concurrently getting access to better real-time data - a necessity for efficiently managing congestion in low-voltage grids [19]. Information about power flow and power demand enables for locating congestions and sinks in the grid, allowing the DSO to optimally diverge power.

Further, operational data is used in simulation and modelling tools to develop well-suited prediction models. With precise prediction models, the network can react to the volatility from the renewable resources and from the new load patterns. Flexible networks are more dependent on a good probabilistic methodology in order to keep the security of supply [16]. This will make the grid more robust, as it can adapt to grid anomalies more easily and cost-efficiently, as there is less need for excessively designing utilities.

Operational data is used in models and simulations to help identify requirements for the future grid. These requirements will contribute to streamlining the design of new grid elements, often meaning that they will reflect and respond to local grid characteristics. The installation and integration of microgrids and multi-infrastructure, such as smart cities, is dependent on accurate models and data availability [15].

With the increasingly large portion of flexible resources in the grid, new risks associated with communication systems emerge. In areas where VERs are becoming more prevalent and defining for power system operation, so is the gain from targeting these for malignant (cyber) attacks [16]. This can threaten the security of supply.

2.2.3 Ancillary Services

The goal of the grid operator is to provide a robust and cost-efficient network. This will mostly regard ensuring the security of supply and maintaining stable operational characteristics. The system operation can be supported by ancillary services. Ancillary services are services that are supplied by generation, transmission, and control equipment in the network [20]. The system operator can buy ancillary services to supplement existing generators and power appliances to ensure a reliable supply with a good power quality [21]. It can also help mitigate power flow issues and guarantee a faster recovery after a disturbance [22]. Ancillary services include voltage regulation, harmonic compensation, and several services related to power balancing, as spinning reserve, load following, backup supply, and peak shaving [23, 24].

The operational responsibility lies with the DSO and is thus compelled to ensure the delivery of power. The existing overhead transmission lines may pose as an inhibiting factor for growing electrification in Norway. The DSO would consequently be forced to take action. Peak shaving is a common method for mitigating congestion issues and will often be the most cost-efficient option for this problem. The goal of peak shaving is to limit the largest power demands in the network. It can be performed either by reducing the total power demand or by shifting the power usage to an off-peak period.

2.2.4 Peak Shaving and Congestion Management

The transmission line, thus its rating, is designed to sustain normal peak power flows. In the event of a transmission line sustaining large power flows that exceeds a certain limit it may experience congestion issues. Frequently occurring congestion issues could incur implementing ways to manage this. Transmission line congestion is a gradually increasing problem, both for regional and distribution level networks [19]. Ways to manage these efficiently are, however, emerging concurrently.

As discussed in Section 2.1, the loads are evolving towards larger peaks for shorter time periods, e.g. charging of electric vehicles or ferries. The DSO may be compelled to perform peak shaving in order to meet the requirements for this type of load and an overall increasing and varying demand. Peak shaving refers to leveling out peaks in the electricity demand. This will implicitly lead to valley filling - shifting the electricity demand to periods of low demand. A typical load pattern can be seen in Figure 2.1. The impact of peak shaving (labeled *power peak*) and valley filling (labeled *recharge period*) is depicted by the red line. The blue line represents the load prior to peak shaving.

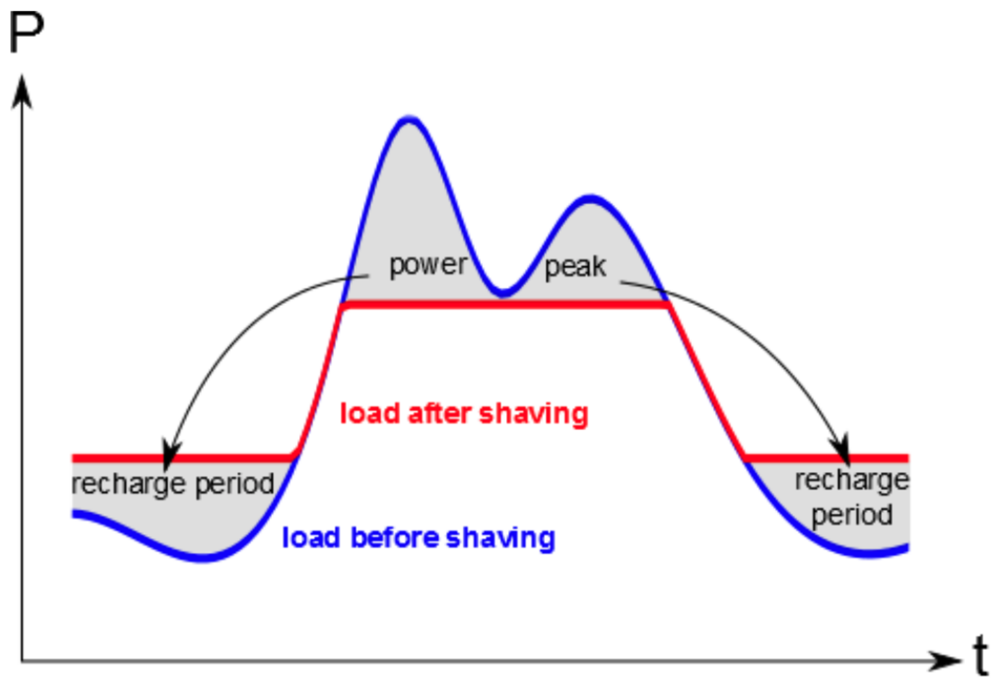

Figure 2.1: Peak shaving principle [25].

A limiting factor for the flow over the line is the line temperature [26]. With a larger current, the line heats up. For most lines, a stable temperature is reached within approximately 5-30 minutes depending on line characteristics [27]. This means that a flow exceeding the rating for a short period will not necessarily exceed the temperature limits. However, for longer periods, a large power flow will heat up the line and can cause permanent damage [28]. Congestion is one of the key issues that must be addressed to hinder high temperatures.

An alternative way of performing congestion management is transmission line reinforcements or the installation of parallel transmission lines, thus increasing overall power transfer capacity. An advantage of this solution is that it requires little to no active control in order to serve its purpose, standing in contrast to active management solutions such as peak shaving. Managing congestion issues by investing in grid infrastructure is likely to become more expensive in the future compared to earlier [19]. This is due to the installation of new renewable energy resources, such as PV units, and small-scale hydropower and wind power [19]. The grid operator can also increase the transmittable capacity by performing smaller grid reinforcements, for instance by installing reactive power compensators or additional transformers. The grid operator can defer investments in grid reinforcements by reducing the peaks. As seen in the previous sections, the future power demand is unforeseeable and large capacity upgrades may be excessive if the load demand decreases [5].

The strain on transmission lines can also be alleviated by decreasing overall power demand during peak operation periods. This strategy can be employed in two ways: either by an end user that actively lowers its consumption or the DSO performing load shedding. Load shedding is the deliberate shutdown of electric power in a distribution grid, i.e. causing blackouts. It is a controlled option for responding to unplanned events [29]. This is done to protect the power system from damage that can arise from power system imbalances in demand and production. For Norwegian DSOs, this would imply large expenses related to energy not supplied.

A more available and viable solution for decreasing power demand in peak power flow periods is to perform peak shaving by shifting the power consumption, which is the case illustrated in Figure 2.1. The end user can shift parts of its load, for instance by charging their electric car during the night. Methods for incentivising end users to do this are described in Section 2.3.

Another solution is to use the flexibility from storage systems [19]. By charging when the demand is low, the energy is available locally on the downstream side of the limiting line when the demand is high. Thus, the total load, as seen from the congested line, is changed without affecting the load profile of the end users. Implementing nodal prices could encourage the extended use of flexible resources for congestion management (see Section 2.3.2). This would also apply to load shifting.

Further, the peak load in a distribution system can be defined as the local load subtracted by the local production. Thus, peak shaving can be obtained by local power generation. Power is, therefore, produced locally and the peak power demand from the overlying grid is reduced [30].

Peak shaving is also an advantage for the participants in the power network. The power producers will not need backup generators to stand by, and can reduce their operation and maintenance costs [31]. Consumers can reduce their costs by shifting the load from peak to off-peak periods, and take advantage of lower electricity prices.

2.2.5 Flexibility Resources

Flexible resources have a large potential for providing ancillary services to the distribution grid. The main focus of this thesis will lie with peak shaving, but flexible resources are associated with other ancillary services as well. In transitioning towards a more integrated and complex system, flexible resources, such as energy storage systems, are increasingly being deployed. Flexible resources enable having active end users that provide power generation at the distribution level. This will allow for the power system to progress from the traditional one-way system [18]. The case study in this thesis concerns a microgrid with battery energy storage systems.

Battery Energy Storage Systems

Battery Energy Storage Systems (BESS) can contribute with several services to the grid, and be beneficial for several grid actors [1]. The study in [32] investigates for which ancillary service utilising battery energy storage systems would be most cost-efficient. It finds that applying BESS's to power trading, voltage control with active power, and congestion management will maximise their utility.

The use of batteries in the power trade is driven by changes in power prices. The battery will charge when the price is low and discharge when it is high. Thus, the battery owner will make a profit by exploiting fluctuations in electricity prices. This requires that the high power prices are for example 20% larger than the low power prices, if one expects 20% losses in battery charge/discharge cycles [32].

In congestion management, batteries are utilised for manipulating the load profile of a system by shifting the power consumption. This operational strategy is implemented in systems downstream of congested transmission lines, effectively decreasing the largest power flows. This is a solution for short-term congestions during a period of the day. The battery will charge in periods of low line flows such that the peaks are reduced. The system affected by the congested line will have the same load demand but will get the power from the battery instead of importing it over the line.

Additionally, the battery can perform other ancillary services to support the power quality in the grid [1]. It can deliver voltage and frequency support, and be used for reactive power compensation.

Microgrid

When microgrids are connected to the grid, it can provide flexibility through the implemented storage and production devices. The microgrid can provide ancillary services to the DSO, such as peak shaving.

The integration of microgrids in the distribution network introduce both challenges and opportunities. Microgrids can affect the grid performance with better power quality and reliability, but will also require larger cooperation with the DSO [33]. Business cases for integration of microgrid include the ownership constellation, the commercial potential, and the regulatory conditions [34].

In addition to being a flexible resource for the DSO, the microgrid owner can also benefit through power trading. The microgrid owner profits from electricity price variations. With a correlation between the electricity price and the load profile, power trading can prove to be profitable for both the DSO and the microgrid owner.

With a large storage capacity, the microgrid can go off-grid even in areas with low availability of renewable energy [35]. However, in order to drive the microgrid owner to connect the microgrid to the overlaying grid, there must be some advantages. The advantage for the microgrid to be connected to the distribution grid is to avoid using the backup generators, and economic compensation. In locations with large grid connection costs, it is more profitable to go off-grid for the microgrid [35].

Microgrids can also contribute with several ancillary services to maintain the stability of the distribution grid. Some ancillary services include voltage regulation and reactive power compensation, peak shaving and congestion management [33, 24]. This can help with energy savings, improved reliability and investment postponement [34].

As mentioned, an on-grid operation of Rye Microgrid will enable for provision of alternative ancillary services. Some of these services will, per contra to the strategies implemented in the thesis, not have the inherent self-interest associated with peak shaving and congestion management services that gets supplied through power trading. They will instead largely depend on new regulations and economic compensation from transmission and distribution system operators.

An example of an existing microgrid in Norway is Sandbakken Microgrid. The microgrid is connected to the distribution grid on the island of Kirkøy in Hvaler. It is supplying a waste reception station and produces power from PV units and wind turbines, with a total generation of 171 MWh per year. The microgrid is equipped with a battery energy storage system of 260kWh capacity [36]. The first priority of the operation of Sandbakken is maximum self-consumption and will secondly act as a flexible resource for the DSO. The battery energy storage system installed in Sandbakken provides peak shaving as a service for the local DSO [37]. This is reflected in the pricing strategy. Sandbakken adopts a local pricing model, that is based on price bids from local consumers and compared to a minimum price depending on the state of charge of the battery [38]. Sandbakken microgrid can be self-reliant for 20 hours [36].

2.3 Regulations and Market Models

There are several regulations that apply to an end user in a network. This includes power system licensing (i.e. wind turbines and PV farms), trading licenses for trading in commercial power markets (i.e. NordPool), network tariffs, and connection-point regulations. Another increasingly important feature of the power system is how consumers and prosumers are encouraged to interact and contribute to efficiently operate the power system. Applying variations of market pricing schemes and giving incentives through network tariffs could largely influence end user operation, cost, and earnings.

There are generally two ways to encourage end users for regulating consumption and production [19]:

- *Market-based instruments* - This method is based on establishing price signals that reflect capacities in the surrounding area of end users as part of a power market. This method is presented in Section 2.3.2.
- *Incentive-based instruments* - This category will regard regulating network tariffs to reflect capacities in the surrounding area of an end user. Adjusting the capacity-based tariff and discounting for interruptible contracts can provide incentives for shifting loads and production. The difference from market-based instruments lies predominantly in that the price signals for this method are set administratively. The network tariffs that apply to the case study are presented in Section 2.3.3.

Section 2.3.1 presents the regulatory considerations that apply to the system in the case study.

2.3.1 Regulatory Considerations

Prosumers are regarded as customers that have a rated feed-in active power production of less than 100 kW. It is also a requirement for customers to not have production and power system equipment that would be subjugated to licensing. A prosumer is also legally bounded to sell its power surplus to an electricity supplier and can therefore not participate in the power market or sell power directly to another end user [39]. A prosumer is exempt from being charged the fixed component that is part of the total network tariff. The network tariff is further discussed in Section 2.3.3.

The case study, described later in this thesis, will regard a microgrid that has a connection-point rating of more than 100 kW and is therefore subjugated to other legislative standards. The case study power system is absolved from the arrangement where prosumers are exempt from paying the fixed component in the total network tariff. If these types of producers intend to participate in the power market or sell power directly to another end user, a special type of licensing is required as well [39].

2.3.2 Market Pricing Scheme

The current European standard of power market pricing is based on the concept of bidding zones. This model assumes that there is no structural congestion internally, which ensures a uniform electricity pricing within each bidding zone [40]. NordPool covers the power market for Nordic and Baltic countries [41]. The market model implemented in NordPool is an auction-based day-ahead zonal market that establishes an equilibrium between supply and demand. The hourly electricity prices within each bidding zone are calculated through bids and offers from producers and consumers. The prices are published for each hour for the coming day [42].

The zonal market approach, as in NordPool, is based on a highly simplified version of the grid and has strong simplifications of the physical characteristics [40, 43]. This approach can be susceptible to cross-zonal congestion - a case in which the internal transmission lines have insufficient capacities to transmit the contracted power. The DSO will in this case be forced to adjust the production and consumption in order to diverge the power flow. This stands apart from nodal pricing, where each node in the grid acts as a bidding zone. This market model takes all transmission constraints into account and is often called locational marginal pricing [40]. The final price will depict the cost of energy and the cost of delivering it at the location of the node and will be determined close to real-time. Nodal pricing will, on the contrary to zonal pricing, enable optimal dispatch and congestion management through the market design [43].

A literature study done in [19] states that a zonal pricing scheme restricts market participants in reacting upon price signals that reflect the physical limitations of the power system. It also indicates how a market that employs a nodal pricing scheme would enable balanced incentives. Producers would discourage from producing power in areas in which the price is low and power consumers would be encouraged to lower their consumption in areas with high prices, and vice versa. There have been multiple discussions regarding the move towards a nodal pricing scheme in Europe in order to improve local price signals. The transition from zonal to nodal pricing has, however, proved to be a tedious and complex task with regard to technical and regulatory specifications [40]. Currently, the market model and technology inhibit the transition to local market prices [19].

2.3.3 Network Tariff

End users with highly rated power system equipment are subjugated to a different legislative standard than households. This will regard both licensing and network tariffs. The network tariffs vary based on the network owner. They will usually consist of two components: a constant component and a component taking local power system traits into consideration. The second term is set on the basis of conditions at the connection point and is strongly correlated to the marginal loss cost of the capacity of the power system in the surrounding area [44]. The marginal loss cost will be referred to as the customer-dependent cost. A power producer can be situated in a highly favourable location of the network that enables an overall reduction in system losses. This would imply that power equipment that provides peak shaving and congestion mitigation services would be subjugated a negative marginal loss cost for power feed-in, i.e. receive payment for utilising the network [44]. As discussed in Chapter 5, the proposed strategies of the system model require active utilisation of power feed-in and demand - a bidirectional flow across the connection point. According to [44], a connection point that has both power demand and power feed-in will have a marginal loss cost percentage that is symmetrical about zero, meaning equal pricing of feeding in power and using power.

Tensio is the DSO responsible for the power grid in the area in which Rye Microgrid is located (more information about the case study in Chapter 4 and Chapter 5). The network tariffs from Tensio for commercial customers and businesses that use and produce power are presented in Table 2.1 and Table 2.2, respectively. The customer-dependent variable component of the network tariff is often the deciding factor for the profitability of customers. The case study will regard a microgrid providing peak shaving and congestion management services to the DSO and it could therefore be assumed that the customer dependent component would be negative, i.e. discounted or be paid for the service through the variable component. However, as mentioned earlier, the variable component, or marginal loss cost component, is required to be symmetrical about zero, meaning that power trading by utilisation of a battery would efficiently generate a nullification of the variable component through having the approximately equal in- and outflow of power through the connection point.

Table 2.1: Overview of network tariffs from Tensio for commercial power demand customers in the distribution grid [45].

Type	**Fixed Component kr/year**	**Rated Power Component kr/kW/month**	**Variable Component øre/kWh**	**Comment**
Tariff with rated power component	8817.80	Active Power: 0-100 kW: 111 100-400 kW: 92.35 over 400 kW: 81.63	6.51	Fuse larger than 125 A (230 V)

Table 2.2: Overview of network tariffs from Tensio for commercial power production customers in the distribution grid [45].

Power Production Tariff		
Area	Fixed Component øre/kWh	Variable Component øre/kWh
HV and LV	1.21	Customer Dependent
Power Demand Tariff *		
Area	Fixed Component kr/year	Variable Component øre/kWh
HV and LV	2099.90	Customer Dependent

* Prices only regard power production customers that require power for the operation of the power station. Power for other purposes will be calculated using the standard power demand network tariff.

This thesis regards a customer that does not follow the standards in the definition of either a *commercial power producer* or a *commercial power consumer*. As mentioned in Table 2.2, the power demand prices for power production customers will only regard power utilised for the operation of the station. It can therefore be questioned whether the power demand implicated by power trading would be regarded as "operation of the power station". This thesis will make the assumption that the power station presented in the case study has a contract declaring the customer dependent variable component to be 6.51 øre/kWh. The *Rated Power Component* and *Fixed Component*, seen in Table 2.1, are disregarded. An overview of the network tariffs that the microgrid are subjugated is presented in Table 2.3.

Table 2.3: Overview of network tariffs that apply to microgrid in the case study.

Power Production Tariff	
Fixed Component øre/kWh	**Variable Component øre/kWh**
1.21	-6.51
Power Demand Tariff	
Fixed Component kr/year	**Variable Component øre/kWh**
2099.90	6.51

Chapter 3

Multi-Period Optimal Power Flow: Theory and Applications

This thesis will utilise multi-period optimal power flow, which is a type of optimal power flow that links multiple optimisation problems. In this chapter, the basics of an optimal power flow (OPF) will be presented, before extending to a multi-period optimal power flow. The application of MPOPF in other studies is also reviewed, and the solver Interior Point OPTimisation (IPOPT) is presented.

3.1 Optimal Power Flow

Optimal power flow is a set of optimisation problems in electric power system engineering, that seeks to find the optimal operational points of an electric power system subject to physical constraints on electric laws. An OPF is any optimisation problem that includes the power flow equations as constraints [46]. The net active and reactive power flow injections P_i and Q_i at a bus i can be written as follows [47]:

$$P_i = \sum_{k=1}^{N} |V_i||V_k|(G_{ik}cos(\delta_i - \delta_k) + B_{ik}sin(\delta_i - \delta_k)) \tag{3.1}$$

$$Q_i = \sum_{k=1}^{N} |V_i||V_k|(G_{ik}sin(\delta_i - \delta_k) - B_{ik}cos(\delta_i - \delta_k)) \tag{3.2}$$

V is the bus voltage magnitude and δ is the bus voltage angle with N number of buses. G and B are respectively the real and imaginary part of the impedance Y, calculated from the resistance R and reactance X :

$$Y = \frac{1}{Z} = \frac{1}{R + jX} = \frac{R}{R^2 + X^2} - j\frac{X}{R^2 + X^2} = G + jB \tag{3.3}$$

A typical trait of an OPF is that some variables in the power flow equations are defined within a range, and varied in order to meet certain criteria. The method will achieve the objective while also guaranteeing the technical feasibility of the system. The optimal power flow will conclusively calculate the power flows in an electric network that meet the requirements of the objective function and its accompanying constraints. Typical characteristics of the variables, the objective function, and the constraints are presented in the subsections that follow.

3.1.1 Variables

There are several different types of variables in an OPF problem. As opposed to the basic power flow of an electric power system, such as the Newton-Raphson power flow, some variables in the OPF are allowed to vary within its given boundaries. By tuning the varying variables, OPF enables for attaining values that permit the optimal operation of the system. The variables in an OPF can be classified as follows:

- **Decision variables:** are the controllable variables and are a set of quantities that need to be determined in order to solve the problem. The OPF problem is solved when the best possible values of the decision variables are found. In electrical engineering these variables will typically include real and reactive bus power injection, bus voltage magnitude and angle, and, as stated in Section 5.2.3, battery energy storage power output.
- **State variables:** are considered as the variables describing the state of the system. These will give a measure of how the system responds to changes in decision variables and are therefore uncontrollable. Typically this set of variables include voltage magnitude and angle, but also bus power injections that are not considered as decision variables.
- **Parameters:** include constant values implemented into the mathematical model. Typically this set of values include the voltage angle of the reference bus (zero degrees) and power consumption of loads.

3.1.2 Objective Function

The objective function defines the problem by representing the desired target through a mathematical formulation of the decision variables. The formulation is solved within a range of allowed values in order to find the best solution of the objective function. Typical objective functions in OPF can be to minimise the total generation cost, to maximise the profit of a user of the system (for instance a prosumer), or to maximise social welfare by including all the end users of the system. This optimisation includes information regarding the costs of the variables. Other objective functions concern physical aspects of power system operation, for instance, to minimise the line losses of a network, or minimise the power production.

3.1.3 Constraints

The optimal values of the decision variables are found subject to constraints. These regulate and determine limits of variables and depict physical constraints. The constraints will effectively define the feasibility region of the problem. Typically, optimisation constraints are divided into two groups; inequality constraints and equality constraints. Inequality constraints establish operational limits of power system units, for example, power limits on generator output or energy storage capacity limits. Equality constraints are constraints that implement physical requirements that the optimal solution has to fulfill, for example, the power balance in a system.

3.1.4 Problem Formulation

The elements from the previous section are structured in a mathematical problem formulation. x is the vector of variables in the system, $f(x)$ is the objective function, $g_i(x)$ and $h_i(x)$ are respectively equality and inequality constraints. The optimisation problem is formulated as follows:

$$\begin{aligned} \text{minimise} \quad & f(x) \\ \text{subject to} \quad & g_j(x) = 0, \; j = 1, \ldots, n_{eq}. \\ & h_i(x) \leq 0, \; i = 1, \ldots, n_{ineq}. \end{aligned} \tag{3.4}$$

3.2 Multi-Period Optimal Power Flow

The OPF problem described above is an instantaneous picture of the network. To evaluate the operation over time, one can study a series of OPFs for a period by performing an MPOPF, also called dynamic optimal power flow (DOPF).

The linking variable in a series of OPF is the state of the storage system, as the other variables are instantaneous. In order to implement energy storage systems into OPF problems, it is required to capture the time dependencies that are inherent to energy storage units. In MPOPF this is done through intertemporal constraints that couple different time steps. The problem is, thus, transformed into a multi-period problem. The time-dependent behaviour of the battery regards the state of charge that must be held within its upper and lower bounds. The optimisation problem will now have an extra layer of complexity - the charging and discharging decisions made in one time period will directly affect the optimal decisions for other time periods.

Converting an OPF problem to a multi-period problem will extend the set of variables and units of the problem. A typical OPF problem may have n_g generators, n_d loads and n_b buses. Assuming that the time-horizon is divided into T time steps, the system will now have $T \cdot n_g$ generators, $T \cdot n_d$ loads, and $T \cdot n_b$ buses. The same will regard all variables. The MPOPF problem can be understood as a simultaneous optimisation of multiple coupled OPF problems. Figure 3.1 illustrates a possible way of visualising the structure of an MPOPF problem.

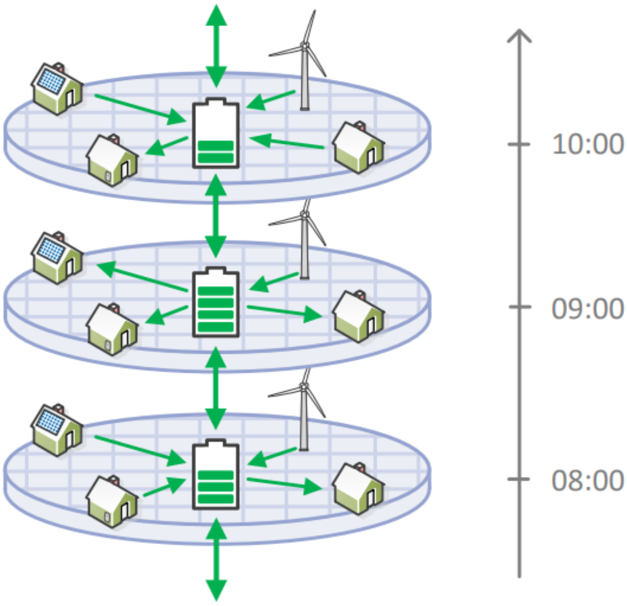

Figure 3.1: Illustrative figure of MPOPF [48]

3.3 Solution Method

The case study in this thesis will introduce an AC multi-period optimal power flow problem. This is a nonlinear problem, as AC OPFs are inherently nonlinear [48]. A nonlinear problem is defined as having either a nonlinear objective function or constraints containing nonlinear terms. An AC MPOPF can also be regarded as a non-convex problem [48]. This is a consequence of the sinusoidal expressions in Equations (3.1) and (3.2). Non-convex problems allow for both local and global optima to exist. The number of nodes and units in the case study network, as well as the length of the time horizon, will additionally make this a large-scale problem.

An MPOPF problem includes inequality constraints, as the system must respect limits, such as for voltage and branch flows. There are several methods to account for inequality constraints in an optimisation problem, one of these methods is the interior point method [48]. In this method, the inequality constraints are transformed from $h(x) \leq 0$ to $h(x)+s = 0$, where $s > 0$. The inequality constraints $s > 0$ are added to the objective function by barrier terms, usually in the form of logarithmic functions. The barrier terms limit the definition area of the objective function according to the corresponding constraints. The barrier terms are scaled by a barrier parameter μ. The reformulated objective function pushes the constraints into the feasible region and decreases μ as the algorithm converges into an optimal solution.

The barrier optimisation problem takes the form:

$$\begin{aligned} \text{minimise} \quad & \phi(x) = f(x) - \mu \sum_{i=1}^{m_{ineq}} log(s_i) \\ \text{subject to} \quad & g_j(x) = 0,\ j = 1, \ldots, n_{eq} \\ & h_i(x) + s_i = 0,\ i = 1, \ldots, n_{ineq} \end{aligned} \tag{3.5}$$

An advantage of the interior point method is that the problem becomes an equality-constrained problem. This makes it an efficient method for large-scale problems with many constraints [49].

3.3.1 IPOPT

An optimisation method for nonlinear problems is IPOPT. It can solve nonlinear and non-convex problems. IPOPT uses a barrier strategy with filter for nonlinear interior point methods [49].

The inequality constraints of the optimisation problem are included in the objective function with the barrier function as described above. The solution of the barrier problem is computed through a line-search framework with the use of a filter. The optimisation problem has two goals, both minimising the objective function ϕ and minimising the constraint violation θ. An alternation between two points that improves either one or the other variable can occur. To avoid this, a filter is implemented with a set of ϕ and θ pairs from the previously tested iterations. A trial point is accepted if it is not in the filter. An additional second-order correction is performed in the line search to improve the step size of the trial point if it is rejected. The step size is used to calculate the search direction of the line search [49].

A flow chart of the algorithm of IPOPT is presented in Appendix A.

The IPOPT solver proves to have reliable global convergence properties [50]. The advantage of the filter method is that the steps can be larger as the trial point is tested in the filter [49]. Also, the interior point method allows convergence from poor starting points [51]. On the other hand, the algorithm does not improve extensively given a nearby starting point from the solution [51].

By comparing the percentage of solved problems from a standard test set of a numerical study, the IPOPT showed a strong performance compared to other solvers [51].

The IPOPT has, as shown, favorable properties for solving nonlinear and non-convex optimasation problems. It is therefore chosen as solver in the case study.

3.4 Applications of MPOPF

This section will give a description of how other papers and studies have adopted an MPOPF model. This is done to show the extent of use and the potential applications of this method. The reviewed studies vary in system type, model and objective function. Advantages and challenges are compared. Research regarding MPOPF in microgrids is limited, therefore studies of MPOPF applied to other systems are included. These systems have similar characteristics.

The charging scheme of a battery is a typical research area in MPOPF. According to [32], applying batteries for power trade and congestion management in the distribution grid is the most advantageous use. The reviewed studies include both objective functions related to economic advantage and system operation. The thoughts and ideas from these studies have inspired the case study objective.

Economic Advantage

The use of batteries to minimise the system cost is presented in [52]. Both the generation cost in the system and the cost of charging and discharging the battery are taken into account. The battery is found to be an efficient way to peak shave the power generation for the periods with the largest load in order to keep the generation limits of the generators of the system.

To identify the advantages of MPOPF, the study in [53] compares an OPF in a single period with an OPF in a multi-period. The problem studies the use of wind generation in a network. The storage system can be used for reducing the fluctuations from wind, for alleviating transmission line congestions, and for economic gain by displacing the low-cost wind to high-cost periods. The studied objective function is the economic utilisation of wind power charging from the low-cost wind generation and discharging at high-cost peak hours. The results from the multi-period model proved it to be a more profitable solution than the single-period model. The single-period model is unable to exploit the future electricity price fluctuations, whereas the multi-period model has the insight to do this.

A distributed network in Norway with renewable resources as a small-scale hydropower plant, rooftop photovoltaics, and a wind farm, in combination with storage systems in EVs is studied in [7]. The objective function aims at minimising the cost of import from the upstream grid. The simulations include forecasts of the renewable generation and prediction models for EV charging. The study finds that an optimal charging strategy saves the total cost of the system.

A network with a high penetration of renewable distributed energy sources is studied in [54]. The economic advantages of distributed energy are compared to the system export by formulating two objective functions in MPOPFs. One maximises the export in the network and the other maximises the revenue from the export. The nonlinear optimisation problem is solved by an interior point algorithm. The difference between these two objectives is observed when the import transmission line is not constrained. The export will then vary in accordance with the electricity price.

Optimal power flows can be approximated to a DC flow problem. In [55], the transmission congestion is studied by minimising the operating cost. The flow is approximated to DC flow to simplify the calculations, as the study focuses on the violation of the transmission capacity of active power. This makes the problem linear and easier to solve through a linear programming method.

System Operation

In addition to typical cost optimisation problems, the security of supply and physical aspects of power system operation are also the subject in MPOPFs. The storage systems can reduce the line losses both by providing local power and by using the storage to reduce the line flow at peak hours. The study in [56] uses distributed energy storage systems to minimise line losses. It finds that the losses for an entire day can be reduced. The study states that this method is transferable to longer time periods, e.g. to a year. The study uses the interior point algorithm IPOPT.

The global losses in a three-phase low voltage grid are minimised in [57]. The network operation is optimised with an MPOPF over a day-ahead and predefined time period of 24 hours. The solution is found through a nonlinear solver using an interior point algorithm. During the operation, the values are validated in order to reduce the deviation between the actual and expected net load profile. The proposed model is found to result in lower system losses and improved integration of renewable energy sources without compromising the security of supply.

A DC MPOPF is performed on an islanded microgrid in [58]. The power equations are linearised around the operating point and solved by a linear programming method. The results are compared to real-time simulations and are found to represent the system accurately.

Summary

The studied applications of MPOPF are summarised in Table 3.1

Table 3.1: Summary of the MPOPF litterature review.

Ref.	Title	Objective function	Model
[7]	Integration of PEV and PV in Norway using multi-period ACOPF — Case Study	Minimise the cost of import from the upstream-grid	AC MPOPF
[52]	A multi-period optimal power flow model including battery energy storage	Minimise total generation cost	AC MPOPF
[53]	Optimal Power Flow with energy storage systems: Single-period model vs. multi-period model	Minimise generation cost	1) AC OPF 2) AC MPOPF
[54]	Dynamic Optimal Power Flow for Active Distribution Networks	1) Maximise the export in the network 2) Minimise the revenue of the export	AC MPOPF
[55]	New approach for dynamic optimal power flow using Benders decomposition in a deregulated power market	Minimise generation cost	DC MPOPF
[56]	Line loss reduction with distributed energy storage systems	Minimise line loss	AC MPOPF
[57]	A multi-temporal optimal power flow for managing storage and demand flexibility in LV networks	Minimise global losses	AC MPOPF
[58]	Dynamic optimal power flow for DC microgrids with distributed battery energy storage systems	Minimise network power consumption	DC MPOPF
[59]	Active Distribution Grid Management Based on Robust AC Optimal Power Flow	Minimising the operating costs of the DSO	AC MPOPF

Chapter 4

Rye Microgrid

The case of study in this report is Rye Microgrid, which is one of four demonstration sites in the European REMOTE project [60]. The project concerns off-grid or islanded microgrids with hybrid storage systems. The main goal of the REMOTE project is to study the added value of a hydrogen storage system compared to a battery-only storage system in a microgrid with renewable sources. The target is to get a 98% availability in islanded mode. The REMOTE project is funded by the European Commission Horizon 2020 program for developing European competitiveness in innovation and research.

Rye Microgrid, seen in Figure 4.1, is a joint project between TrønderEnergi, SINTEF, and a local farmer. TrønderEnergi is a renewable energy production company located in Trondheim, Norway. SINTEF is an independent research organisation.

Figure 4.1: Picture taken at Rye Microgrid [61].

The microgrid is based around a farm at Langørgen Øvre at Rye, 12 km outside Trondheim. The surrounding area is rural, with several farms. There is a small community centre with some shops, offices and a school, and because of the proximity to Trondheim, there is a lot of residential homes. The microgrid has a wind turbine as a private initiative, and TrønderEnergi contributed to developing the rest of the microgrid as a part of the REMOTE project. The schematic of the microgrid can be seen in Figure 4.2.

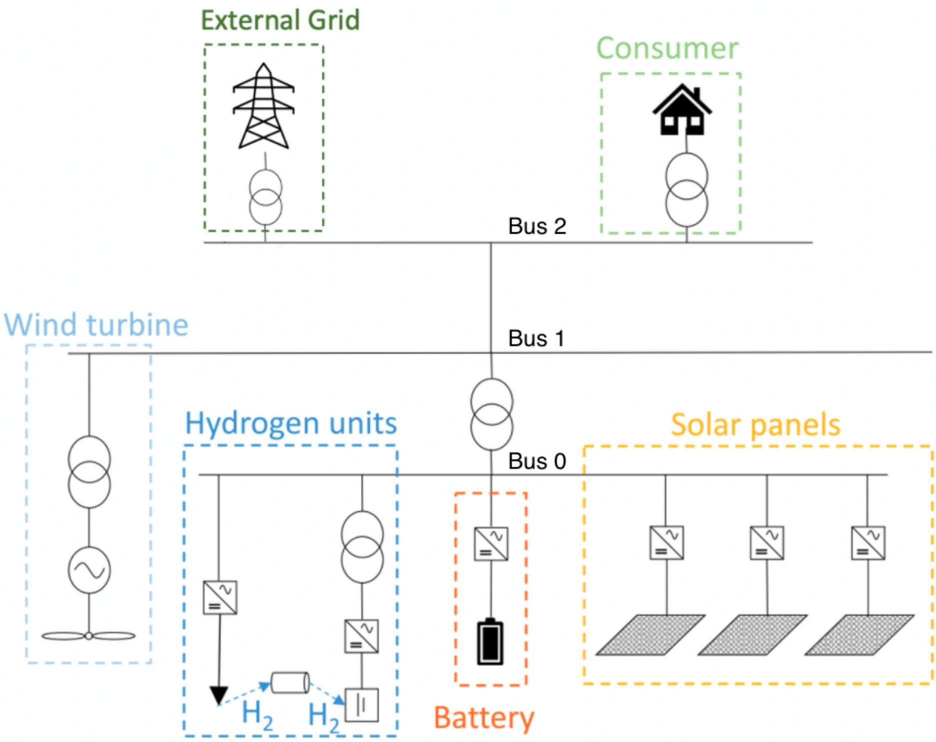

Figure 4.2: Schematic of the main components of Rye Microgrid [12][11]

There are two main sources in Rye Microgrid, a wind turbine, and solar panels. Additionally, there is a backup system with a diesel generator that covers power demands in periods of insufficient energy availability in the energy storage systems and the DERs. The loads in the system are the Langørgen farm and the small barracks for the maintenance of the microgrid. As the main sources are intermittent and largely dependent on weather conditions, there are two energy storage systems in the microgrid to balance the generation with the load, a battery, and a hydrogen tank.

This chapter aims at providing a reference point for the assumptions made in the modelling of the microgrid and the surrounding distribution grid, seen in Chapter 5. It will describe the main components of the microgrid, data collected from the microgrid, and features of the distribution grid. The technical data is summarised in Table 4.1.

Table 4.1: Technical Data of Rye Microgrid

Element	**Type**	**Rating**
Wind Turbine	Vestas V27	225 kW
Photovoltaic Unit	REC Twinpeak2	86.2 kW
Battery Converter	NA	400 kVA
Electrolyser	Hydrogenic	55 kW
Fuel Cell	Ballard	100 kW
BESS	LG Chem	554 kWh
HESS	NA	3.3 MWh

4.1 Wind Turbine

The wind turbine was the first element to be installed in the microgrid in 2015. It is a Vestas V27 with a rated power of 225 kW [12]. The rotor diameter is 27 m and the hub height is 31.5 m. It is connected to an asynchronous generator and the grid through a transformer.

The wind turbine production is measured in the substation at the transformer between the wind turbine and the grid. The power at this substation over the course of the last year is given in Figure 4.3. As seen in the figure, the power output is variable and its dependency on seasonal changes is obvious.

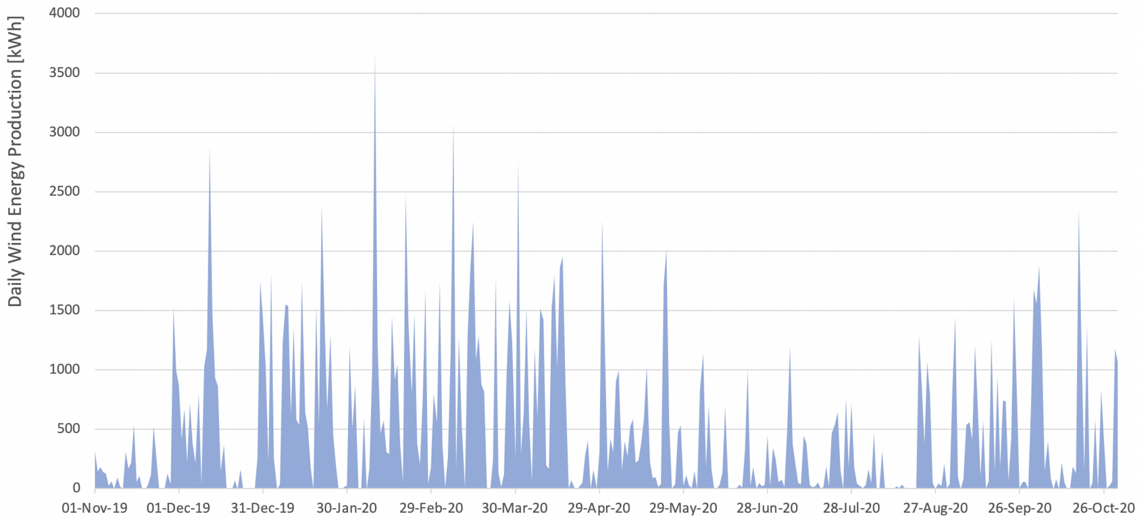

Figure 4.3: Production from Wind Turbine 1. nov. 2019 - 1. nov 2020.

4.2 Photo Voltaic Unit

The photovoltaic unit was installed in April 2019. The modules are delivered by REC TwinPeak2 and consist of nine strings of 32 panels, resulting in a total installed capacity of 86.4 kW [12]. The solar panels produce DC current, which has to be converted to AC current by three inverters. These are delivered by SolarEdge and have an efficiency of 98%, resulting in transmitted power of 82.8 kVA.

The power output from the last year is given in Figure 4.4. The production is largest during the summer season and depicts the low irradiance during the darkest months of winter. It is also worth mentioning the opposite dependency on season between wind and solar irradiance.

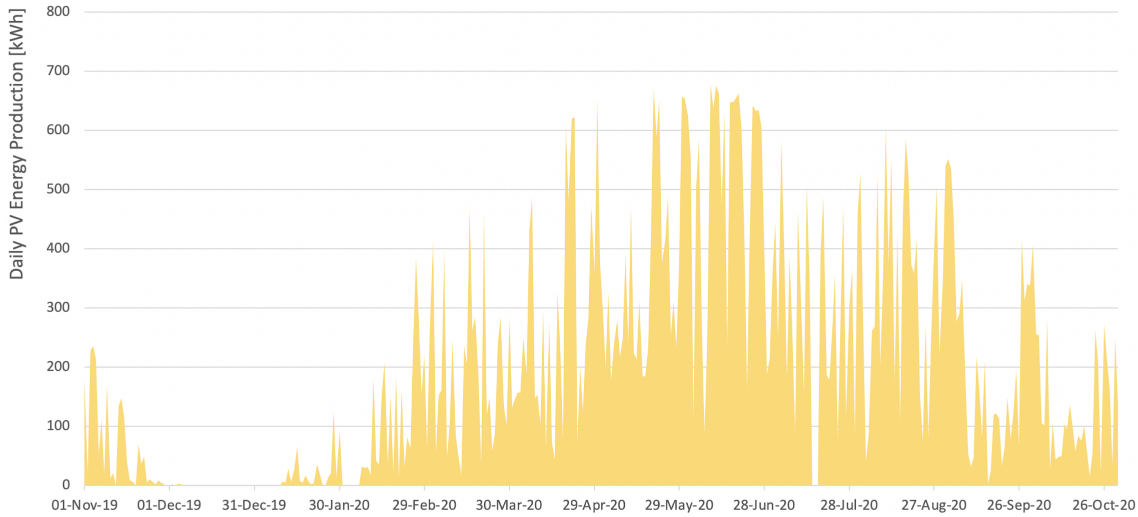

Figure 4.4: Production from Photo Voltaic Unit 1. nov. 2019 - 1. nov 2020.

4.3 Battery Energy Storage System

To cope with imbalances in load and production, a BESS is installed in the microgrid. The battery is composed of 85 lithium-ion battery modules with an energy capacity of 6.67 kWh each, giving a total of 554 kWh [12]. The battery is connected to the microgrid through a bidirectional converter with a maximum apparent power of 400 kVA and efficiency of 97.2% [62]. The converter is bidirectional and can operate in all four quadrants.

The operation of the BESS will affect the lifetime of the battery. The state of charge is the percentage of available energy in the battery compared to the full capacity. The recommended use of the BESS is a state of charge (SOC) between 20% and 90%. The lifetime of the battery is 4000 complete cycles, resulting in approximately ten years with 400 cycles per year when used within the recommended SOC [12].

4.4 Hydrogen Energy Storage System

The hydrogen energy storage system (HESS) was installed in the microgrid in February 2021 and is composed of an electrolyser, a hydrogen tank, and fuel cells.

A rectifier converts AC-current to DC-current that is injected in the electrolyser to produce hydrogen. The electrolyser has a capacity of 55 kW. The hydrogen is stored in a tank with a capacity of 3.3 MWh [11]. The fuel cells convert the stored hydrogen to DC-current, which is inverted to AC-current. The rated power is 100 kW with an efficiency of 50%. This means that the usable capacity from the hydrogen storage is 1.67 MWh.

The HESS has a larger storage capacity with 3.3 MWh (1.67 MWh usable capacity) than the BESS with 554 kWh. However, the response time of the HESS is slower than the BESS. The starting of the electrolysis causes wear on the system parts. This system will often be applied to operate during longer periods of high demand and low distributed energy resource (DER) production [11]. This makes the HESS a long and medium-term storage, and the BESS a short and medium-term storage.

4.5 Load

There are two loads connected to the microgrid; Langørgen farm and the maintenance barracks on the microgrid site. The farm is connected to the rest of the microgrid with a 1 km long cable. It is composed of three buildings; a house and two barns, and the main loads are power-intensive equipment as grain drying and milking robots. These are not constantly used and will lead to periods of high consumption. The microgrid is designed for an annual consumption of the farm of 126.75 MWh, yielding an average active power consumption of 15 kW, with maximum values up to 70 kW [12]. The load of the barracks is negligible compared to the farm.

Chapter 5

General Methodology and Modeling

This chapter specifies how this thesis will model the systems and individual units in the case study, as well as which methods and formulations that the model simulations are composed of. The system model consists of Rye Microgrid and an electrically confined area of the surrounding distribution grid. These are modelled to depict the real systems to such detail that the proposed methods and findings are applicable to them and other similar systems. The system will largely depict Rye Microgrid, presented in Chapter 4, but some minor modifications and assumptions will be made for streamlining simulations. The objective of this thesis is to explore to which degree the provision of congestion management services from the microgrid owner is profitable without direct incentives from the DSO and the simulations that are conducted will reflect this matter. A multi-period optimal power flow approach is chosen to explore how optimal performance characteristics are obtained. This method is properly described in Chapter 3. Detailed descriptions regarding the system model are given in Section 5.1, while the mathematical is presented in Section 5.2.

5.1 System Model

5.1.1 Photo Voltaic Unit and Wind Turbine

In the system model, the PV unit and the wind turbine are modelled as producing loads - meaning loads with opposite signs of the convention. The reason for this is their inherently non-dispatchable nature; the inability to regulate and control the power production from these units, hence having a fixed value for each time step. The production variables, P_{PV} and P_{Wind}, are in addition deterministic and not a decision variable. Power curtailment is also assumed unnecessary, enabling this type of modelling. Real data is utilised as input for these units. The data is composed of segments of the plots presented in Figure 4.4 and Figure 4.3.

The integration of these two intermittent sources of electric energy into the model will allow for observation of how these may affect storage planning and the influence on power flow congestion. These observations will be important for the future distribution grid where the expected amount of energy from solar and wind power sources will increase.

5.1.2 Battery Energy Storage System

The real Rye Microgrid is installed with a battery energy storage system and a hydrogen energy storage system, but both will be modelled as batteries in the system model. This simplification is made on the basis of how typical HESS control strategies are. These strategies will generally govern HESS as seasonal storages, i.e. long-term storage, making this type of storage less suitable for flexibility services in the distribution grid.

The technical specification of the batteries is presented in Table 5.1. Both batteries are connected to bus 25 (see Figure 5.1). The system will have a total storage capacity of 2224 kWh. The converter capacity for each battery is limited to 200 kVA, for both charging and discharging. The batteries have a maximum efficiency of 97.2 % during ideal conditions [62]. The model charge and discharge efficiency are slightly lowered to 95 % in the model.

A fundamental part of the system model is the BESS. In congestion management models the battery will store energy in times of excess energy in the local area distribution grid and discharge when the energy is needed. This is, among other things, done to prevent stress on transmission lines. Storing and discharging energy can also be a profitable process. The price of electricity will most of the time reflect how saturated the distribution grid is on electric energy. A surplus of energy will drive the prices downwards, while energy scarcity will drive the prices upwards.

Table 5.1: Technical specification of battery setup.

	BESS 1	**BESS 2**
Connection bus	25	25
Energy rating [kWh]	554	1670
Charge rating [kVA]	200	200
Discharge rating [kVA]	200	200
Charge efficiency [%]	95	95
Discharge efficiency [%]	95	95
Depth of discharge limit [%]	20	20

Battery Degradation

In multi-period optimisation problems with cost-related objective functions, the degradation of the battery can be modeled as a cost. The lifetime of a battery is typically determined by a certain amount of charging cycles. The main variables in the lifetime decision are the charge rate of the battery, the depth of discharge (DOD), the SOC, and the temperature.

This thesis will model the battery degradation cost as done in [63]. The case study model implements a cost for each charging cycle cost of 5 175 NOK/kWh (using current exchange rate) [64].

$$c_d = \frac{\textit{Battery Price}}{\textit{Total Transferable Energy in Life Cycle}} \tag{5.1}$$

The total transferable energy is calculated as follows [65, 66, 67]:

$$\textit{Total Transferable Energy in Life Cycle} = 2 \cdot CC(DOD) \cdot DOD \cdot E \cdot \mu^2 \tag{5.2}$$

, where E is the rated energy capacity, μ is the battery efficiency and CC is the lifetime with respect to the DOD. The value is doubled to take account of both charging and discharging. The total lifetime of the batteries in the model is 4000 complete cycles.

5.1.3 Distribution Grid

The overlaying distribution grid that surrounds the microgrid is also integrated into the system model. The topology of the grid is structured to mimic the real surroundings. The lengths of transmission lines, bus locations, and end user locations are approximated from satellite images. The number of end users and types of end users are based on visual examinations of the satellite images. This is a rural area and it is therefore assumed to only consist of overhead transmission lines. The network configuration is presumed to be a 22 kV radial system.

The loads in the distribution grid model are based on data described in Norwegian law regarding power system regulation and follow a standard called FASIT [9]. They are used in load calculations by Norwegian distribution system operators and provides a realistic representation of typical power consumption of various loads. The FASIT standard defines the active power consumption of various types of end users in Norway. The individual active power consumption consists of a constant and a temperature-dependent variable. The temperatures are gathered from a weather station close to Rye Microgrid. The reactive power consumption of the various types of end users is characterised by a power factor. The area is occupied by relatively few and far apart housings and industries, an area often found in distant areas of the Norwegian landscape.

As rural areas most often have overhead transmission lines, this is what is used in the simulation as well. An overview of the transmission line parameters can be seen in Table 5.2. The line parameters values are stated in the Standard Type Library of PandaPower [68].

Table 5.2: Overhead transmission line parameters [68].

Line type	**R** $[\Omega/km]$	**X** $[\Omega/km]$	**Line capacitance** $[nF/km]$	**Current capacity** $[kA]$
48-AL1/8-ST1A 20.0	0.5939	0.372	9.70	0.210

The distribution grid is represented by a radial 27-bus system. An overview of the distribution of end users can be seen in Table 5.3. The topology is presented in Figure 5.1. Black lines represent overhead transmission lines. Slack bus/infinite bus is bus 23. The bus which the microgrid is connected to bus 25/26. The slack bus is modelled as an infinite generator in the network model. The power output from the slack bus will be referred to as power *import*.

Table 5.3: Overview of the distribution of end users at the buses.

	Amount						
Bus Number	**Residential**	**Farm**	**Farm MG**	**Industry**	**School**	**Commerce**	**Office**
1	2	1	-	-	-	-	-
2	4	1	-	-	-	-	-
3	1	2	-	-	-	-	-
4	7	2	-	-	-	-	-
5	-	-	-	-	-	-	-
6	14	2	-	-	-	-	-
7	6	-	-	-	-	-	-
8	4	-	-	-	-	-	-
9	9	-	-	-	1	-	1
10	7	1	-	-	-	1	-
11	11	2	-	-	-	-	1
12	8	-	-	-	-	-	-
13	-	-	-	-	-	-	-
14	-	-	-	-	-	-	-
15	16	2	-	-	-	-	-
16	2	-	-	-	-	-	-
17	1	1	-	-	-	-	-
18	11	-	-	-	-	-	-
19	9	4	-	-	-	-	-
20	5	2	-	1	-	-	-
21	12	-	-	-	-	-	-
22	15	-	-	-	-	-	-
23	-	-	-	-	-	-	-
24	3	-	-	-	-	-	-
25	-	-	-	-	-	-	-
26	-	-	-	-	-	-	-
27	-	-	1	-	-	-	-

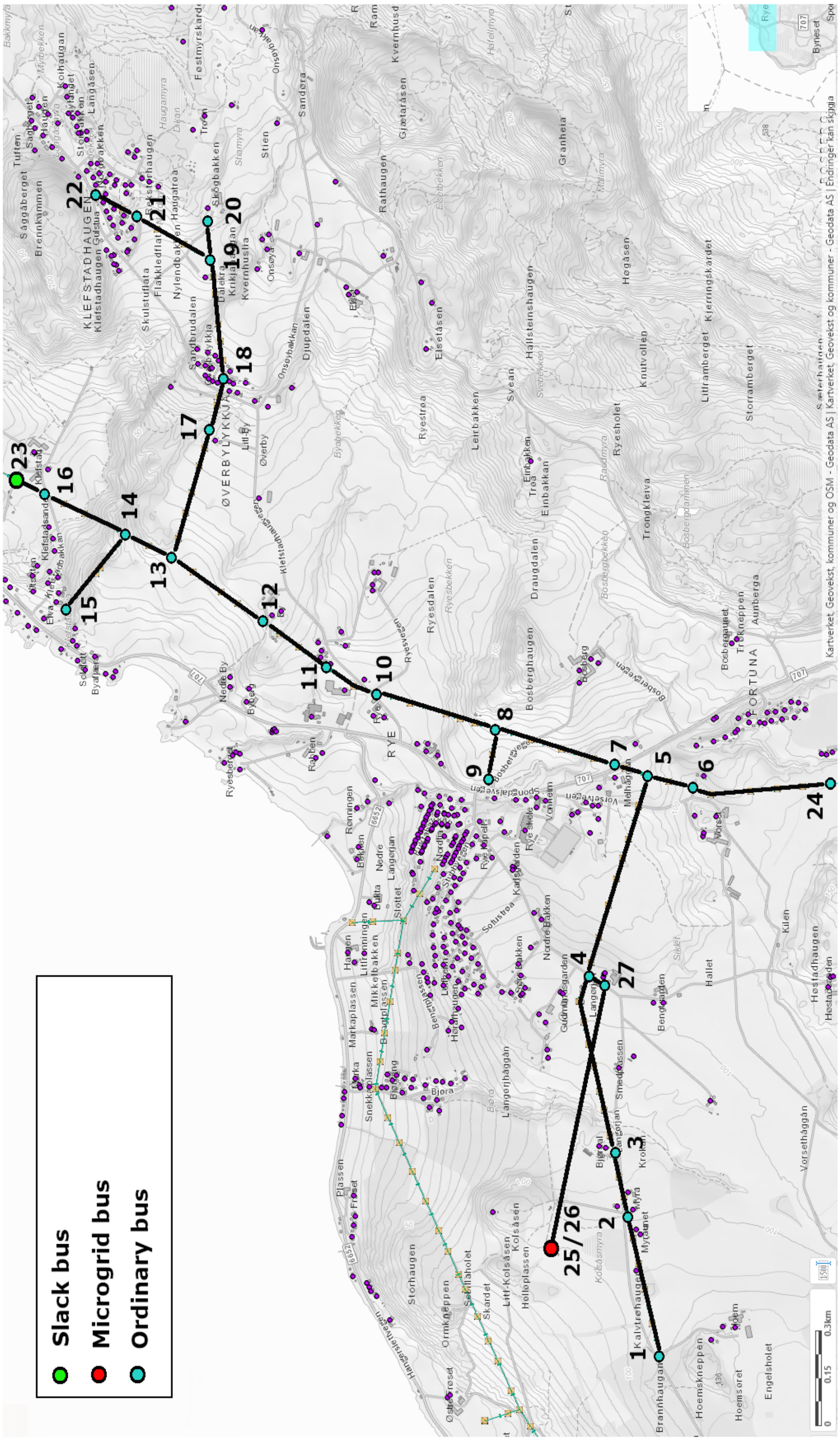

Figure 5.1: Distribution grid topology.

5.2 Mathematical Model

With the increasing complexity of the power system, it is important to develop solutions that can profit from it. The future power system is likely to have larger peak-to-peak values and a higher uncertainty caused by the integration of more variable energy resources. Large-scale storage devices enable for optimisation across multiple time steps in power generation and storage scheduling, and have the potential to largely benefit from fluctuations in power flow and electricity prices. The simulation method proposed in this thesis is MPOPF. The simulations will follow the methodology presented in Chapter 3. This method has the ability to identify the optimal operation of the storage units for reaching the goals set in the objective functions.

In order to study the effects of various factors influencing the outcome of the storage and power import scheduling and profitability, several cases will be presented. These cases will differ in regard to which units are implemented into the system model and the goal of the objective function formulation. As there are considerable fluctuations in distribution grid consumption levels, DER power production levels, and electricity price levels all cases will consider simulations of a diversified selection of period in year 2020. The cases are presented in Section 5.2.3.

5.2.1 Notation

Table 5.4: Definition of data sets.

Set	Definition
T	Time horizon
N	Buses
R	Reference bus
B, B^R	Branches, forward and reverse orientation
G, G_i	Generators and generators at bus i
L, L_i	Loads and loads at bus i
S, S_i	Storage and storage at bus i

Table 5.5: Definition of variables and terms for objective function

Variable/Term	Definition
P_g	Active power output from generator
Q_g	Reactive power output from generator
P_s	Active power output from storage
Q_s	Reactive power output from storage
P_l	Active power consumption from load
Q_l	Reactive power consumption from load
P_{ij}	Active branch power flow from bus i to j
Q_{ij}	Reactive branch power flow from bus i to j
S_{ij}	Apparent branch power flow from bus i to j
P_I	Import of active power
Q_I	Import of reactive power
C_{spot}	Elspot price
P_{sd}	Battery active discharge power
P_{sc}	Battery active charge power
$P_{totalload}$	Total active power consumption of the network
P_{PV}	Active power production from PV unit
P_{Wind}	Active power production from wind turbine
$P_{lineloss}$	Active power loss in transmission lines
Q_{Wind}	Reactive power production from wind turbine
Q_{line}	Reactive power loss in transmission lines
V_i^{min}	Minimum limit of voltage magnitude at i^{th} bus
V_i^{max}	Maximum limit of voltage magnitude at i^{th} bus
δ_i^{min}	Minimum limit of voltage angle at i^{th} bus
δ_i^{max}	Maximum limit of voltage angle at i^{th} bus
η_d	Discharge efficiency of the battery
η_c	Charge efficiency of the battery
E_i	Energy level of battery i
E_i^{max}	Energy capacity limit of battery i
E_i^{init}	Initial energy level of battery i
E_i^{end}	Final value of energy level of battery i
$P_{inverter}^{max}$	Rating of the battery inverter
$Y_{ij}, Y_{ij}^c, Y_{ji}^c \quad \forall(i,j) \in B$	Branch pi-section parameters
$T_{ij} \quad \forall(i,j) \in B$	Branch complex transformation ratio
$s_{ij}^u \quad \forall(i,j) \in B$	Branch apparent power limit

5.2.2 Constraints

1. **Power balance**

   The model utilises a nodal power balance constraint to ensure that the power is balanced - all power sinks are saturated. This constraint maintains the balance of power generated, power discharged from a battery, and power consumed at each respective bus. The battery is assumed to only provide active power and is therefore not included in Equation (5.4).

$$\sum_{k \in G_i} P_{g,k}^t - \sum_{k \in S_i} P_{s,k}^t - \sum_{k \in L_i} P_{l,k}^t = \sum_{(i,j) \in B_i \cup B_i^R} P_{i,j}^t \quad \forall i \in N \tag{5.3}$$

$$\sum_{k \in G_i} Q_{g,k}^t - \sum_{k \in L_i} Q_{l,k}^t = \sum_{(i,j) \in B_i \cup B_i^R} Q_{i,j}^t \quad \forall i \in N \tag{5.4}$$

2. **Voltage Limit**

   Limits on bus voltage magnitude and angle are set as follows:

$$V_{min} \leq V_i^t \leq V_{max} \quad \forall i \in N \tag{5.5}$$

$$\delta_{min} \leq \delta_i^t \leq \delta_{max} \quad \forall i \in N \tag{5.6}$$

3. **Storage State**

   Power output from the battery is split into two variables; one representing storage discharge power and one representing storage charge power.

$$P_s^t = P_{sd}^t + P_{sc}^t \tag{5.7}$$

   The following constraint is an intertemporal constraint that couples all the time steps, t, within the time horizon, T. It states that the stored energy in the current time-step is equal to the stored energy in the previous time-step plus the charged energy minus the discharged energy.

$$E_i^t = E_i^{t-1} + (P_{sc}^t \cdot \eta_c - \frac{P_{sd}^t}{\eta_d}) \cdot \Delta t \quad \forall i \in S \tag{5.8}$$

4. **Storage Capacity**

   Constraint on the energy capacity of the batteries. The lower bound of the energy capacity is assumed to be 20 % of the maximum energy capacity - meaning that the maximum depth of discharge is 20 %.

$$0.2 \cdot E_{i,max} \leq E_i^t \leq E_{i,max} \quad \forall i \in S \tag{5.9}$$

   Constraint stating the initial energy level of the battery. The initial value is set to 100 % in the simulations.

$$E_i^0 = E_i^{init} \quad \forall i \in S \tag{5.10}$$

   Constraint setting the final value of the battery energy level. The final value is set to 100 % in the simulations.

$$E_i^T = E_i^{end} \quad \forall i \in S \tag{5.11}$$

5. **Storage charging and discharging limits**

   Two inequality constraints describe the charge and discharge rate limits for the battery. These are equal to the converter power conversion rates.

$$0 \leq P^t_{sc,i} \leq \cdot P^{max}_{converter} \tag{5.12}$$

$$0 \leq P^t_{sd,i} \leq P^{max}_{converter} \tag{5.13}$$

6. **Branch flow**

   Constraint defining branch flow using branch pi-section parameters and complex transformation ratio.

$$S_{ij} = (Y_{ij} + Y^{c*}_{ij})\frac{|V_i|^2}{|T_{ij}|^2} - Y^*_{ij}\frac{V_i V^*_j}{T_{ij}} \quad \forall (i,j) \in B \tag{5.14}$$

$$S_{ji} = (Y_{ij} + Y^c_{ij})|V_j|^2 - Y^*_{ij}\frac{V^*_i V_j}{T^*_{ij}} \quad \forall (i,j) \in B \tag{5.15}$$

7. **Branch Thermal Limit**

   Upper thermal limit for apparent branch flow.

$$|S_{ij}| \leq s^u_{ij} \quad \forall (i,j) \in B \tag{5.16}$$

5.2.3 Simulation Cases and Objective Functions

This subsection will present the simulation scenarios/cases of this thesis. They are designed to highlight various factors that influence the successful deployment of a market in which microgrid owners are incentivised to provide congestion mitigation as an ancillary service to the DSO through power trading. All cases are nonlinear, non-convex, and deterministic. They are deterministic in terms of the presupposed knowledge of DER power production levels and Elspot price market values that are fed into the simulation model.

All simulations will have a run-time of one week. A time horizon of one week provides simulation conditions that allow for disclosing decisive factors that influence the scheduling of storage and slack bus resources, while also being within reason of what a stochastic model could forecast. The data used in the simulation is gathered from the year 2020. In order to observe the seasonal effects two simulations will be run for each simulation scenario; one in the winter and one in the summer.

Base Case

The results from the Base Case will serve as a reference point for the other cases presented in this thesis. This case incorporates the same units as the previously discussed model except for the battery energy storage. The power import is therefore the main source of electric energy and will project a very similar load generation profile as the total power consumption of the distribution grid. The objective function of this scenario is presented in Equation (5.17). As there is only one power source in the distribution grid of the base case, this objective serves the same purpose as minimising losses, but will in reality only adhere to the instantaneous power demand.

$$
\begin{aligned}
\min_{P_I} \quad & \sum_{t=1}^{T} P_I^t \\
\text{s.t.} \quad & P_I^t - \sum_{k \in L_i} P_{l,k}^t = \sum_{(i,j) \in E_i \cup E_i^R} P_{i,j}^t \quad \forall i \in N \\
& Q_I^t - \sum_{k \in L_i} Q_{l,k}^t = \sum_{(i,j) \in E_i \cup E_i^R} Q_{i,j}^t \quad \forall i \in N \\
& V_{min} \leq V_i^t \leq V_{max} \quad \forall i \in N \\
& \delta_{min} \leq \delta_i^t \leq \delta_{max} \quad \forall i \in N \\
& S_{ij} = (Y_{ij} + Y_{ij}^{c*}) \frac{|V_i|^2}{|T_{ij}|^2} - Y_{ij}^* \frac{V_i V_j^*}{T_{ij}} \quad \forall (i,j) \in B \\
& S_{ji} = (Y_{ij} + Y_{ij}^{c}) |V_j|^2 - Y_{ij}^* \frac{V_i^* V_j}{T_{ij}^*} \quad \forall (i,j) \in B \\
& |S_{ij}| \leq s_{ij}^u \quad \forall (i,j) \in B
\end{aligned}
\tag{5.17}
$$

Case 1: Non-Weighted Maximum Profit

This case is designed to exclusively profit the owner of the microgrid. Through the exploitation of the battery charge and discharge schedule, the microgrid owner can largely profit from the fluctuations in electricity prices. It is assumed that the microgrid owner can sell and purchase active power for the same price; the Elspot Price. The objective function maximises the profit throughout the time horizon by discharging/selling power at a high cost and charging/buying power at a lower cost. The formulation also considers the degradation cost of the battery (see Section 5.1.2). As the formulation does not contain any perspectives of slack generator/import variables it is in theory indifferent to congestion mitigation and peak shaving. However, in the presence of any correlation between network power consumption fluctuations and Elspot price fluctuations this model will indirectly be encouraged to mitigate the occurrence of congestion in import transmission lines.

$$
\begin{aligned}
\max_{P^t_{sd},P^t_{sc}} \quad & \sum_{t=1}^{T} P^t_{sd} \cdot C^t_{spot} - P^t_{sc} \cdot C^t_{spot} - P^t_{sc} \cdot D \\
\text{s.t.} \quad & P^t_I - \sum_{k \in S_i} P^t_{s,k} - \sum_{k \in L_i} P^t_{l,k} = \sum_{(i,j) \in E_i \cup E^R_i} P^t_{i,j} \quad \forall i \in N \\
& Q^t_I - \sum_{k \in L_i} Q^t_{l,k} = \sum_{(i,j) \in E_i \cup E^R_i} Q^t_{i,j} \quad \forall i \in N \\
& V_{min} \leq V^t_i \leq V_{max} \quad \forall i \in N \\
& \delta_{min} \leq \delta^t_i \leq \delta_{max} \quad \forall i \in N \\
& E^t_i = E^{t-1}_i + (P^t_{sc} \cdot \eta_c - \frac{P^t_{sd}}{\eta_d}) \cdot \Delta t \quad \forall i \in S \\
& 0.2 \cdot E_{i,max} \leq E^t_i \leq E_{i,max} \quad \forall i \in S \\
& E^0_i = E^{init}_i \quad \forall i \in S \\
& E^T_i = E^{end}_i \quad \forall i \in S \\
& 0 \leq P^t_{sc,i} \leq \cdot P^{max}_{converter} \\
& 0 \leq P^t_{sd,i} \leq P^{max}_{converter} \\
& S_{ij} = (Y_{ij} + Y^{c*}_{ij}) \frac{|V_i|^2}{|T_{ij}|^2} - Y^*_{ij} \frac{V_i V^*_j}{T_{ij}} \quad \forall (i,j) \in B \\
& S_{ji} = (Y_{ij} + Y^c_{ij}) |V_j|^2 - Y^*_{ij} \frac{V^*_i V_j}{T^*_{ij}} \quad \forall (i,j) \in B \\
& |S_{ij}| \leq s^u_{ij} \quad \forall (i,j) \in B
\end{aligned}
\tag{5.18}
$$

Case 2: Weighted Maximum Profit

This case will largely build on the previously described case. As mentioned, a correlation between the network consumption fluctuation and Elspot price fluctuations would enable an operation benefiting both the microgrid owner and the DSO. The microgrid owner would earn money from load-shifting, buying power at a low price, and selling higher, while the DSO would be provided a valuable service in the form of congestion mitigation and peak shaving. However, as a result of regional and local differences in power consumption, production, and exchange the electricity price in the Elspot area in which a consumer/producer is situated will not always portray local conditions. This means that the price a consumer pays for the electricity does not always have to reflect local power consumption and production levels. The problem formulation in Equation (5.19) tries to take local price signals into consideration. This is done by weighting the objective function seen in Equation (5.18) with the total load in the network at time step t. By doing this the objective function will have a perspective on how power is consumed. The formulation will in many ways be analogous with a nodal pricing scheme.

$$
\begin{aligned}
\max_{P_{sd}^t, P_{sc}^t} \quad & \sum_{t=1}^{T} P_{totalload}^t P_{sd}^t \cdot C_{spot}^t - P_{totalload}^t P_{sc}^t \cdot C_{spot}^t - P_{sc}^t \cdot D \\
\text{s.t.} \quad & P_I^t - \sum_{k \in S_i} P_{s,k}^t - \sum_{k \in L_i} P_{l,k}^t = \sum_{(i,j) \in E_i \cup E_i^R} P_{i,j}^t \quad \forall i \in N \\
& Q_I^t - \sum_{k \in L_i} Q_{l,k}^t = \sum_{(i,j) \in E_i \cup E_i^R} Q_{i,j}^t \quad \forall i \in N \\
& V_{min} \leq V_i^t \leq V_{max} \quad \forall i \in N \\
& \delta_{min} \leq \delta_i^t \leq \delta_{max} \quad \forall i \in N \\
& E_i^t = E_i^{t-1} + (P_{sc}^t \cdot \eta_c - \frac{P_{sd}^t}{\eta_d}) \cdot \Delta t \quad \forall i \in S \\
& 0.2 \cdot E_{i,max} \leq E_i^t \leq E_{i,max} \quad \forall i \in S \\
& E_i^0 = E_i^{init} \quad \forall i \in S \\
& E_i^T = E_i^{end} \quad \forall i \in S \\
& 0 \leq P_{sc,i}^t \leq \cdot P_{converter}^{max} \\
& 0 \leq P_{sd,i}^t \leq P_{converter}^{max} \\
& S_{ij} = (Y_{ij} + Y_{ij}^{c*}) \frac{|V_i|^2}{|T_{ij}|^2} - Y_{ij}^* \frac{V_i V_j^*}{T_{ij}} \quad \forall (i,j) \in B \\
& S_{ji} = (Y_{ij} + Y_{ij}^{c}) |V_j|^2 - Y_{ij}^* \frac{V_i^* V_j}{T_{ij}^*} \quad \forall (i,j) \in B \\
& |S_{ij}| \leq s_{ij}^u \quad \forall (i,j) \in B
\end{aligned}
\tag{5.19}
$$

Case 3: Peak Shaving Import

There are two parties involved in the ancillary service market model presented in this thesis - the microgrid owner and the DSO. The two lastly presented formulations mostly take the perspective of the microgrid owner. The formulation in Equation (5.20) will concentrate directly on congestion mitigation and peak shaving through the pricing of import across the slack bus. As identified in Section 2.2.3, congestion management and peak shaving are and will become increasingly important in order to maintain a stable and balanced power system without major investments in grid infrastructure. The battery charge and discharge scheduling depicted in the objective function is not governed by price fluctuations and will only act upon fluctuations in active power consumption in the network.

$$
\begin{aligned}
\min_{P_I} \quad & \sum_{t=1}^{T} (P_I^t)^2 \\
\text{s.t.} \quad & P_I^t - \sum_{k \in S_i} P_{s,k}^t - \sum_{k \in L_i} P_{l,k}^t = \sum_{(i,j) \in E_i \cup E_i^R} P_{i,j}^t \quad \forall i \in N \\
& Q_I^t - \sum_{k \in L_i} Q_{l,k}^t = \sum_{(i,j) \in E_i \cup E_i^R} Q_{i,j}^t \quad \forall i \in N \\
& V_{min} \leq V_i^t \leq V_{max} \quad \forall i \in N \\
& \delta_{min} \leq \delta_i^t \leq \delta_{max} \quad \forall i \in N \\
& E_i^t = E_i^{t-1} + (P_{sc}^t \cdot \eta_c - \frac{P_{sd}^t}{\eta_d}) \cdot \Delta t \quad \forall i \in S \\
& 0.2 \cdot E_{i,max} \leq E_i^t \leq E_{i,max} \quad \forall i \in S \\
& E_i^0 = E_i^{init} \quad \forall i \in S \\
& E_i^T = E_i^{end} \quad \forall i \in S \\
& 0 \leq P_{sc,i}^t \leq \cdot P_{converter}^{max} \\
& 0 \leq P_{sd,i}^t \leq P_{converter}^{max} \\
& S_{ij} = (Y_{ij} + Y_{ij}^{c*}) \frac{|V_i|^2}{|T_{ij}|^2} - Y_{ij}^* \frac{V_i V_j^*}{T_{ij}} \quad \forall (i,j) \in B \\
& S_{ji} = (Y_{ij} + Y_{ij}^{c}) |V_j|^2 - Y_{ij}^* \frac{V_i^* V_j}{T_{ij}^*} \quad \forall (i,j) \in B \\
& |S_{ij}| \leq s_{ij}^u \quad \forall (i,j) \in B
\end{aligned}
\tag{5.20}
$$

5.3 Operational Costs and Earnings

The system model will utilise historical Elspot prices from the year 2020. These are collected from NordPool bidding area NO3. The table showing network tariff for the microgrid owner in Section 2.3.3 is reproduced in Table 5.6.

Table 5.6: Overview of network tariffs for the case study microgrid.

Power Production Tariff	
Fixed Component øre/kWh	**Variable Component øre/kWh**
1.21	-6.51
Power Demand Tariff	
Fixed Component kr/year	**Variable Component øre/kWh**
2099.90	6.51

Several metrics are calculated for each case in Chapter 6. In order to properly understand the economical metrics, the following table is given.

Table 5.7: Definition of metrics describing the operational characteristic of the various cases.

Metric	Definition
Battery operation earnings	Earnings from exploiting of Elspot price fluctuations in power trade schemes utilising the battery installed in the microgrid
DER earnings	Earnings from selling power produced by the distributed energy resources installed in the microgrid
Farm electricity cost	Cost of power consumption of the farm in the microgrid
Demand tariff cost	Cost of network tariff. Calculation (for entire time horizon, T): (Fixed component [kr/year]*T [fraction of year]) +(Variable component [kr/kWh]*Power Demand[kWh])
Production tariff earnings	Earnings from network tariff. Calculation(for entire time horizon, T): (Fixed component [kr/kWh]*Power Feed-In[kWh]) +(Variable component [kr/kWh]*Power Feed-In[kWh])
Total revenue without tariff	Calculation: Battery operation earnings + DER earnings - Farm electricity cost
Total revenue	Calculation: Battery operation earnings + DER earnings - Farm electricity cost - Demand tariff cost +Production tariff earnings

The metrics: *DER earnings* and *Farm electricity cost* are independent of the decision variables and are therefore constant for a given time period. The remaining metrics are governed by decision variables and are therefore correlated to system operation.

5.4 Statistical Analysis

In order to understand and analyse the peak shaving and congestion management capabilities of the various strategies presented, this thesis will propose utilising standard deviation as a metric. The standard deviation is defined as a measure of the amount of variation or dispersion of a set of values [69]. Large values of the standard deviation tend to indicate a large deviance of the set of values from the mean, while low values indicate a small deviance from the mean. The standard deviation of measured power flows in a transmission line will therefore have traits that indicates performance levels of peaks shaving and valley filling strategies. Peak shaving will in theory aim at forcing the power flow to approach the mean. As implied earlier, a low value of the standard deviation of a power flow could indicate that large power flows have been shifted to periods of low power flows.

Using the results from the Base Case as a reference point, the analysis presented in Chapter 6 will, among other things, evaluate peak shaving and valley filling characteristics by comparing the standard deviation of the power flow. A reduction in standard deviation from the Base Case could indicate an improvement in these characteristics. The comparison is done by carrying out a F-test. A F-test is a statistical tool for comparing standard deviations. It is used to test if the standard deviations of two populations are equal to each other [70]. The test can be a two-tailed or one-tailed test. This thesis will perform a one-tailed test. A one-tailed test is a test to examine whether the standard deviation of one population is either greater than or less than the standard deviation of the second population. In other words, it is used to see if a new process or strategy reduces the variability in a set of values. This thesis will not present more theory on the statistical analysis as this will only act as means of comparison between *Standard deviation Import* and *Standard deviation Base Case*.

A positive test, meaning that the F-test has found that the standard deviation of one of the cases is less than the standard deviation of the Base Case, will in Chapter 6 be stated as being statistically significantly different or having a statistically significant reduction.

Two statistical metrics will be presented in Chapter 6. In order to properly understand these, the following overview and explanation is given in Table 5.8.

Table 5.8: Definition of metrics describing the statistical characteristic of the various cases.

Metric	Definition
Standard deviation Import	The standard deviation of the power flow from the slack bus for the case presented for the time horizon, T.
Standard deviation Base Case	The standard deviation of the power flow from the slack bus for the Base Case for the time horizon, T.

5.5 Software

The system simulation utilises multiple tools for structuring and simulating the problem. Two programming languages are used and several packages within these. The model topology and technical specification is defined in PandaPower - a Python package for electric power system analysis and calculation. The model is subsequently parsed to PowerModels. PowerModels is a Julia package made for steady-state power network optimisation.

PowerModels provides abilities to structure and modify both the optimisation problem and the network model. Generally speaking, this package acts as a platform for coupling power system analysis and optimisation modelling. It helps with specifying the mathematical formulations of the constraints, variable limits, and objective functions, subsequently fed into a solver. The solver used in this thesis is IPOPT (see Section 3.3.1). JuMP is a modeling language in Julia and helps with formulating various classes of optimisation problems. It assists PowerModels with formulating and indicating variables, constraints, and objective functions that are a part of the optimisation problem. A visual representation of the program/package utilisation is presented in Figure 5.2. Further details about the code architecture and the data flow are presented in Appendices B.1 and B.2

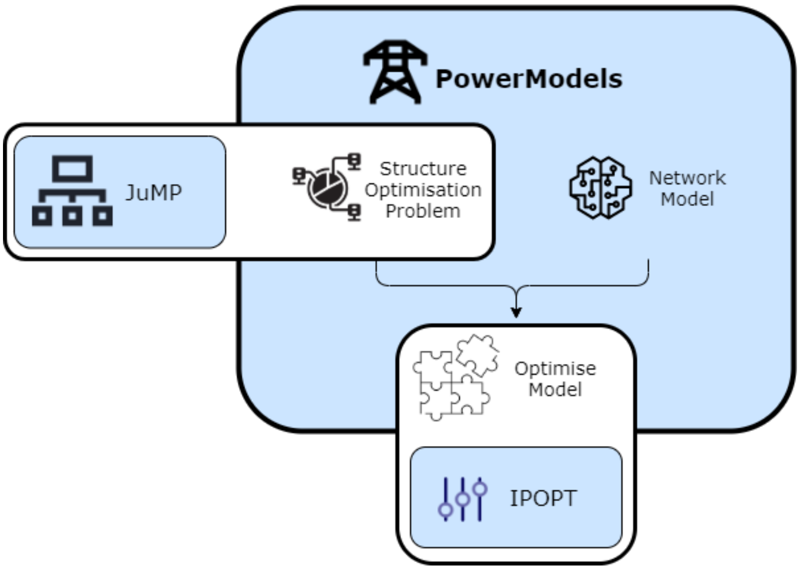

Figure 5.2: Overview of programs and software used in the optimisation model

Chapter 6

Results

The case study is carried out as described in Section 5.2.3. The results are presented and commented on in this chapter. As discussed, all simulations will regard one period in the winter; 01.01.2020 to 07.01.2020, and one in the summer; 15.06.2020 to 21.06.2020. Deterministic data for the simulations are presented in Section 6.1.

The case results will be presented with a dual perspective on the outcome. As stated in the introduction of this thesis, the goal of the scenario formulations is to uncover how the objectives of the microgrid owner and the DSO may coincide. The case simulations are presented in Sections 6.2 to 6.5. This chapter will also present a sensitivity analysis for the battery capacity installed in the microgrid. This is found in Section 6.6.

6.1 Deterministic Data

The simulation results are based on a deterministic approach. The power production level from the PV unit and the wind turbine, as well as the Elspot price, is assumed known for the time horizon, T. These data sets are common for all simulation scenarios/objective functions.

6.1.1 Data: January

Figure 6.1 shows the power production levels of the PV unit and the wind turbine for the first seven days of January. As observed, the PV unit has close to, or, zero power output. The wind turbine reaches a peak value of approximately 140 kW. For comparison, the rating of the turbine is 225 kW. Winters in Norway will deliver little to no sunlight, depending on how far north one is situated. Power profiles from PV units in this season will therefore commonly appear as the one seen below.

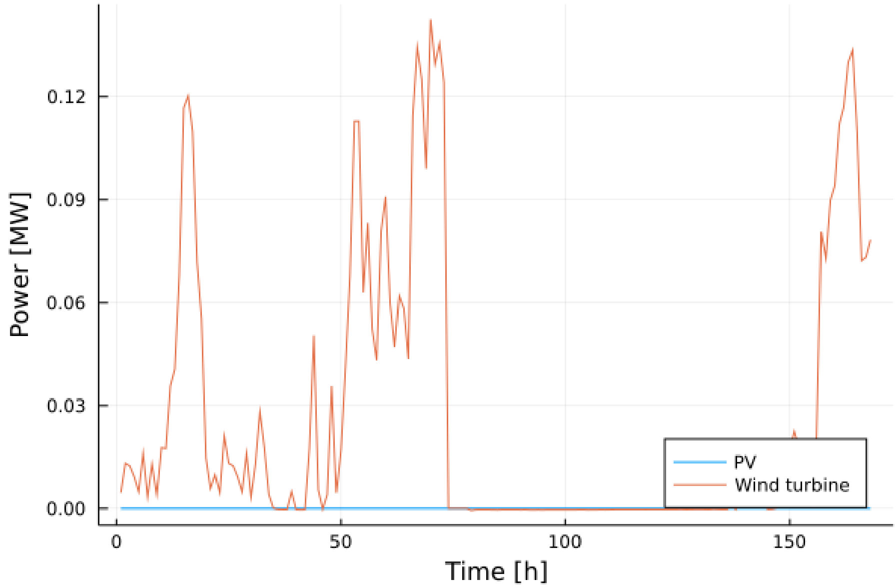

Figure 6.1: Power production level of the PV unit and the wind turbine situated the microgrid in the period 01.01.2020 to 07.01.2020.

The Elspot price will have a significant impact on the operation of the system model. Large fluctuations and inconsistencies, as observed in Figure 6.2, will therefore largely dictate the battery energy storage system and slack generator scheduling in Case 1 and 2. Case 3 will on the other side have an imperceptive relation to the cost of charging, discharging, and producing electric power.

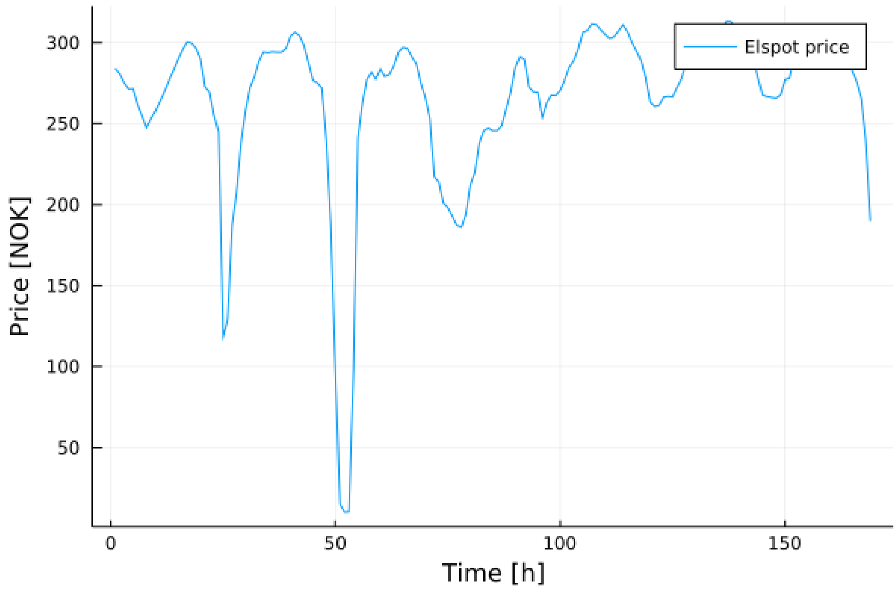

Figure 6.2: Elspot price fluctuations in the period 01.01.2020 to 07.01.2020 for the Elspot area in which the microgrid is situated.

6.1.2 Data: June

The power production profile of the PV unit and the wind turbine in June is noticeable different from the one in January. Figure 6.3 reveals how seasonal changes in Norway have provided a significantly higher level of irradiance and the PV units will consequently have a much higher average power output. The average wind power production levels have in the meantime declined in this time period.

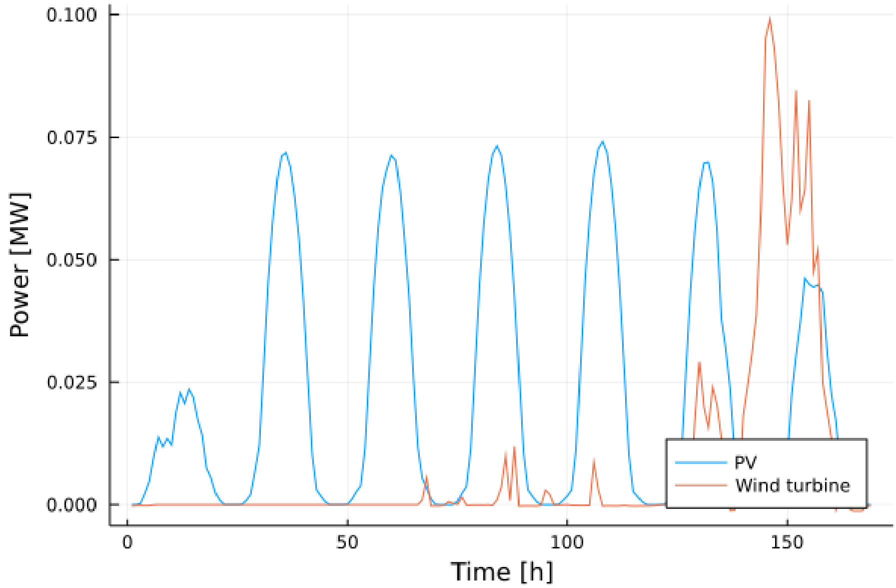

Figure 6.3: Power production level of the PV unit and the wind turbine situated in the microgrid for the period 15.06.2020 to 21.06.2020.

An apparent feature of the Elspot price profile for June, seen in Figure 6.4, is the considerable reduction in average price compared to Figure 6.2. The year of 2020 is infamously known for its large fluctuations and unpredictability in electricity prices. The objective functions that use the Elspot prices will however disregard the overall drop in prices and will mostly recognise and respond according to fluctuations in price.

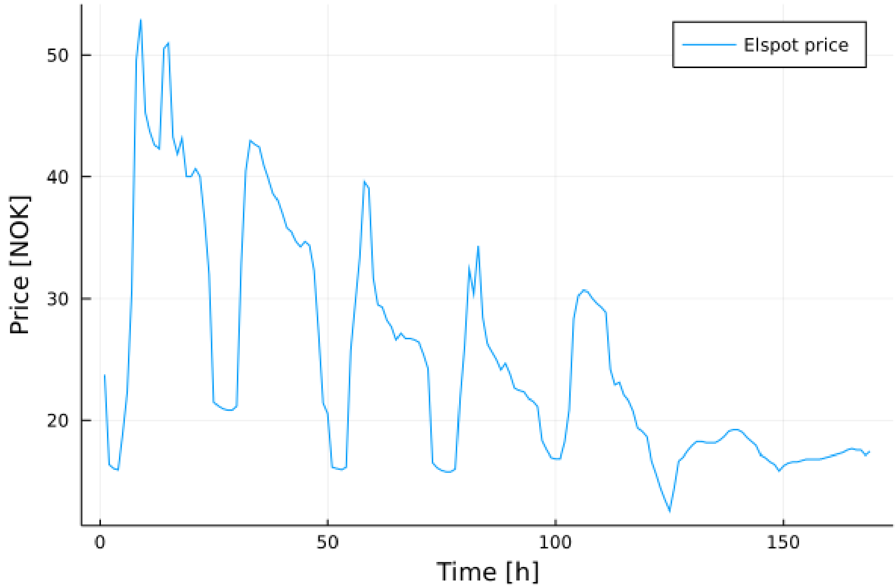

Figure 6.4: Elspot price fluctuations in the period 15.06.2020 to 21.06.2020 for the Elspot area in which the microgrid is situated.

6.2 Base Case

The Base Case implements a model that will represent a reference point for the operational success of the other cases presented in this chapter. Equation (5.17) formulates the problem that has been optimised. This strategy is characterised by an objective function that seeks to minimise the inflow of active power to the distribution grid model from the overlaying distribution grid without the use of storage systems.

6.2.1 Simulation Results: January

Unsurprisingly, the active power output from the slack generator will closely match the active power consumption of the distribution grid. The difference in active power profiles is a result of the power production from VERs and losses during transmission. From the production data presented in Figure 6.1, it is evident why there is a larger difference in power consumption and import for the first half of the time horizon, contrary to the second half. The power profile of the total power consumption in the network and total active power import to the distribution grid can be observed in Figure 6.5.

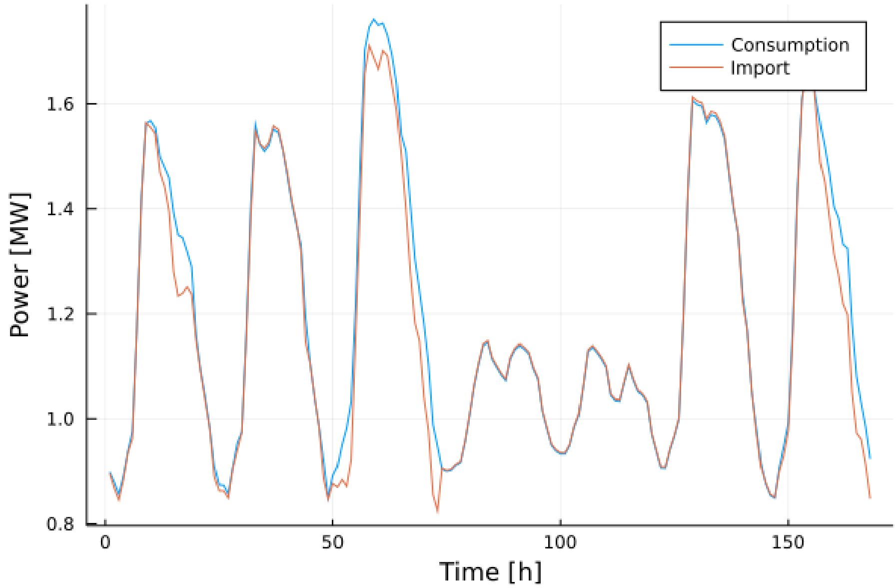

Figure 6.5: Active power profile of network consumption and power import in January.

6.2.2 Simulation Results: June

The tendencies described in Section 6.2.1 can also be observed in the simulation case in June. Import of power across the slack bus is the only source of controllable active power and will therefore follow the active power consumption curve closely. The increased output from the PV unit, seen in Figure 6.3, causes the decline in power import during peak consumption hours - periods of larger irradiance. Figure 6.6 shows the active power profile of network consumption and power import in June.

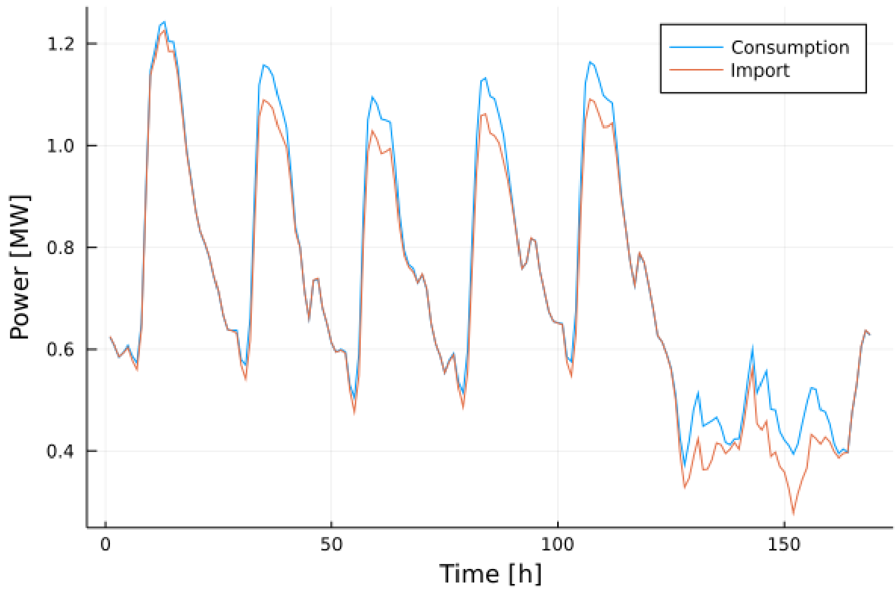

Figure 6.6: Active power profile of network consumption and slack generator in June.

6.3 Case 1: Non-Weighted Maximum Profit

The objective of this problem formulation is to maximise the profit of the microgrid owner. A profit can be obtained by smart control of the battery. This involves charging the battery when the price of electricity is low and discharging the battery when the price is high. The objective function of this case is indifferent to the relation between power consumption and discharge/charge schedule.

6.3.1 Simulation Results: January

Figure 6.7 shows the total consumption of active power in the grid, active power flow in and out of the battery, and import of active power for the time horizon, T, for the simulation period of the first seven days of January. From the figure, it is evident that the storage power flow schedule has an impact on the import of active power. From the perspective of the microgrid owner, this would be the best operational strategy, but as we see from Figure 6.7 it does not significantly reduce the strain on the import transmission line during peak active power consumption hours.

Table 6.1 shows an overview of the operational characteristics of the strategy. The microgrid owner has a total revenue of 630.19 NOK. The system will largely profit from DER earnings, battery operation earnings, but also production tariff earnings. The demand tariff cost is larger than the production tariff cost and the farm electricity cost will almost equalise the DER earnings. This storage strategy lacks in congestion management performance. There is an increase in the peak value of the active power import of 6.38 % and an insignificant reduction in standard deviation.

As recognised in the increased peak value, the strategy has produced a large surge in import in the 8^{th} hour. This occurrence can be traced back to multiple factors. First of all; the objective function has found it optimal to charge at a high consumption hour, meaning that the import needs to sustain both the consumption of the local distribution grid and the charge rating of the battery. Second of all, which is the reason for the objective function finding it optimal to charge at this hour, is a sum of how the battery SOC and the Elspot price develops during the hours before and after this occurrence. Up until the 8^{th} hour the battery is not fully charged, as recognised in Figure 6.8. This is due to the initial discharge of the battery because of high initial Elspot price. The optimisation strategy has subsequently determined it is not optimal to charge before the 8^{th} hour, at which time there is a price drop, and chooses to exploit the lower price. This drop can be observed in Figure 6.2. The occurrence of this surge in power demand reveals how sensitive the strategy is to fluctuations in price, but also the limited scope of time it is able to handle.

Table 6.1: Case 1, January - Overview of costs and earnings from simulation, and statistical representation of the strategy performance.

	Metric	Value
Microgrid	Battery operation earnings [NOK]	713.46
	DER earnings [NOK]	1133.06
	Farm electricity cost [NOK]	1013.84
	Demand tariff cost [NOK]	803.68
	Production tariff earnings [NOK]	601.19
	Total revenue without tariff [NOK]	832.68
	Total revenue [NOK]	630.19
DSO	Reduction in peak value [%]	-6.38
	Standard deviation Import [%]	23.74 *
	Standard deviation Base Case [%]	25.85

* Not significantly different from the standard deviation in the Base Case

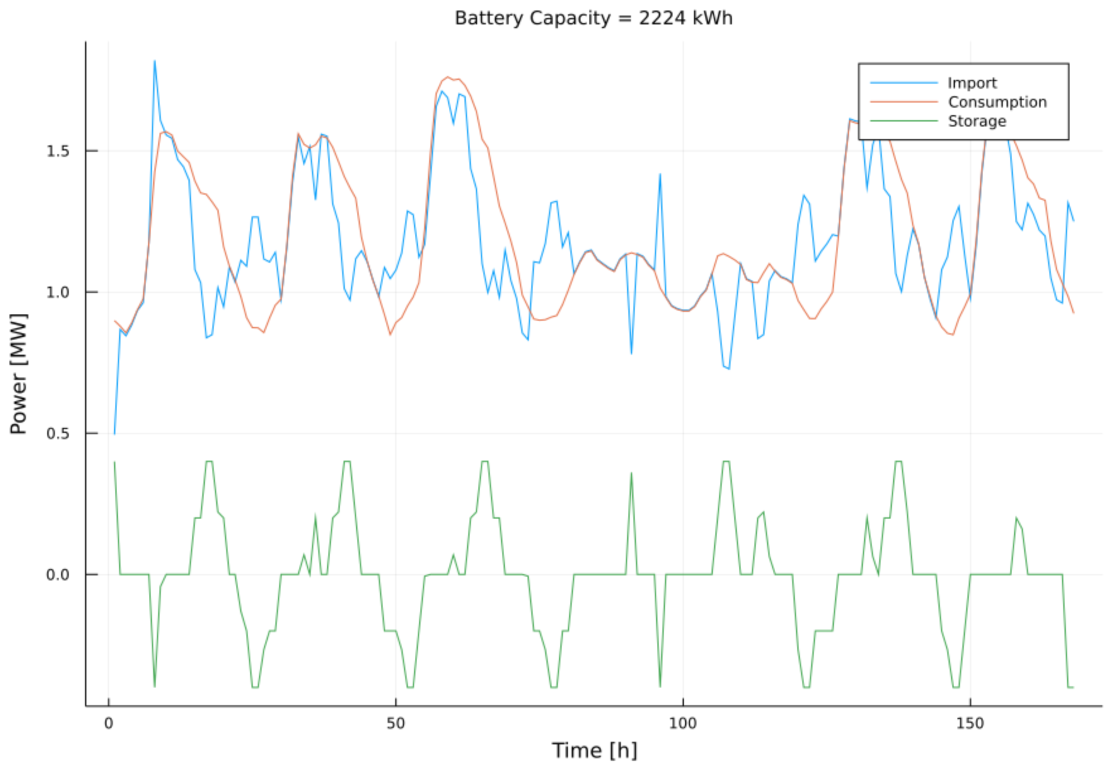

Figure 6.7: Case 1, January - Flow of total consumption of active power in the grid, the active power flow in and out of the battery, and the import of active power for the time horizon, T

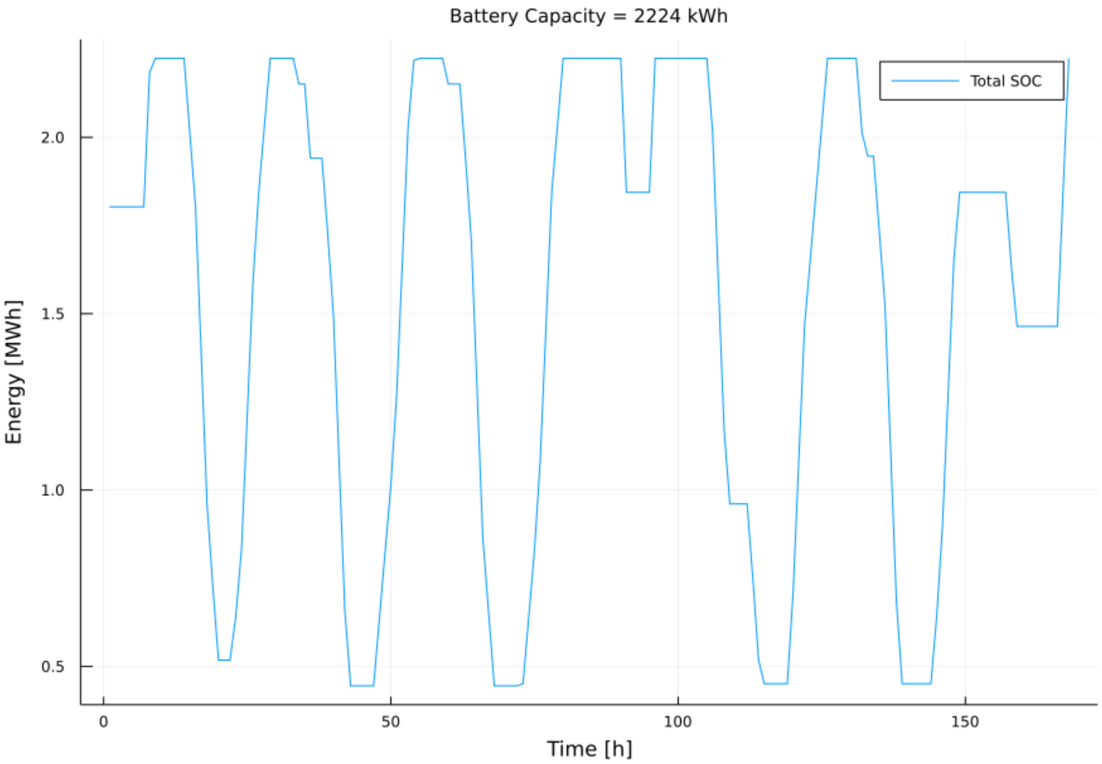

Figure 6.8: Case 1, January - Sum of state of charge of the two batteries for the time horizon, T.

A useful tool for examining the active power profile of the import to the local distribution grid is a duration plot. Figure 6.9 shows a comparison of the duration plot of the active power import for the Base Case and Case 1. This plot can help reveal at what power rating the strategy has improved the flow across the slack bus. An improved flow, from the perspective of the DSO, can generally be classified as a shift of the curve to the right. Such a shift would indicate that the highest rated power flows have been diminished, which could imply a mitigation of congestion tendencies in the transmission line. A rather small shift can be observed in the plot. The power flow from between approximately the 20^{th} to 50^{th} hour has been shifted to the right, characterised by the increase in active power of the red line between approximately the 80^{th} to 160^{th} hour. However, these tendencies do not suffice for an apparent mitigation of congestion as the peak value of the import profile, seen on the far left side, is higher than the Base Case and has an unequivocally similar active power flow for the peak ~20 hours.

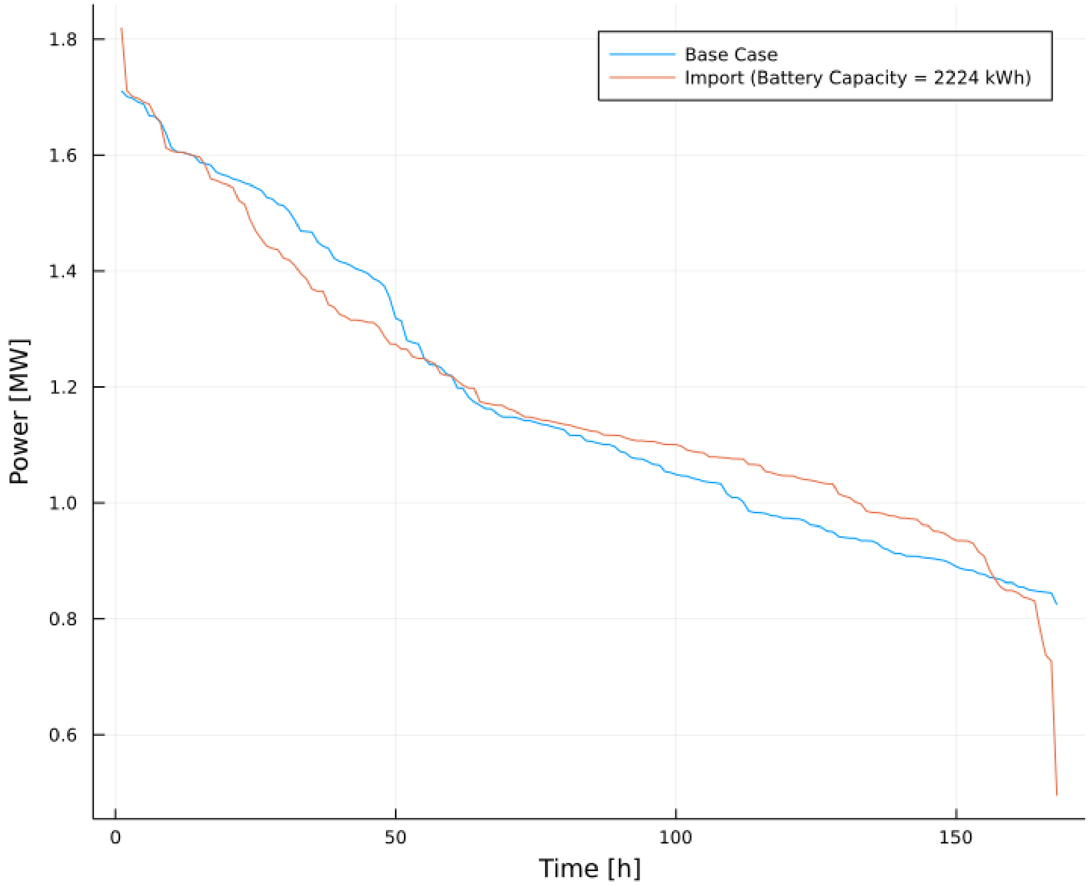

Figure 6.9: January - Duration plot of Case 1 active power import and Base Case active power import. Case 1 active power import is referred to as *Import (Battery Capacity = 2224 kWh)*.

6.3.2 Simulation Results: June

Judging by Figure 6.10 there is an improvement on import of power. The plots show a reduction of power flow during the peak power consumption hours for most days. Most of the charging of the batteries will happen during low power consumption periods. As for January, the simulation of the system in June experiences the same occurrence of a large surge in power flow during a high consumption hour. This is at approximately hour 13. The occurrence in this simulation does have the same cause and effect as the one in January, as seen from Figure 6.4 and Figure 6.11 which shows the same tendencies.

Table 6.2 reveals how there is a large decrease in profit compared to the simulation case in January. The microgrid owner has a total revenue of 52.69 NOK and a total revenue of 177.41 NOK by neglecting the network tariffs for one week of operation. As indicated in the last paragraph, there is also a large increase in peak active power value of 16.43 %.

Table 6.2: Case 1, June - Overview of costs and earnings from simulation, and statistical representation of the strategy performance.

	Metric	Value
Microgrid	Battery operation earnings [NOK]	129.29
	DER earnings [NOK]	130.48
	Farm electricity cost [NOK]	82.35
	Demand tariff cost [NOK]	741.74
	Production tariff earnings [NOK]	617.01
	Total revenue without tariff [NOK]	177.41
	Total revenue [NOK]	52.69
DSO	Reduction in peak value [%]	-16.43
	Standard deviation Import [%]	23.07 *
	Standard deviation Base Case [%]	24.1

* Not significantly different from the standard deviation in the Base Case

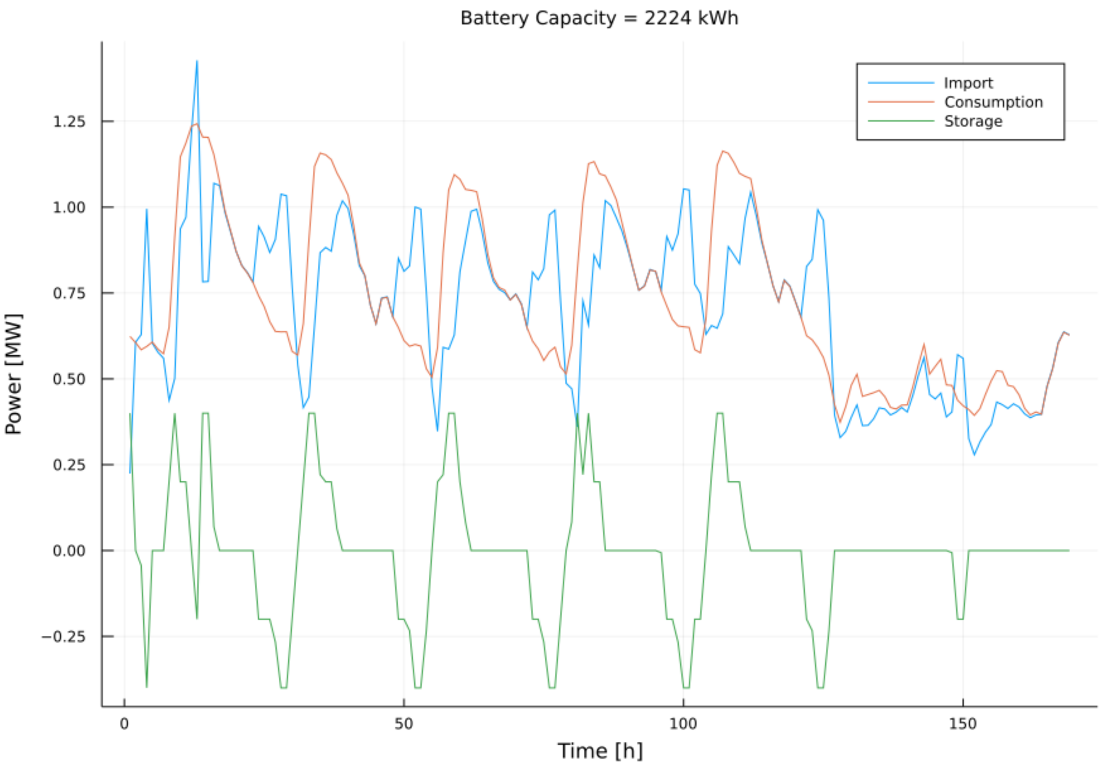

Figure 6.10: Case 1, June - Flow of total consumption of active power in the grid, the active power flow in and out of the battery, and the import of active power for the time horizon, T

The duration plot of Case 1 simulation in June compared to the Base Case simulation in June, seen in Figure 6.12, shows promising results in terms of shifting the active power import rating to the right. The operational strategy is, however, unsuccessful in decreasing the peak value.

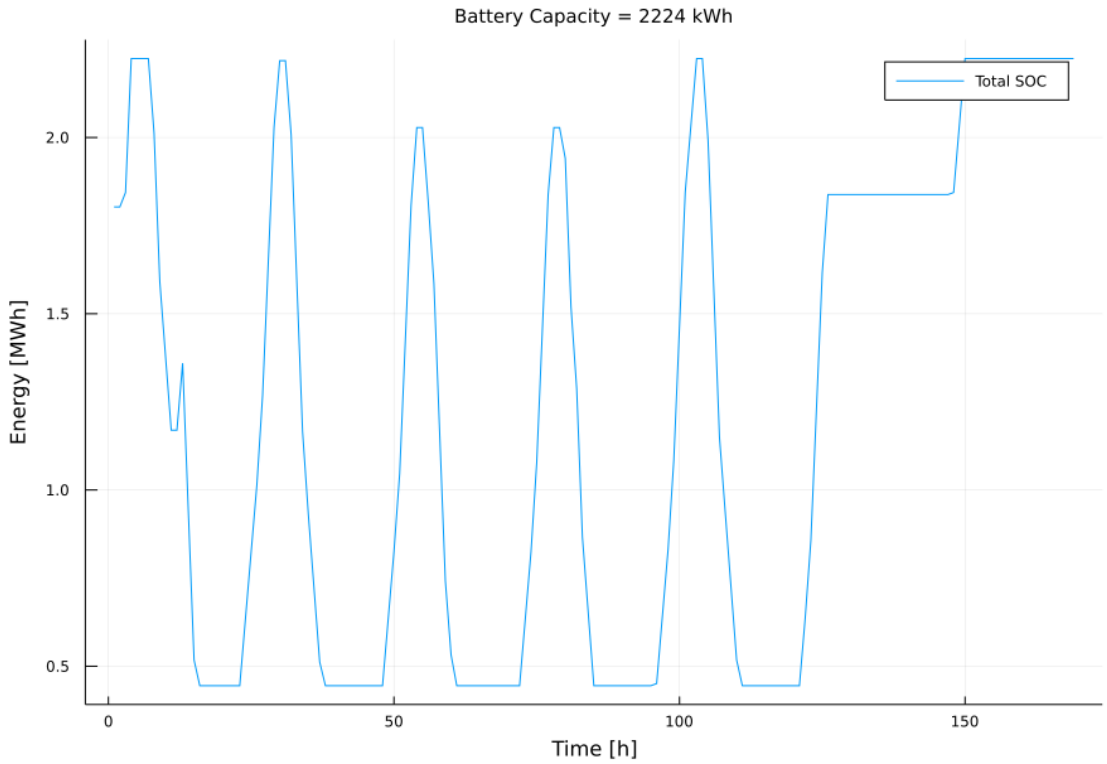

Figure 6.11: Case 1, June - Sum of state of charge of the two batteries for the time horizon, T.

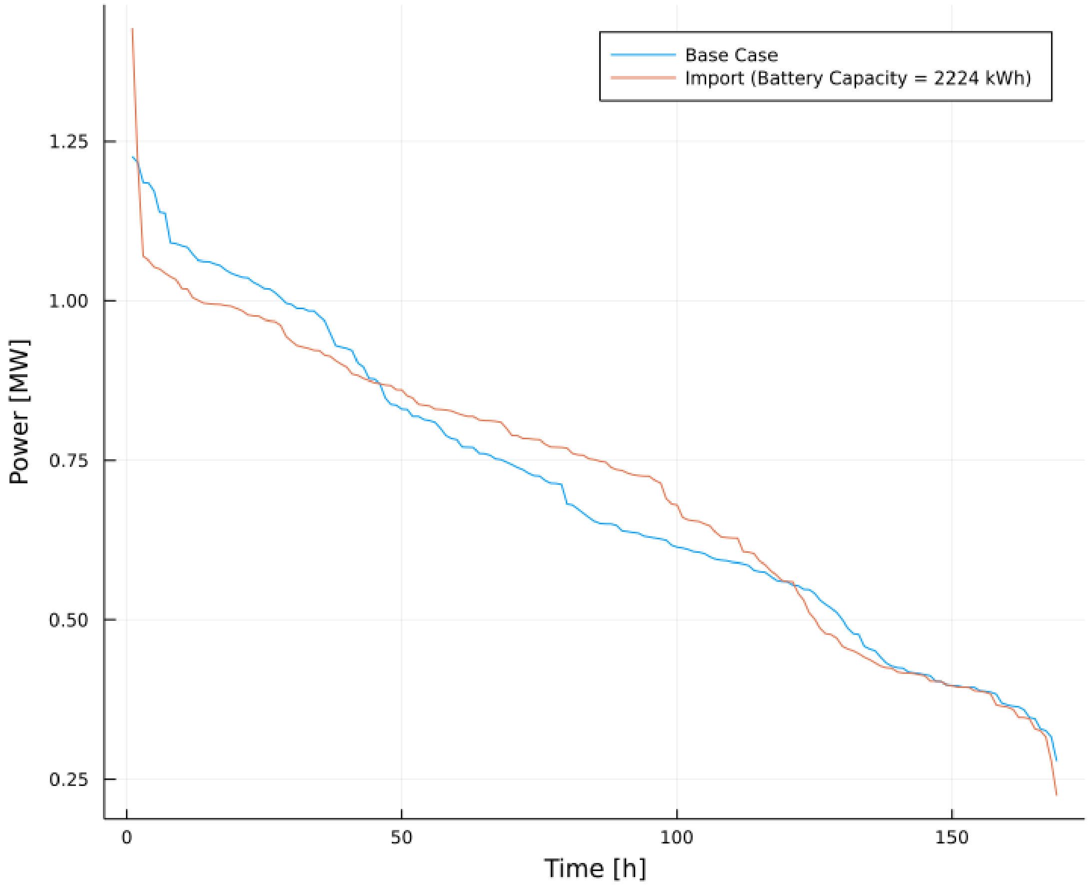

Figure 6.12: June - Duration plot of Case 1 active power import and Base Case active power import. Case 1 active power import is referred to as *Import (Battery Capacity = 2224 kWh)*.

6.4 Case 2: Weighted maximum Profit

This case is derived from Case 1 and is structurally similar to it. Case 2 has in the meantime a decisive difference in the cost of charging and discharging the battery. By weighting the Elspot price with the total consumption in the distribution grid for the individual time steps, the battery charge and discharge scheduling should to some degree adhere to local consumption conditions.

6.4.1 Simulation Results: January

Both Table 6.3 and Figure 6.13 has favourable characteristics in terms of perspectives from both the microgrid owner and the DSO. The overview of cost and earnings shows that the microgrid owner is not economically deceived by implementing a battery charge strategy that will benefit the DSO and still earns 446.11 NOK during this week, compared to the 630.19 NOK in Case 1. The fractional difference between Case 1 and Case 2 is even less when considering the total revenue without network tariffs. The peak value of the active power import is also reduced by 3.16 % and has a statistically significant difference between the standard deviation of Case 2 and the Base Case. This would imply that there is less deviation from the mean value of the import of active power flow, ensuring a more stable flow across the slack bus and less long-lasting high-strain periods on the transmission line. The same tendencies are depicted in the time series plot, Figure 6.13. The battery charges at lower consumption periods and discharges when the power consumption in the distribution grid is high.

Table 6.3: Case 2, January - Overview of costs and earnings from simulation, and statistical representation of the strategy performance.

	Metric	Value
Microgrid	Battery operation earnings [NOK]	560.66
	DER earnings [NOK]	1133.06
	Farm electricity cost [NOK]	1013.84
	Demand tariff cost [NOK]	905.78
	Production tariff earnings [NOK]	672.01
	Total revenue without tariff [NOK]	679.88
	Total revenue [NOK]	446.11
DSO	Reduction in peak value [%]	3.16
	Standard deviation Import [%]	17.71 *
	Standard deviation Base Case [%]	25.85

* Significantly different from the standard deviation in the Base Case

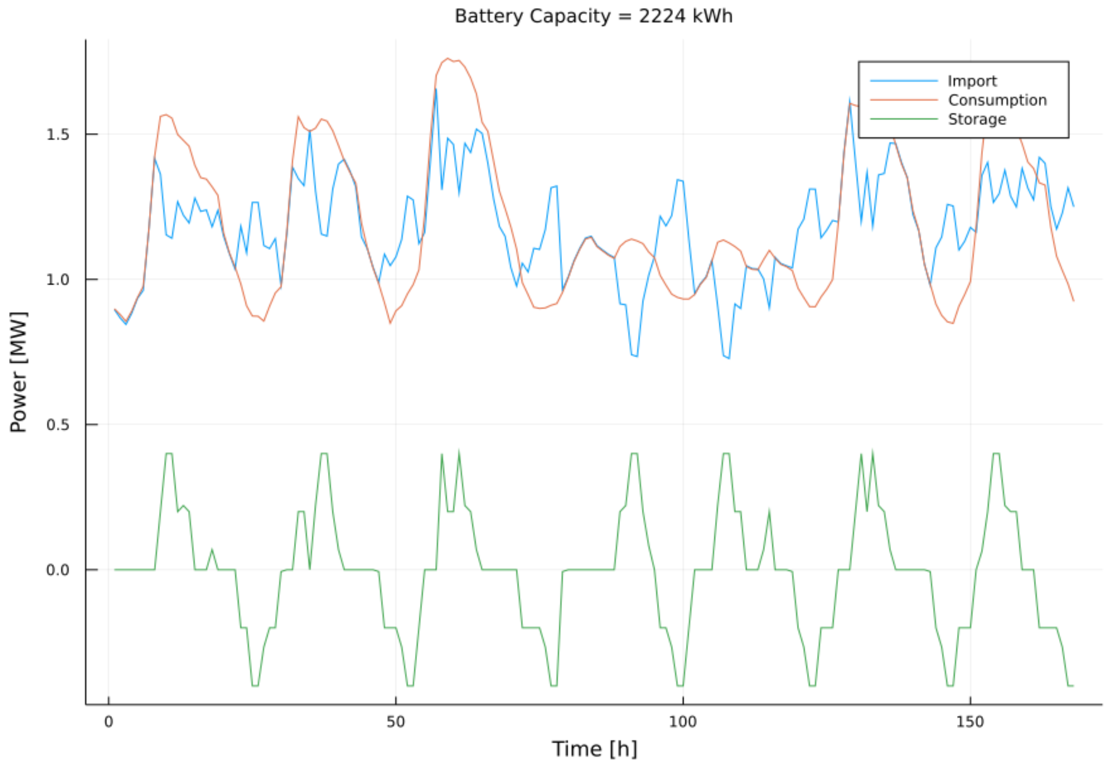

Figure 6.13: Case 2, January - Flow of total consumption of active power in the grid, the active power flow in and out of the battery, and the import of active power for the time horizon, T

Figure 6.14 reveals the significantly positive contribution to load flow shifting the strategy proposed in Case 2 has. The peak value of the power flow is reduced and a large area from the top ∼50 hours has been moved to the right of the duration curve. This implies that the hours with a high power flow have been reduced.

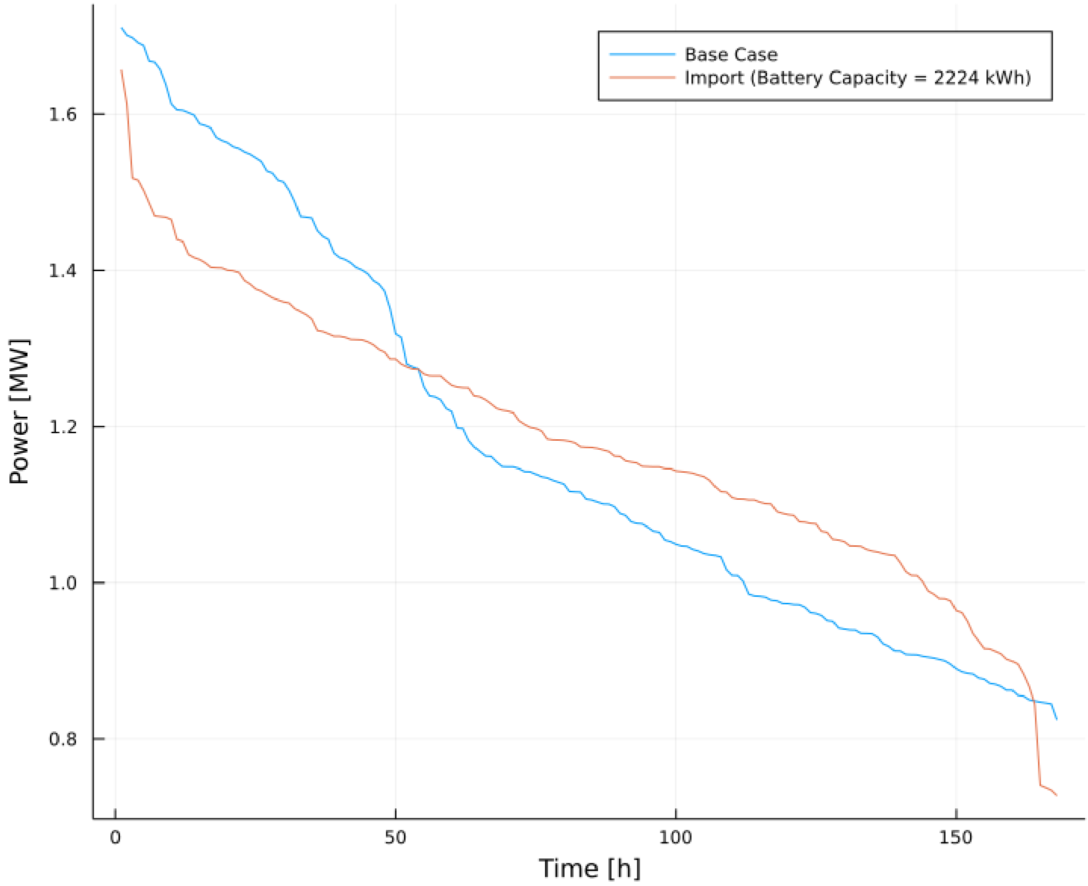

Figure 6.14: January - Duration plot of Case 2 active power import and Base Case active power import. Case 2 active power import is referred to as *Import (Battery Capacity = 2224 kWh)*.

6.4.2 Simulation Results: June

Similarly to the results in January, the simulation results from June has favourable characteristics. Compared to Case 1 simulation of June, there is a large performance improvement in terms of reduction of peak value and standard deviation. As seen in Table 6.4, the overall reduction in peak value is 12.78 %, compared to the increase in peak value of 16.43 % in Case 1. There is also a statistically significant reduction in the standard deviation of Case 2 compared to the Base Case. The total revenue of the farmer was 52.69 NOK for Case 1, while Case 2 generates a revenue of 25.68 NOK - the slight disadvantage of the weighted maximum profit objective formulation. Comparing the total revenue without tariff does, however, redeem this strategy somewhat, where Case 1 produces a revenue of 177.41 NOK and Case 2 160.80 NOK.

Figure 6.15 shows that the strategy presented in Case 2 has efficient congestion management and peak shaving capabilities. The dependency on Elspot price is still evident in the import curve. The first peak of the active power import curve is due to a large drop in price, seen in Figure 6.4. This strategy can therefore be perceived as a compromise between maximising the profit of the microgrid owner and providing congestion management and peak shaving services to the DSO.

Table 6.4: Case 2, June - Overview of costs and earnings from simulation, and statistical representation of the strategy performance.

	Metric	**Value**
Microgrid	Battery operation earnings [NOK]	112.67
	DER earnings [NOK]	130.48
	Farm electricity cost [NOK]	82.35
	Demand tariff cost [NOK]	769.49
	Production tariff earnings [NOK]	634.37
	Total revenue without tariff [NOK]	160.80
	Total revenue [NOK]	25.68
DSO	Reduction in peak value [%]	12.78
	Standard deviation Import [%]	19.54 *
	Standard deviation Base Case [%]	24.10

* Significantly different from the standard deviation in the Base Case

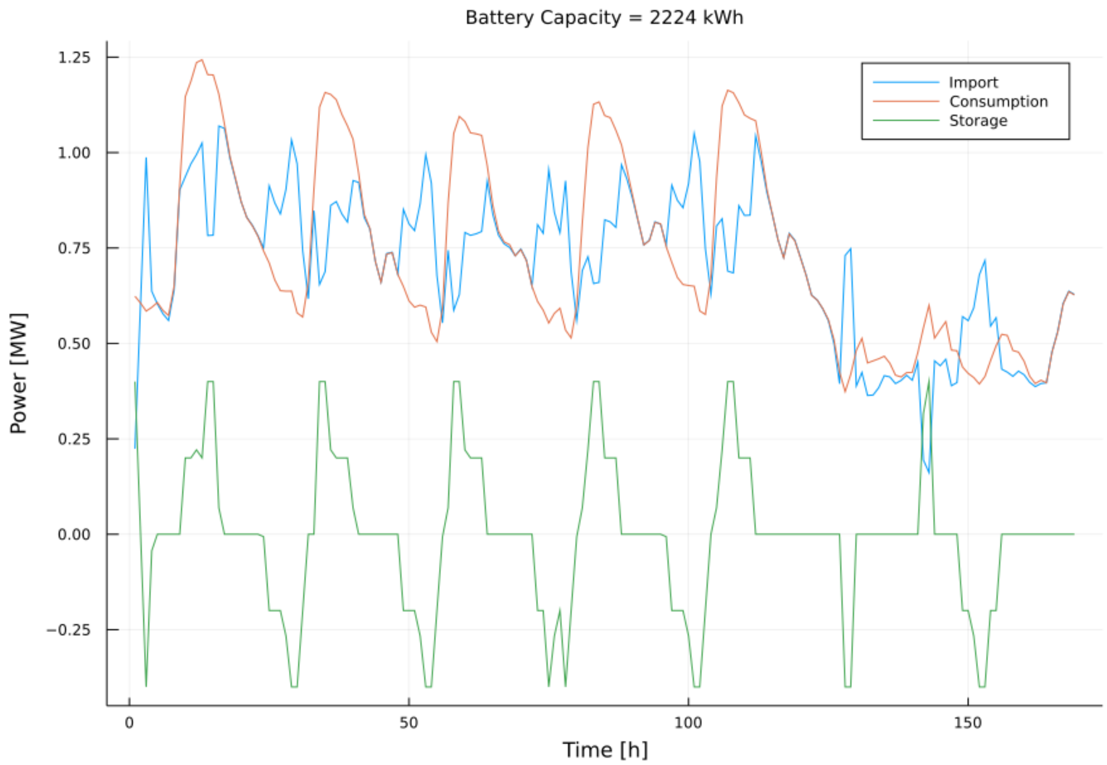

Figure 6.15: Case 2, June - Flow of total consumption of active power in the grid, the active power flow in and out of the battery, and the import of active power for the time horizon, T

The duration curve of this storage strategy simulated in June, presented in Table 6.4, depicts a very similar profile to the duration curve of the simulation in January. The peak values are largely decreased and a considerable fraction of the highly rated power flows have been shifted to the right of the duration curve. This implies a significant potential to reduce transmission line congestion and provide peak shaving services.

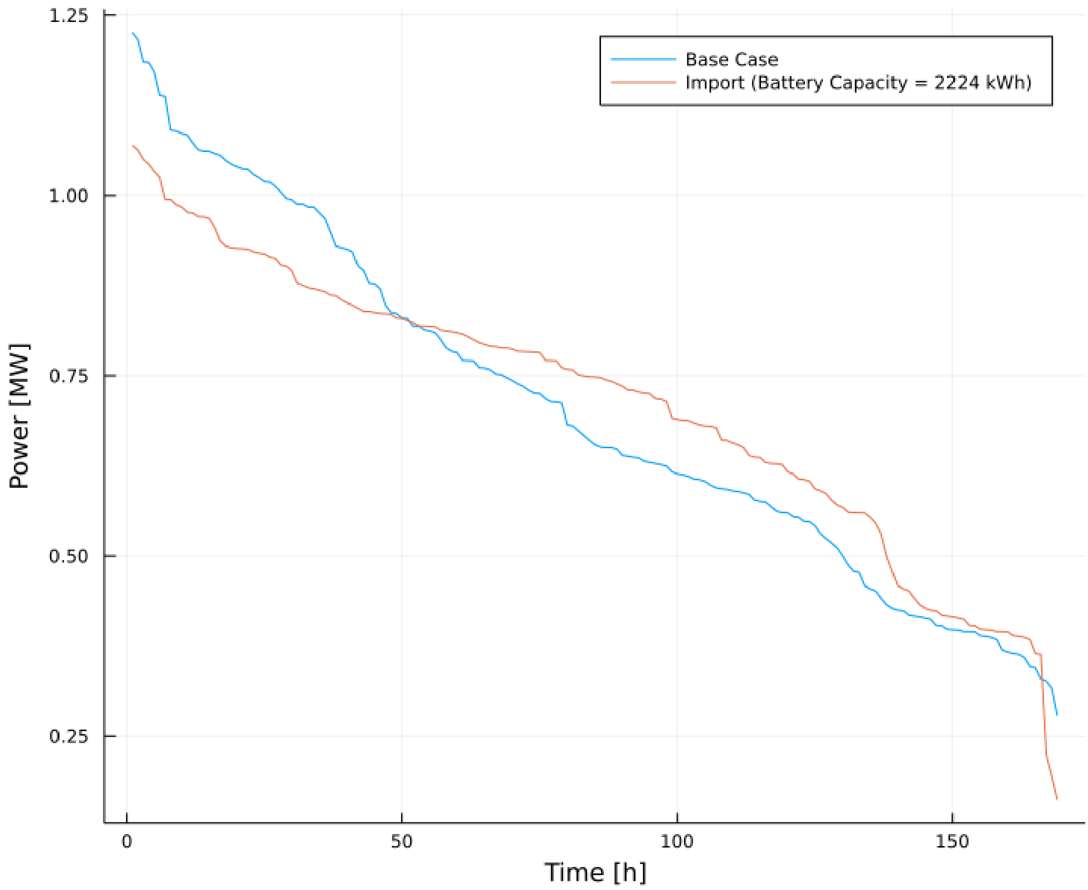

Figure 6.16: June - Duration plot of Case 2 active power import and Base Case active power import. Case 2 active power import is referred to as *Import (Battery Capacity = 2224 kWh)*.

6.5 Case 3: Peak Shaving

Case 3 represents the perspective of a DSO and the objectives they endeavour. The case strategy does not directly consider how the system operation will affect battery operational costs. However, a correlation between network power consumption fluctuations and Elspot price fluctuations will indirectly induce a profit for the microgrid owner. The quadratic cost function seen in Equation (5.20) will penalise large values of active power import, consequently reducing peak values. Through this, the system model will shave the peaks of the active power import curve.

6.5.1 Simulation Results: January

Table 6.5 shows an overview of the quantitative results from Case 3 simulation in January. Surprisingly, there is a relatively large revenue for the microgrid owner, a total of 318.62 NOK. The strategy also performs well in terms of congestion management and peak shaving capabilities, the best among all cases presented for January. The peak value of the active power import curve is reduced by 14.64 % and there is a statistically significant reduction in standard deviation from the Base Case. Figure 6.17 also reveals the successful mitigation of large peaks throughout the entire simulation horizon, T. The batteries will charge when the consumption levels are low and discharge when the consumption levels are high.

Table 6.5: Case 3, January - Overview of costs and earnings from simulation, and statistical representation of the strategy performance.

	Metric	Value
Microgrid	Battery operation earnings [NOK]	369.44
	DER earnings [NOK]	1133.06
	Farm electricity cost [NOK]	1013.84
	Demand tariff cost [NOK]	670.37
	Production tariff earnings [NOK]	500.34
	Total revenue without tariff [NOK]	488.66
	Total revenue [NOK]	318.62
DSO	Reduction in peak value [%]	14.64
	Standard deviation Import [%]	14.55 *
	Standard deviation Base Case [%]	25.85

* Significantly different from the standard deviation in the Base Case

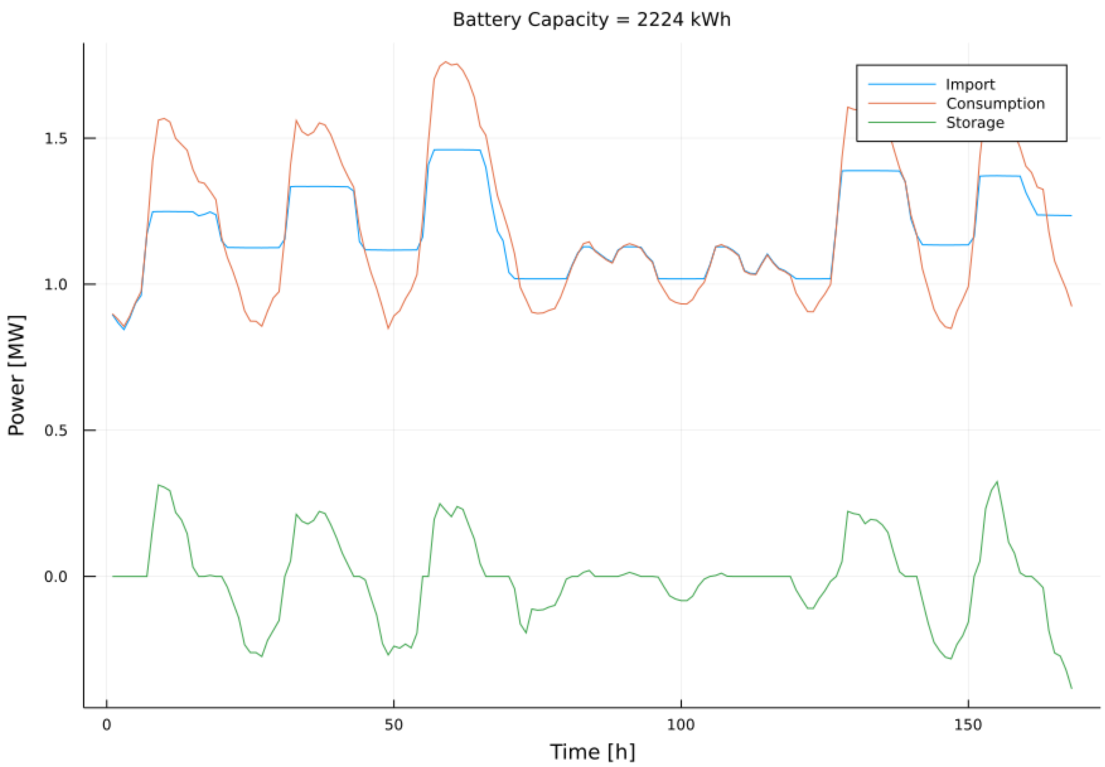

Figure 6.17: Case 3, January - Flow of total consumption of active power in the grid, the active power flow in and out of the battery, and the import of active power for the time horizon, T

A large improvement from the Base Case can be observed in Figure 6.18. A substantial shift towards the right is seen. The active power rating at which the power is delivered is hence at a much lower level utilising the battery charge schedule compared to a system without storage units. The maximum value is decreased and a large portion of active power from the top ~ 60 hours has been shifted downwards in the duration curve.

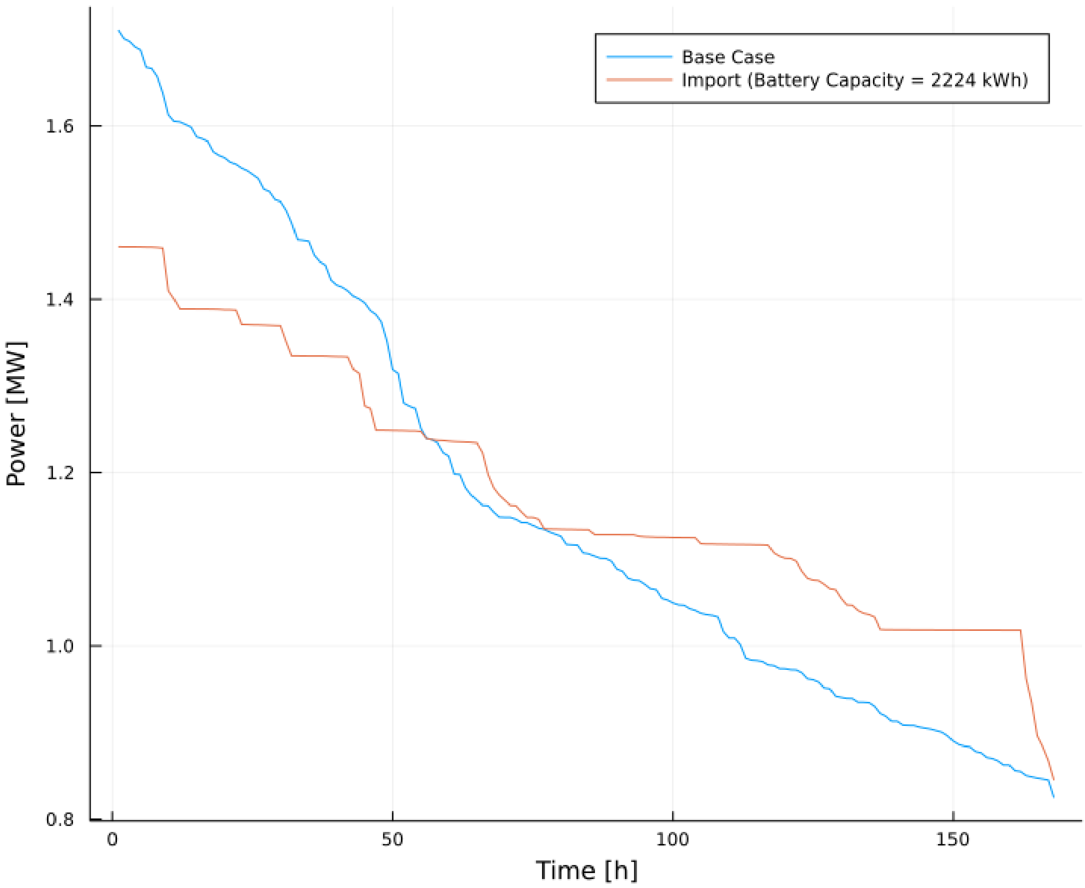

Figure 6.18: January - Duration plot of Case 3 active power import and Base Case active power import. Case 3 active power import is referred to as *Import (Battery Capacity = 2224 kWh)*.

6.5.2 Simulation Results: June

The simulation for June shows similar tendencies as the simulation in January. The operation benefits both the DSO and the microgrid owner. It has beneficial capabilities within both congestion mitigation and peak shaving, but also profitability for the microgrid owner. The microgrid owner is left with a total revenue of 38.89 NOK, which is surprisingly higher than the total revenue for Case 2. Comparing the total revenue without tariff does on the other side indicate otherwise, pointing towards the significance of network tariffs. The peak value is reduced by 21.96 %, while a large and statistically significant drop in standard deviation is also observed. An overview of the metric values is presented in Table 6.6.

Figure 6.19 shows an accurate depiction of peak shaving and valley filling. Large values are reduced and lower values are increased due to battery charge and discharge. The overall fluctuations in active power flow across the slack bus is reduced.

Table 6.6: Case 3, June - Overview of costs and earnings from simulation, and statistical representation of the strategy performance.

	Metric	Value
Microgrid	Battery operation earnings [NOK]	67.64
	DER earnings [NOK]	130.48
	Farm electricity cost [NOK]	82.35
	Demand tariff cost [NOK]	539.01
	Production tariff earnings [NOK]	462.13
	Total revenue without tariff [NOK]	115.77
	Total revenue [NOK]	38.89
DSO	Reduction in peak value [%]	21.96
	Standard deviation Import [%]	16.58 *
	Standard deviation Base Case [%]	24.10

* Significantly different from the standard deviation in the Base Case

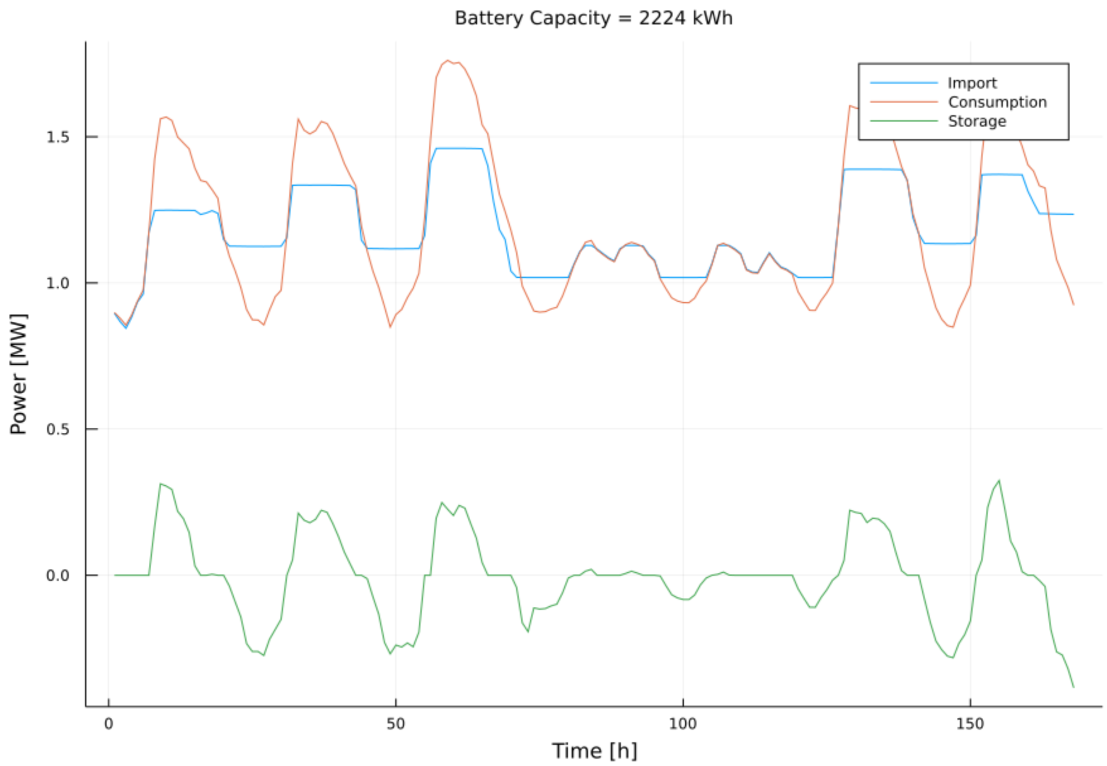

Figure 6.19: Case 3, June - Flow of total consumption of active power in the grid, the active power flow in and out of the battery, and the import of active power for the time horizon, T

Similarly to January the battery charge and discharge strategy produce a favourable duration curve. The overall curve is flattened, ensuring that power transfer into the local distribution grid will occur at lower power ratings. The duration curve is seen in Figure 6.20.

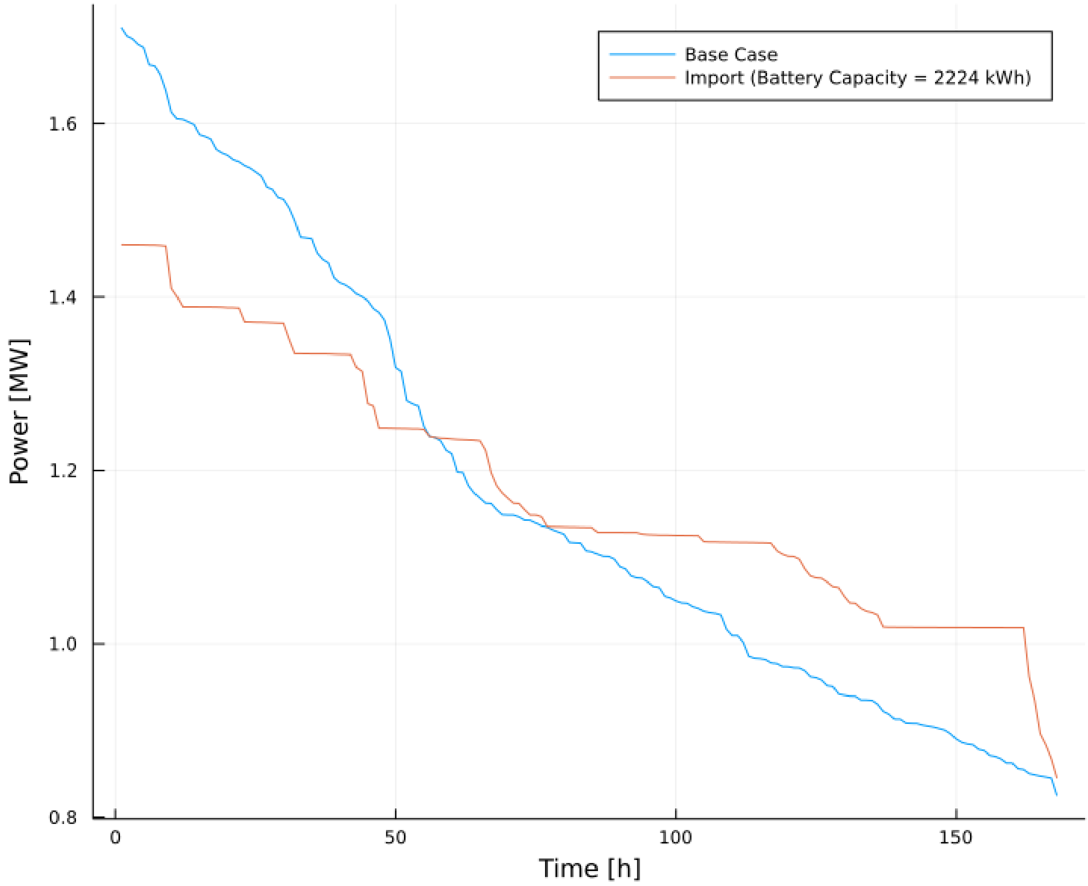

Figure 6.20: June - Duration plot of Case 3 active power import and Base Case active power import. Case 3 active power import is referred to as *Import (Battery Capacity = 2224 kWh)*.

6.6 Sensitivity Analysis

In order to observe the system's sensitivity to battery capacity, a sensitivity analysis is performed. The sensitivity analysis will regard Case 2 simulated in January. Several battery capacities are simulated. As seen in Table 5.1, the system model has 2 battery energy storage systems installed. The energy rating of BESS 2 will be changed for this analysis, while the energy rating of BESS 1 will remain the same.

A comparison of simulations in which the total battery capacity of the microgrid is 555 kWh, 1108 kWh, 1662 kWh, and 2224 kWh is presented in Figure 6.21. The results reveal the notably large increase in battery operation earnings from 554 kWh to 1108 kWh. The earnings have almost doubled for a doubled capacity. The increase in total revenue without tariff is not as large as there are constant costs and earnings associated with the operation as well. Tripling the battery capacity does not triple the battery operation earnings and the profit seems to stagnate when nearing 2224 kWh of installed capacity. The congestion management and peak shaving capabilities are evidently similar for 554 kWh and 1108 kWh of installed capacity. The change in the reduction of peak value is relatively small, but the standard deviation shows that having a larger battery capacity installed gives a modest advantage.

Table 6.7: Overview of costs and earnings from the sensitivity analysis simulations, and statistical representation of strategy performance utilising the individual battery capacities.

	Metric	Value			
		554 kWh	1108 kWh	1662 kWh	2224 kWh
Microgrid	Battery operation earnings [NOK]	220.78	409.22	528.63	560.66
	DER earnings [NOK]	1133.06	1133.06	1133.06	1133.06
	Farm electricity cost [NOK]	1013.84	1013.84	1013.84	1013.84
	Demand tariff cost [NOK]	366.58	565.84	735.64	905.78
	Production tariff earnings [NOK]	282.87	428.18	549.53	672.01
	Total revenue without tariff [NOK]	340.00	528.44	647.85	679.88
	Total revenue [NOK]	256.29	390.78	461.74	446.11
DSO	Reduction in peak value [%]	1.14	1.35	3.16	3.16
	Standard deviation Import [%]	24.15	22.60 *	20.06 *	17.71 *
	Standard deviation Base Case [%]	25.85	25.85	25.85	25.85

* Significantly different from the standard deviation in the Base Case

Figure 6.21 shows the active power import to the distribution grid for the four battery capacities examined in the sensitivity analysis. The figure substantiates the statistical results presented in Table 6.7 to a large extent. An evident characteristic is the rise in performance regarding reducing active power peaks, not only the highest peak, in the system with a total battery capacity of 2224 kWh compared to the other battery capacities.

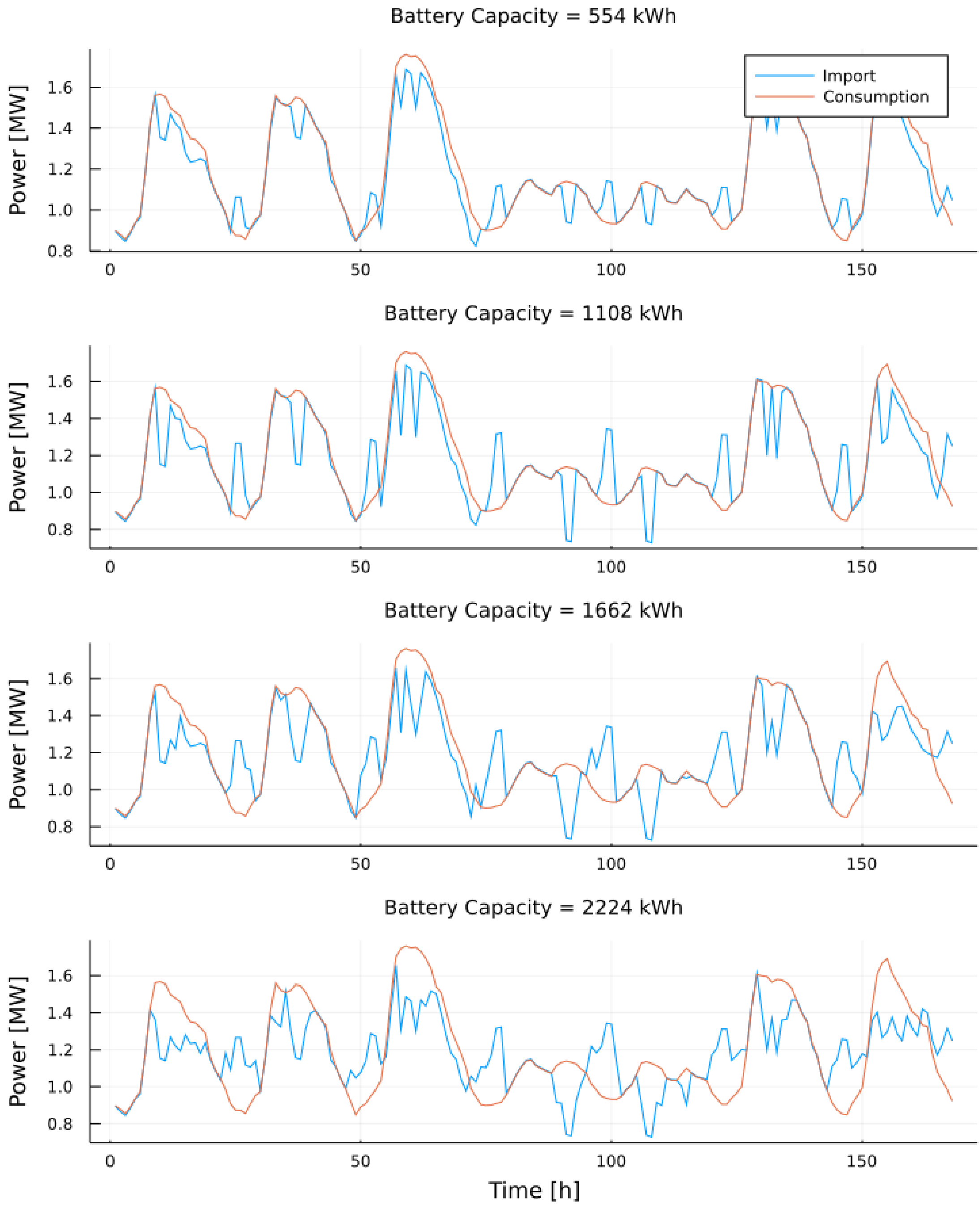

Figure 6.21: Plots for the power import and network consumption for four different values for the installed battery capacity in the microgrid.

The same sensitivity analysis was conducted for Case 1 and Case 3. The results show similar tendencies as the presented analysis for Case 2, and can be found in Appendices C.1 and C.2.

Chapter 7

Discussion

The employment of multiple strategies has been carried out in this case study. It has helped identify in what areas the objectives of the DSO and the microgrid owner differentiate and concur, but also examined how the battery capacity installed in the microgrid will affect the operation of the system. How have seasonal and power system characteristics affected the operation of the system model? Section 7.1 discusses this.

The discussion will also investigate how the existing Norwegian market model and regulations facilitates for the self-interest of market players to provide peak shaving and congestion management services. It will also evaluate the maturity of the proposed concept with regard to the gradually changing power system. Does the concept reflect future needs? This is discussed in Section 7.2.

Drawbacks related to the model structure and assumptions made are acknowledged in Section 7.3. Finally future work is discussed in Section 7.4.

7.1 Model Operation Assessment

The case study simulations have proved that there are several factors to consider when evaluating the performance of the case strategies. Battery discharge and charge scheduling, seasonal effects on energy resources, pricing schemes, network tariffs, and congestion management and peak shaving capabilities are among the most important. The case study implements the aspect of both the DSO and the microgrid owner. Case 1 is single-minded in its pursuit to maximise the profit of the microgrid owner, while Case 3 is single-minded in terms of its peak shaving design. Case 2 can be perceived as a compromise between the two. An overview of the results can be found in Table 7.1.

Table 7.1: Overview of costs and earnings, and statistical representation of strategy performance of all cases.

	Metric	January			June		
		Case 1	Case 2	Case 3	Case 1	Case 2	Case 3
Microgrid	Battery operation earnings [NOK]	713.46	560.66	369.44	129.29	112.67	67.64
	DER earnings [NOK]	1133.06	1133.06	1133.06	130.48	130.48	130.48
	Farm electricity cost [NOK]	1013.84	1013.84	1013.84	82.35	82.35	82.35
	Demand tariff cost [NOK]	803.68	905.78	670.37	741.74	769.49	539.01
	Production tariff earnings [NOK]	601.19	672.01	500.34	617.01	634.37	462.13
	Total revenue without tariff [NOK]	832.68	679.88	488.66	177.41	160.80	115.77
	Total revenue [NOK]	630.19	446.11	318.62	52.69	25.68	38.89
DSO	Reduction peak value [%]	-6.38	3.16	14.64	-16.43	12.78	21.96
	Standard deviation Import [%]	23.74	17.71 *	14.55 *	23.07	19.54 *	16.58 *
	Standard deviation Base Case [%]	25.85	25.85	25.85	24.10	24.10	24.10

* Significantly different from the standard deviation in the Base Case

Case 1, in which the non-weighted maximum profit strategy was implemented, showed little influence on the overall power system performance with relation to congestion management and peak shaving and did in fact negatively impact peak value reduction. As seen in Table 7.1, the peak value is increased for both January and June. The improvement in *Standard deviation Import* is also insignificant for both months. This strategy will on the other side largely profit the microgrid owner. It produces the highest earnings from battery operation and total revenue among all cases. The indifference to ancillary services is, however, obvious and will to a little degree reflect the objective of the DSO.

A striking tendency of Case 1 is the sensitivity to fluctuations in price - a small change in price induces major responses in charging and discharging of the battery (see Figures 6.2 and 6.7). Weighting Case 1 with the total load in the network, as done in Case 2, addresses the issue of little correlation between network consumption fluctuations and Elspot price fluctuations, but also mitigates for some of the sensitivity to price fluctuations. The simulation results show that the problem formulation produces beneficial operational characteristics for both the DSO and the microgrid owner. The largest power flow in the import transmission line is reduced for the case simulation of both January and June, as seen in Table 7.1. The microgrid owner gains profit from the operation, a somewhat smaller profit compared to Case 1, but will largely support the grid infrastructure with peak shaving. The strategy is evidently agreeable with the aims and objectives of either party involved.

The Case 3 objective function reflects the DSO target. The quadratic formulation produces active power import profiles which distinctively depict peak shaving and valley filling characteristics. The strategy formulation has superior peak shaving and congestion management capabilities to the other cases. The reduction in peak value for January and June is much higher than for the other cases. This case also has the lowest *Standard deviation Import*, which corroborates the results in Figures 6.17 and 6.19. For the simulation of

Case 3 in January, the total revenue is the lowest, but will still produce a total revenue of 318.62 NOK compared to the 446.11 NOK total revenue of Case 2. The simulation in June will, surprisingly, produce a total revenue that ranks above Case 2 in June. This is not recognised in the total revenue without network tariffs. The tendency observed would therefore indicate that Case 2 produces an increase in active power demand to active power feed-in ratio, consequently increasing the demand tariff to production tariff ratio. The same is not observed in Case 3.

To summarise the findings in the three cases:

- The microgrid owner will have the largest total revenue in January, i.e. winter season load profiles, DER production profiles, Elspot price profiles, and network tariff has traits that makes it more profitable to apply this concept in this period.
- Case 1 is the best strategy for profiting the microgrid owner. It should, however, be emphasised that all cases are profitable for the microgrid owner. Concluding on the extent of the profitability and the feasibility in adopting the strategies proposed in real-life systems falls out of scope for this thesis, as it does not consider the cost of installation, operation or maintenance.
- There is a large difference in peak shaving and congestion management performance between the three different cases. Case 1 has a close to negligible influence on the power flow in the import transmission line. Case 2 shows promising results for providing these services, especially in June. Case 3 is, not surprisingly, the most efficient strategy for reducing the largest power flow peaks.

This thesis has not presented installation and unit costs related to microgrid and battery operation. Concluding on the optimal battery storage capacity will consequently be challenging. The sensitivity analysis of the installed battery capacity will nonetheless serve a purpose in giving an indication of what to expect from installed battery capacity. A recognisable trait in the results of the sensitivity analysis, seen in Section 6.6, is the percent change in battery operation earnings between the various battery capacities. It is obvious that the fractional increase in battery capacity installed does not equate to the same fractional increase in battery operation earning for all increments of battery capacity. Table 6.7 does regardless show a close to doubling in battery operation earnings from an installed battery capacity of 554 kWh to 1108 kWh. For the system model, there is a price ceiling that is predominantly restricted by the converter capacity. This limits the incremental profit from installing additional battery capacity.

7.2 Concept Maturity

7.2.1 Market Framework

As referred to in Section 2.2, data reliability and availability would play a crucial role in the transition to flexible networks and will mitigate the power system vulnerability to variations introduced by variable energy resources and new grid elements. As this thesis chose a deterministic approach to 'predicting' the variations in the power system, probabilistic forecasts have received little recognition. Applying the methodical concepts and structure of the ancillary service system presented in this thesis to a real-life system would in reality be extensively contingent on communication systems and reliable prediction models. The ability to perform peak shaving and exploit price fluctuations is dependent on this, as the battery scheduling needs to take into account future movements in DER production levels, Elspot prices, and load demands. There are limitations associated with the existing communication systems in Norway, but the roll-out of smart meters could help realise the concept presented in this thesis.

As indicated in Sections 2.2.1 and 2.3, there is a general lack of clear and well-defined laws and regulations that apply to the case study system and the strategy it implements. The case study introduced a system in which the rated power at the connection point to the distribution grid was above 100 kW, as per current regulatory standards is above the limits of what a prosumer is defined as. Lacking in network tariff standards and reimbursement standards for ancillary services, the case study aimed at uncovering if the microgrid owner could gain a profit independently of these (using an assumed network tariff), while at the same time providing peak shaving and congestion management capabilities. The simulation results proved that this outcome is attainable. Case 2 and 3 implement strategies that have good peak shaving and congestion management capabilities, while also being profitable for the microgrid owner.

The pricing scheme of the power market will naturally dictate the response in electricity prices to variations in the power system. The current model in Norway and large parts of Europe is a day-ahead zonal market model. As mentioned in Section 2.3.2, the nodal pricing model will include the perspective of local price signals, hence the price will have a larger correlation with congestion tendencies in the local electricity grid. The simulations presented in the case study are based on prices from NordPool - a zonal market scheme. Local characteristics are consequently largely neglected in the prices implemented into the optimisation model. Case 2 tries to address this issue and seeks to alleviate for little correlation between electricity prices and demand. The case can therefore be regarded as implementing a pricing scheme that is analogous to nodal pricing. As indicated in Section 7.1, the Case 2 strategy is evidently agreeable with the aims and objectives of both the DSO and the microgrid owner. Case 1, on the other hand, utilises a zonal pricing scheme. As the results show, the microgrid from Case 1 will not be an asset for peak shaving and congestion management. This could point towards the advantages of a nodal pricing model for these services.

7.2.2 Incentives

The DSO has a clear incentive for mitigating congestion issues and performing peak shaving, such as is done in Case 2 and 3. One of the most prevalent benefits is deferring from unnecessary investments in grid infrastructure. Utilising the microgrid presented in the case study proved to largely influence the active power flow of a critical import line and the strategy could prevent congestion on this line. Section 2.2 also states that distributed production and flexible loads can contribute to better security of electricity supply in terms of energy availability, power capacity, reliability of supply, and power quality. Advocating for the implementation of a market framework that would favour the operation of ancillary service systems could therefore pose as valuable to the DSO in the future.

Case 1, 2 and 3 corroborates the concept of profitable power trading through exploiting market price fluctuations (i.e. battery operations earnings), while concurrently providing peak shaving and congestion management services. There are therefore economic incentives for an owner of flexible resources to provide such services to the DSO.

Section 2.1 refers to how Norway is experiencing an increase in DERs, EVs and active consumers in the distribution grid. This increase is associated with challenges and opportunities for the operation of the distribution grid. This thesis advocates for exploiting these opportunities and has shown that there are incentives to do so. It will also argue that the results are translatable to other systems and can give an indication of how smaller systems, such as EVs, can collectively impact the operation of the distribution grid. Typical battery size of an EV is 88 kWh (Ford Mustang Mach-E) [71]. A neighbourhood with several EVs is translatable to systems in the sensitivity analysis. As implied by Table 6.7, this neighbourhood could have an impact on congestion management.

7.3 Model Deficiencies and Assumptions

7.3.1 Unit Modelling and Data

As argued in Section 2.3.3, the *Demand tariff cost* and *Production tariff earnings* are solely based on the assumption that the DSO would commit to a network tariff contract that would be favourable to the microgrid owner in return for ancillary services. In a situation in which the microgrid owner would not provide congestion management and peak shaving services, such as in Case 1, the DSO would not be as compelled to provide terms and conditions favourable for power trading. Case 1 could therefore prove to be non-profitable considering standardised tariffs. Thus, implementing the strategy could prove to be infeasible with the market structure and regulations of today, and the future.

As recognised in Section 6.3.1, there are tendencies revealing the short-term perspective required for finding the optimal solution for the case simulations. The most distinct indication of this is the batteries reaching the maximum depth of discharge for almost every day in the simulation (see Figure 6.8). This characteristic points towards the system not being able to store sufficient energy for mitigation demands that exceed the scope of one day ahead; meaning that the energy stored in the battery will most likely be utilised for the coming day. This can suggest that the implementation of a stochastic model for DER and price anticipation would require a shorter time horizon than the one implemented in this case study. It should, however, be acknowledged that the system model is not adjusted for seasonal changes, such as January-to-June, or mitigation demands relative to transmission line capacities. The optimisation strategy will consequently apply a maximum-effort strategy to mitigate larger peaks and is inconsiderate to whether these peaks approach the transmission line rating. The limited scope of time would therefore most likely only apply to systems in which the BESS capacity would approximately equate to the energy required for avoiding congestions for a time period of one day.

DSOs are incentivised to perform peak shaving and congestion management in power systems by diminishing the stress on transmission lines. As discussed in Section 2.2.3, the limiting factor for the power flow in transmission lines is the line temperature. For most lines, stable temperatures are reached within approximately 5-30 minutes. Large power flows exceeding this time limit can heat up the line and cause deterioration. Having a system model simulation with a time step length of one hour can therefore introduce inaccuracies in terms of analysis and concluding on performance attributes of the system. Shorter time periods within the time step of one hour could in reality reach power flow levels that exceed the thermal limit of the transmission line.

The sensitivity analysis put focus on the sizing of the battery. The simulations conducted in the first parts of Chapter 6 assumed a total installed battery capacity of 2224 kWh. The active power consumption in the model distribution grid is in the meantime averaging at approximately 1.3 MW in January. Bearing the average value in mind the total installed capacity in the simulations is rather large and will for most private individuals pose as an unprofitable investment. This can additionally challenge the decision to model the HESS as a BESS, per described in Section 5.1.2.

The discharge and charge strategies implemented in the system model are largely dictated by Elspot price fluctuations. Seeing that the year 2020 experienced somewhat abnormal fluctuations in prices, the simulation results can be skewed as a result of this. This will perhaps mostly regard simulations made for June - a month with exceptionally low electricity prices (see Figure 6.2 and Figure 6.4).

7.3.2 Objective Function Formulation

A peak shaving objective function formulation should take the rated thermal limit of the transmission line into consideration. This would eliminate issues regarding unnecessary mitigation in summer periods in which the active power consumption is low. Case 2 and 3 would possibly not be implemented as-is for the month of June if this were taken into consideration.

A rigid objective function formulation would in many cases reward charging in periods of high output from DERs. None of the objective functions in the case scenarios presented in this thesis does that. Prioritising this trait in charging strategy could induce lower transmission losses, but would concurrently reduce the profitability of the microgrid owner.

A typical goal for microgrids is self-sustainability. Sandbakken Microgrid, presented in Section 2.2.5, applies a strategy that prioritises self-sustainability and subsequently supports the distribution grid with peak shaving and congestion management services. The implementation of this perspective in the objective function formulations could be advantageous in the event of poor energy availability in the distribution grid.

7.4 Future Work

The case study presented in this thesis has examined the profitability of power trading in conjunction with ancillary service provision using a predefined BESS energy capacity rating. As indicated in Section 6.6, this rating has a large influence on earnings, cost, and overall strategy profitability. Future work could conduct an analysis of the benefits of adopting various BESS energy capacity ratings for reducing the imbalance costs associated with DER production fluctuations. Optimising the energy storage design could include perspectives from this thesis, by taking into account both the profitability of energy storage owners and ancillary service capabilities. As mentioned in Section 7.3.1, this would also apply to the HESS. Further analysis could ratify it as being favourable to model the HESS as-is and not approximate its use to a BESS.

With an increasing penetration of PVs and wind power generators, power system operators are introduced to operational problems as a consequence of the variability and the non-programmability of solar radiation and wind. There is also a variability associated with the power consumption. Accounting for these uncertainties is not done in the case study presented in this thesis, which was based on a deterministic approach to DER, power consumption, and price anticipation. The system model could be extended by implementing a stochastic model for predicting these variances. In doing so, the case study would to a higher degree reflect real-life control systems. As there are inaccuracies associated with stochastic models, the results obtained in this thesis would not be expected.

For an MPOPF problem with energy storage systems, such as the modelled system in this thesis, a stochastic model will largely influence charge/discharge scheduling. The aforementioned tendency of the short-term perspective (i.e. the length of the planning horizon) required for optimal operation of the system would need to be investigated. Regardless, it could be beneficial to include long-term stochastic considerations. As there are greater uncertainties associated with long-term forecasts compared to short-term forecasts, penalising the objective function differently within the two time horizons could help with mitigating the uncertainty associated with the realisation of forecasted values. This would mean that energy storage scheduling is to a greater extent dictated by forecasts within the operational planning horizon than beyond. The optimisation model could also benefit from being implemented using a rolling horizon approach.

Chapter 8

Conclusion

This thesis has investigated if there are drivers in the current market structure that encourage microgrids to provide peak shaving and congestion management services. The study is motivated by the ongoing development in the distribution grid and the potential in exploiting available resources. The simulations use measured power production and load demand data from Rye Microgrid, as well as historical electricity prices from Nord-Pool. The optimisation models are based on a deterministic and nonlinear approach to multi-period optimal power flow. The optimal energy storage system scheduling is found for three different cases. By simulating these cases for two periods, the seasonal variations in DER production, electricity price, and consumption levels are taken into account. The following case summary is given:

- *Case 1 - Non-Weighted Maximum Profit*
  This strategy will largely profit the microgrid owner. It produces the highest earnings from battery operation and total revenue among all cases. The indifference to ancillary services is, however, obvious and will to a little degree reflect the objective of the DSO.
- *Case 2 - Weighted Maximum Profit*
  The microgrid owner profits from the operation, a somewhat smaller profit compared to Case 1, but will largely support the grid infrastructure with peak shaving. The strategy is evidently agreeable with the aims and objectives of either party involved.
- *Case 3 - Peak Shaving Import*
  The strategy formulation has superior peak shaving and congestion management capabilities to the other cases. The microgrid owner profits from this strategy as well.

Employing market-based instruments for encouraging market players to provide ancillary services is largely dependent on price signals reflecting the situation of the local distribution grid. The significance of this is evident from the simulation results from Case 1 and 2. A comparison of the two cases showed that electricity prices that recognises congestions would help the objectives of the microgrid owner and the DSO to align. The quantitative results, therefore, promote implementing a nodal pricing scheme. It is, however, largely acknowledged that this transition is complicated and is inhibited by immature technology and regulations. A more accessible solution could be regulating network tariffs that encourage favourable end user consumption and production.

The thesis raises the question: does the existing Norwegian market model and regulations facilitate for the self-interest of market players to provide peak shaving and congestion management services? The short answer would be; yes. The quantitative results on both economical and peak shaving performance suggest that this is true. Case 3 substantiates the statement; the microgrid owner makes a profit and provides peak shaving. The translation of this notion to other systems is, however, strictly contingent on what regulations apply to the end user. The microgrid in the case study has characteristics that put it subject to poor legislative standards, which led to assumptions being made regarding network tariffs. The case study will, regardless, indicate how smaller systems, that are subjugated to well-defined regulations, can collectively improve the operation of the distribution grid and have a self-interest in doing so.

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Appendix

A Flow chart of IPOPT Algorithm

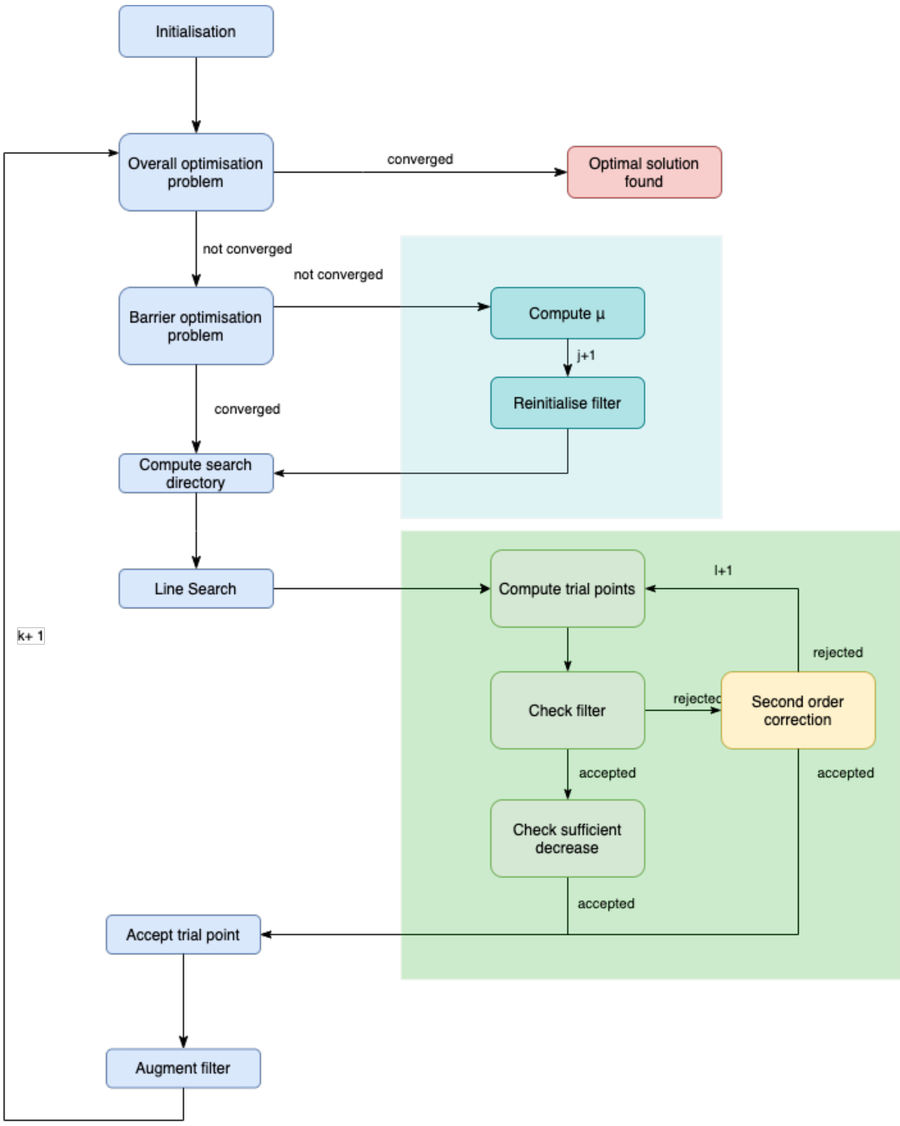

Figure 1: Flow chart of IPOPT Algorithm.

B Software

B.1 Code Architecture

Figure 2 shows the file structure of the project. This can provide a valuable understanding of how the simulation is conducted. `Network_model` is the JSON-file that contains the network specification; power system units and topology description. `Time_series` contains the scheduling of the PV units, wind turbine and the loads in the network. `end_user_distribution.csv` hold information regarding the bus location of the loads in the system and is depicted in Table 5.3. As discussed in Section 5.3, the cost values utilised in the model are based on Elspot prices. These are found in `elspot_prices_2020.csv`.

The optimisation functionalities are found in the `Julia` folder. `Input.jl` contains functions that reads JSON-files and CSV-files, and parses this data to suitable container formats. The main file for the optimisation model is `PMModule.jl` and acts as the control unit for the data flow and structure. Per described in Section 3.2, a MPOPF problem divides the time horizon, T, into t time steps. PowerModels structures this problem in something called a *multi-network*. Each network in a multi-network represents one time step. `PMModule.jl` will assign values to each network with data from `elspot_prices_2020.csv` and `Time_series`, using `end_user_distribution.csv` to allocate these correctly. `OptimisationProblem.jl` builds the optimisation problem - objective functions, variables and constraints. PowerModels has a large set of built-in functionalities regarding definition of variables, constraints and objective functions, but also facilitates for custom definitions of these. These are found in `Variable_custom.jl`, `Constraint_custom.jl` and `Objective_custom.jl`. The results are analysed and plotted in `Calculation.jl` and `Plot.jl`. The plots are saved to the image files in `Plots` folder.

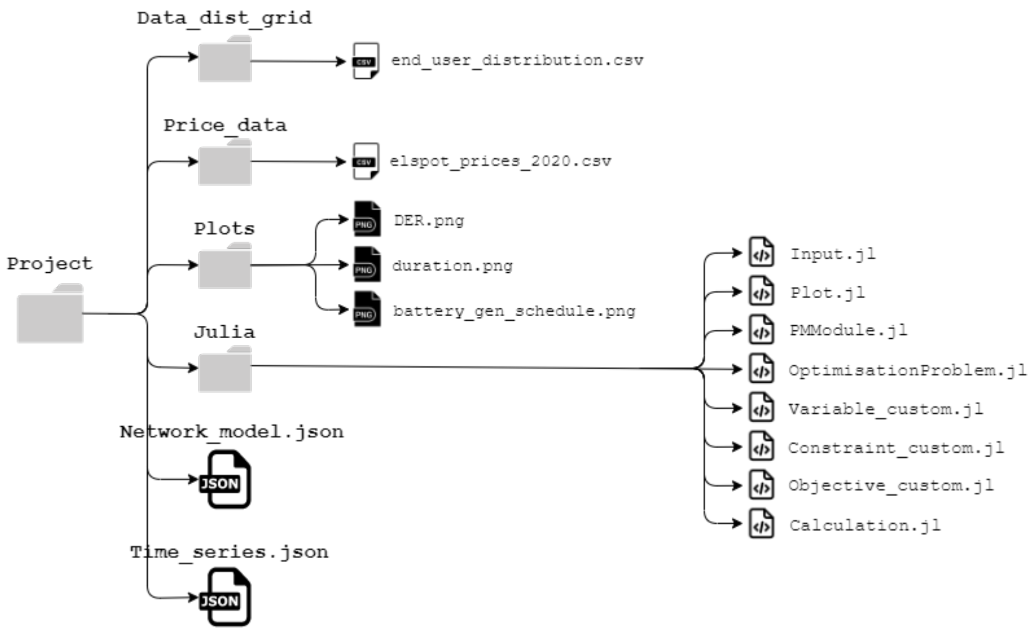

Figure 2: File structure of the Optimisation Model

B.2 Data Flow

A flowchart depicting the flow of data and structuring of the model is presented in Figure 3. The raw data is split into two sets; model data and time series data. The model data regards power system unit definitions and topology data such as transmission line resistance, battery capacity and bus coordinates, while time series data is a set of data describing the predefined values for DER production levels and load consumption.

The network model is configured in Python using PandaPower as the structural template. The model is subsequently parsed to a JSON-file following a MATPOWER format (readable for PowerModels).The time series data is structured using a DataFrame. The data is then saved to a JSON file. The Optimisation Model is defined in Julia using PowerModels. Time series data describes the deterministic values that need to be assigned to their respective time step, t, in the Optimisation Model.

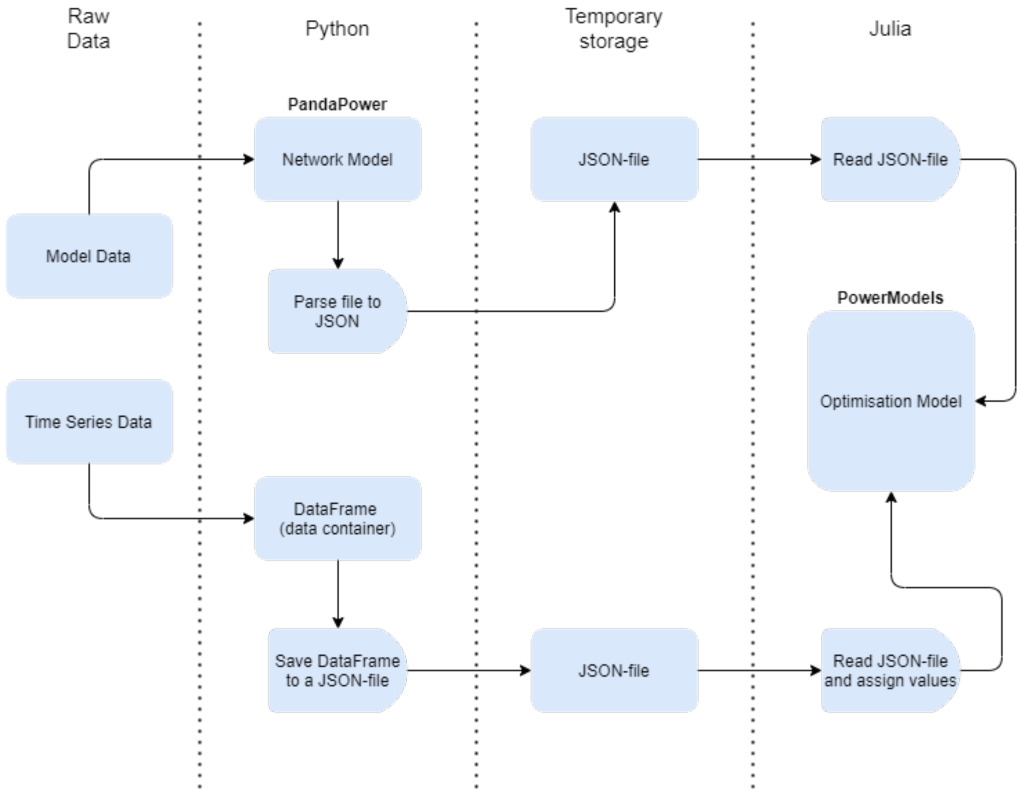

Figure 3: Flowchart of data for the optimisation model specification

C Sensitivity Analysis

C.1 Case 1

Table 1: Case 1 - Overview of costs and earnings from the sensitivity analysis simulations, and statistical representation of strategy performance utilising the individual battery capacities.

		Value			
	Metric	554 kWh	1108 kWh	1662 kWh	2224 kWh
Microgrid	Battery operation earnings [NOK]	245.47	490.93	647.06	713.46
	DER earnings [NOK]	1133.06	1133.06	1133.06	1133.06
	Farm electricity cost [NOK]	1013.84	1013.84	1013.84	1013.84
	Demand tariff cost [NOK]	354.98	558.8	682.23	803.68
	Production tariff earnings [NOK]	274.01	423.6	512.95	601.19
	Total revenue without tariff [NOK]	364.69	610.15	766.28	832.68
	Total revenue [NOK]	283.72	474.95	596.99	630.19
DSO	Reduction in peak value [%]	0.0	-6.38	-6.38	-6.38
	Standard deviation Import [%]	24.54	25.92	24.99	23.74
	Standard deviation Base Case [%]	25.85	25.85	25.85	25.85

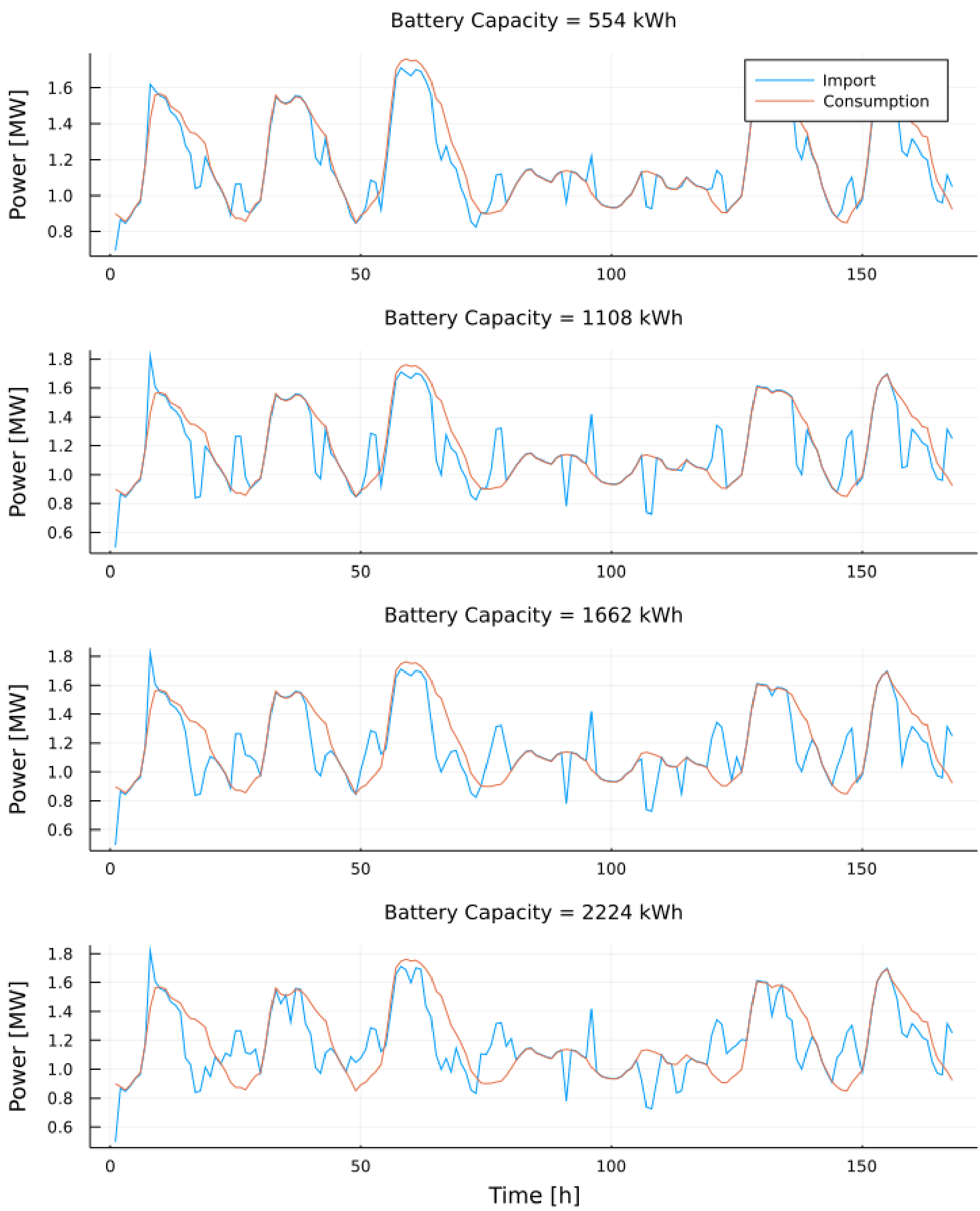

Figure 4: Case 1 - Plots for the power import and network consumption for four different values for the installed battery capacity in the microgrid.

C.2 Case 3

Table 2: Case 3 - Overview of costs and earnings from the sensitivity analysis simulations, and statistical representation of strategy performance utilising the individual battery capacities.

	Metric	Value			
		554 kWh	1108 kWh	1662 kWh	2224 kWh
Microgrid	Battery operation earnings [NOK]	120.97	223.26	299.3	369.44
	DER earnings [NOK]	1133.06	1133.06	1133.06	1133.06
	Farm electricity cost [NOK]	1013.84	1013.84	1013.84	1013.84
	Demand tariff cost [NOK]	283.34	413.96	551.87	670.37
	Production tariff earnings [NOK]	217.23	312.0	413.2	500.34
	Total revenue without tariff [NOK]	240.19	342.48	418.52	488.66
	Total revenue [NOK]	174.08	240.52	279.86	318.62
DSO	Reduction in peak value [%]	5.4	8.72	11.82	14.64
	Standard deviation Import [%]	22.15	19.15	16.58	14.55
	Standard deviation Base Case [%]	25.85	25.85	25.85	25.85

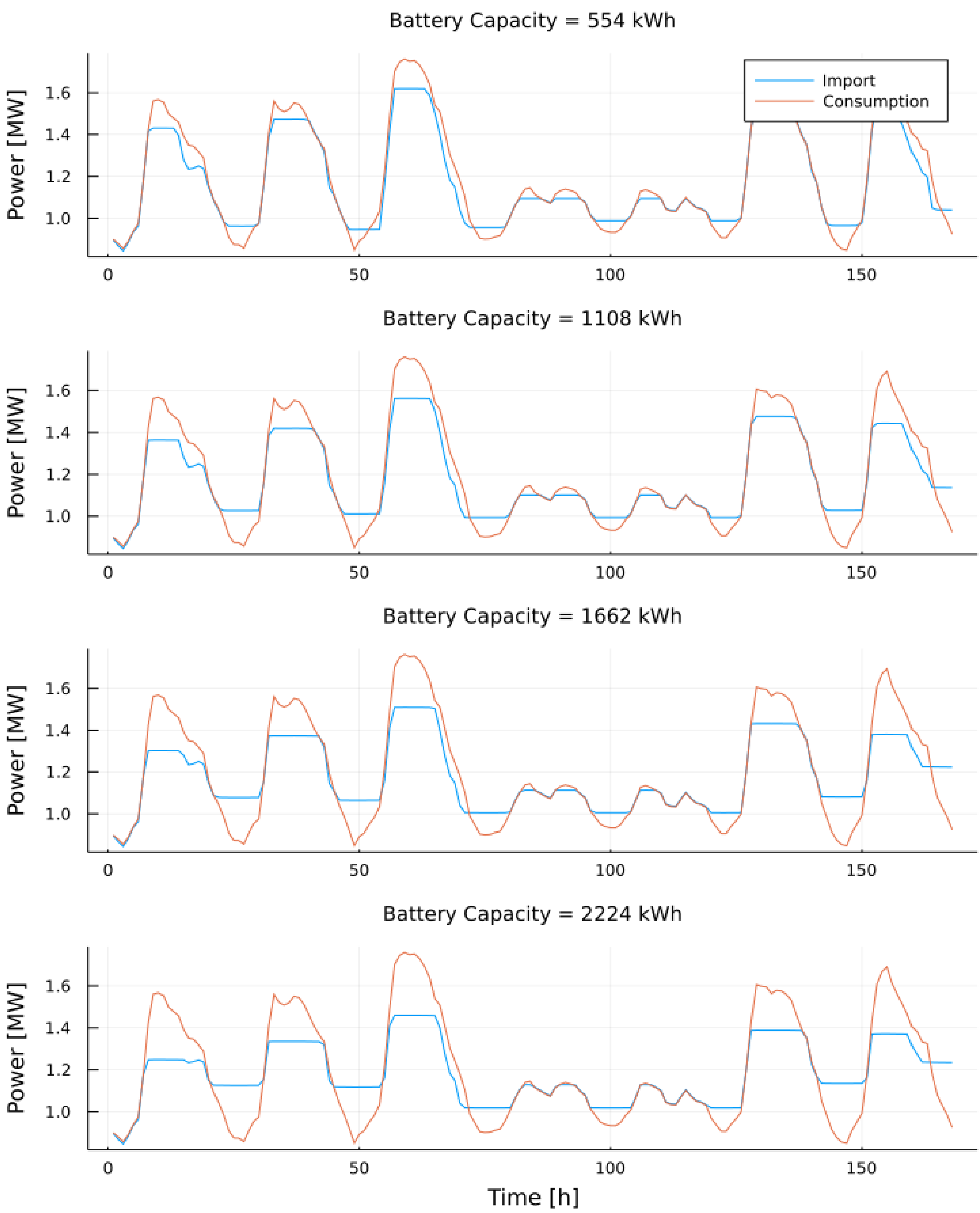

Figure 5: Case 3 - Plots for the power import and network consumption for four different values for the installed battery capacity in the microgrid.

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