Master's thesis

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

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DSO-LEC Optimization Using Demand-Side Flexibility Resources

A Case Study From a German Distribution Grid

Master's thesis in Energy and Environmental Engineering
Supervisor: Dmytro Ivanko
Co-supervisor: Hossein Farahmand

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Electric Power and Energy Systems

Submission date: June 2023

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Abstract

The energy system is changing rapidly, and integrating renewable energy sources upstream poses challenges for the balancing and stability concerns downstream. The grid operators stand before a crossroads, and they can either invest large sums of money into improving their grids or seek out alternatives that could be more economically beneficial. Based on this, a concrete question becomes clear. How can demand-side flexibility resources, such as batteries and load control, contribute to the effective operation of the power grid during the integration of renewable energy sources? This master's thesis aims to answer this question and further strengthen the field of local flexibility market (LFM) research by consolidating research on the topic.

Different types of flexibility, both supply- and demand-side, will be addressed. This difference leads to the topic of local energy communities (LECs), which will be the main focus of this thesis. The LECs are organized end-user participation in the power market. The LECs provide different types of demand-side resources, such as load control, flexible generation, load shedding, voltage control, and batteries which are introduced and discussed. The LECs are a source of flexibility that could greatly benefit the distribution system operator (DSO) in balancing the grid by integrating intermittent energy production. As the end-user becomes a more active participant, they will also gain more bargaining power in the market. The type of market that emerges from this is the LFM, which works as a trading avenue between established market participants, such as the transmission system operator (TSO) and DSO, and end-users wanting to sell their flexibility. However, challenges arise due to inadequate infrastructure, information and communication technologies, and the complexity of end-user behavior, which must be overcome to integrate demand-side flexibility successfully.

The model used in this thesis for DSO and LEC coordination was an SoC AC/AC-OPF model. The model was decomposed with the help of the ADMM algorithm to aid in reducing the size of the problem by decomposing it into smaller sub-problems. The benefits of reducing the problem size were that each sub-problem became much easier to solve mathematically, and the model became more scalable, allowing for more extensive problems to be tackled. This decomposed model consists of four sub-problem groups that each need to be solved to solve the market, two for the Day-Ahead (DA) market and two for the LFM; the DA DSO, DA LEC, FM DSO, and FM LEC models. These are solved by minimizing the deviation between power imported in the LEC and power exported from the DSO. In addition, a sophisticated communication scheme was introduced to ensure information security and corporate integrity concerning sensitive data by transferring only necessary data between market participants through the simple mail transport protocol (SMTP) and internet mail access protocol (IMAP) protocols.

To test the model, a realistic test grid was made, based on data from a German distribution grid provided by the DSO S.W.W. Wundsiedel. This test case provided a more thorough review of the model and, as such, a more accurate discussion about the integration of demand-side flexibility in practice. With this test grid, different scenarios were simulated to test the effect of flexibility resources on the grid. These scenarios range from economic optimization to grid problems such as voltage issues, integration of renewable energy sources, and flexibility trading in the DA market was also simulated. The results from these simulations show that the integration of flexibility provided both economic gains and improved stability in the grid. This highlights that the integration could be utilized to reduce grid expansion needs to meet the challenge of the changing power system.

Sammendrag

Kraftsystemet er i rask endring, og integreringen av fornybare energikilder byr på problemer når det kommer til balanse og stabilitet i nettet. Nettoperatørene står fremfor et veiskille hvor de enten kan investere store summer i å bolstre nettet, eller søke ut alternativer som kan oppnå det samme målet, nemlig et mer stabilt nett. Fra denne problemstillingen trer et spørsmål frem; Hvordan kan fleksibilitet fra sluttkunder, slik som last kontroll og batterier, bidra til å bedre driften av strømnettet under integreringen av fornybare energikilder? Denne masteroppgaven sikter på å svare på dette, samt å styrke forskingsfeltet rundt lokale fleksibilitetsmarkeder (LFM) gjennom å samle kunnskap.

Forskjellige typer fleksibilitet, både sluttkunde og industriell, vil bli presentert. Forskjellene mellom disse leder inn i konseptet lokale energisamfunn (LECs), som vil være et av hovedtemaene i denne masteroppgaven. LEC-ene er definert som en organisert samling av sluttbrukere som deltar i kraftmarkedet. LEC-ene tilbyr forskjellig type fleksibilitet, slik som last kontroll, fleksibel generering, lastkutting, spenningskontroll og batterier som blir diskutert. LEC-ene er en kilde til fleksibilitet som har potensialet til å komme distrubisjonsnettoperatøren (DSO) til gode når nettet skal balanseres under uregelmessig kraftproduksjon, slik som vind- og solkraft. Dette åpner for muligheten til en endring i maktbalansen i kraftmarkedet. Siden sluttbrukere blir en mer aktiv deltaker vil de også oppnå høyere handlingskraft i møte med etablerte markedsdeltakere som transmisjonsnettoperatøren (TSO) og DSO. Dette åpner for en ny type marked for handel av strøm, nemlig LFM, hvor TSO, DSO og sluttbrukere, gjennom aggregatorer, kjøper og selger fleksibilitet for å balansere strømnettet. Utfordringer oppstår grunnet manglende infrastruktur, informasjonsteknologi og kompleksitet bland sluttbruker-oppførsel. Disse utfordringene må overkommes for at integreringen av fleksibilitet fra sluttbrukere skal fungere.

Modellen som ble brukt i denne masteroppgaven for koordinasjon mellom DSO og LEC var en SoC AC/AC-OPF modell. Denne modellen ble dekomponert ved hjelp av ADMM algoritmen for å redusere den matematiske kompleksiteten til problemet. Dekomponeringen resulterte i at fire under-problem-grupper oppsto, hvor hvert problem i hver gruppe var betraktelig lettere å løse enn orginalproblemet. Modellen med de fire under-problem-gruppene besto av to under-problem-grupper for Day-Ahead (DA) markedet, og to under-problem-grupper for LFM, hvor disse er delt inn ettersom hvilken marketsdeltaker de omhandler; DA-DSO, DA-LEC, FM-DSO og FM-LEC. Hvert under-problem løstes med et mål om å minimere forskjellen mellom lastflyt fra DSO og lastflyt inn i LEC, i de nodene hvor DSO og LEC er sammenkoblet. I tillegg til modellen ble en mer realistisk kommunikasjonsmekanisme introdusert for å simulere mer realistisk hvordan modellen kunne bli brukt i praksis. Denne introduksjonen av informasjonsoverføring via mail baserte seg på at all nødvendig informasjon fra lastflytanalysene fra de forskjellige markedsdeltakerne overføres til markedsopperatøren (LFMO) via protokollene simple mail transport protocol (SMTP) og internet mail access protocol (IMAP).

For å teste modellen ble et mer realistisk nett skapt, dette nettet ble basert på data fra et tysk distribusjonsnett som ble forsynt av det tyske nettselskapet S.W.W Wundsiedel. Nettet tilførte en grundigere analyse av modellen, og gjennom dette, en mer grundig diskusjon rundt integreringen av fleksibilitet fra sluttkunder i praksis. Med dette realistiske skapte nettet ble forskjellige scenarier simulert for å observere hvordan markedet løses for dette nettet. Scenariene varierte fra økonomisk analyse til nettproblemer slik som problemer med å oppnå ønsket spenningsnivå. Integrering av mindre generatorer i distribusjonsnettet, samt

fleksibilitetshandel i DA markedet ble også simulert. Resultatene av simuleringene viste til en positiv respons til integreringen av fleksibilitet, både for økonomisk perspektiv og for nettbalansen. Dette viste at integreringen av fleksibilitet kan være et alternativ for nettet som respons til integreringen av fornybare energikilder.

Preface

This master's thesis was written at the Department of Electric Energy (formerly Department of Electric Power Engineering) at the Norwegian University of Science and Technology. It was written during the spring of 2023 and concludes our five-year integrated master's study at *Energi & Miljø*. It has been rewarding to finish this degree writing about such an interesting and relevant topic, giving the authors in-depth knowledge about the power system and market.

We want to thank our supervisor Dmytro Ivanko and co-supervisor Hossein Farahmand for their guidance, close follow-up, and encouraging and constructive feedback. We would also like to thank the German DSO S.W.W. Wundsiedel for providing realistic grid data used to make the test cases.

We would like to thank our respective parents, Kjersti & Odd Inge and Arnstein & Nina, for their continuous support and love, especially during this last year. We would also like to thank our respective significant others, Håkon and Karina, for both their love, support, and encouragement, as well as any emotional and technical support when needed. Lastly we would like to thank our friends and classmates for making these last five years an unforgettable experience.

Trondheim, June 2023

Kaja Bardal & Sebastian Engmo Melle

Contents

List of Tables

List of Figures

Abbreviations

ACOPF	AC Optimal Power Flow
ADMM	Alternating Direction Method of Multipliers
ANN	Artificial Neural Network
BRP	Balancing Responsible Parties
CHP	Combined Heat and Power
DA	Day-Ahead
DLC	Direct Load Control
DER	Distributed Energy Resources
DG	Distributed Generation
DR	Demand Response
DSM	Demand Side Management
DSO	Distribution System Operator
EHV	Extra High Voltage
EMS	Energy Management System
ESS	Energy Storage System
EV	Electric Vehicle
EWH	Electric Water Heater
FM	Flexibility Market
FR	Flexibility Resource
HV	High Voltage
IBP	Incentive-Based Programs
ICT	Information and Communication Technologies
LEC	Local Energy Community
LFM	Local Flexibility Market
LFMO	Local Flexibility Market Operator
LV	Low Voltage
MV	Medium Voltage
NWP	Numerical Weather Prediction
OPF	Optimal Power Flow
P2P	Peer-to-Peer
PV	Photovoltaic System
PBP	Price-Based Programs
RES	Renewable Energy Source
SOC-ACOPF	Second-Order Cone AC Optimal Power Flow
TCL	Thermostatically Controlled Load
TSO	Transmission System Operator
V2G	Vehicle to Grid
VPP	Virtual Power Plant

1 Introduction

1.1 Motivation

The urgency of addressing new challenges brought on by the climate crisis is forcing the power system to transform. Extensive research has consistently emphasized that a transition to greener energy generation is needed. Traditional power generation heavily relies on conventional but environmentally harmful energy sources like coal or gas. However, their high CO_2 emissions and increased negative public perception have made them less desirable. To ensure a more sustainable future, solar and wind power have emerged as promising alternatives to meet the growing power demand. Nevertheless, these renewable resources introduce their challenges due to their intermittent nature, relying on suitable weather conditions for optimal power generation. Consequently, the power system requires increased flexibility.

The power system is also evolving as a response to this changing energy landscape. In the traditional, centralized power market, large-scale power plants generate large amounts of electricity distributed across the transmission grid and delivered to end-users through local distribution grids. As such, the power flow of the system has primarily been uni-directional. However, with the European Green Deal [10], the number of end-users wanting to actively participate in local energy communities might increase. By utilizing their available flexibility resources, the end-users become more engaged and active participants in the power market.

With the emergence of new generating units and more end-user involvement, the power system is becoming decentralized. This shift will significantly impact the amount of flexibility available in the power system and change the location of these flexibility resources [3]. This shift is illustrated in Figure 1.1. Efficient coordination of different market players becomes crucial in the emerging complex flexibility market. However, the current power grid is not yet ready for the challenges related to a more decentralized market structure. Grid operators face substantial costs related to upgrading and maintaining the grid infrastructure. To address these challenges, an alternative solution is emerging: a local flexibility market and the utilization of demand-side flexibility and distributed energy resources.

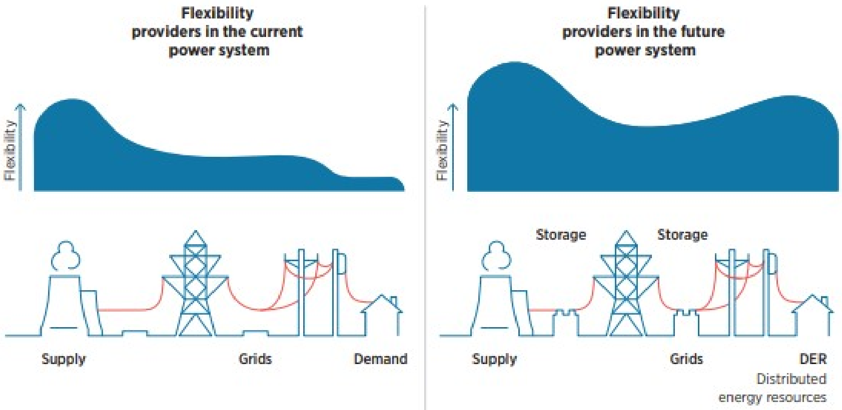

Figure 1.1: Development of flexibility providers [3]

The concept of local flexibility markets offers a promising approach to utilizing the distributed flexibility resources available within the demand side of the grid. By enabling the end-users to participate and utilize their flexibility potential, these markets provide a platform for more effective use of resources, reducing waste and strengthening the overall efficiency and stability of the power system. As the power grid moves towards a decentralized structure, increasing end-user engagement and integration will be essential to utilize their excellent flexibility potential.

1.2 Preliminary work

This master's thesis is a continuation of work conducted in several other master's theses and the joint specialization project of both authors of this thesis, found in [11]. The earlier works are found in [8], [12], and [13], chronologically. Previous theses, namely [8] and [12], focused on the coordination of TSO-DSO collaboration, while [13] and the specialization project looked at adjusting the model so that it could fit the coordination of a DSO-LEC collaboration.

As such, the model used in this master's thesis continues and expands the model used in the earlier works. It was first introduced in [8], consisting of optimizing the coordination of a single TSO and DSO. Here, the model consisted of two OPFs, a DC-OPF for the transmission grid and a SOC-ACOPF for the distribution grid. [12] introduced the ADMM algorithm so that the model could handle several DSOs. [13] adjusted the model again to optimize a DSO-LEC coordination. The model was then adjusted to contain two SOC-ACOPFs, as both coordination parts are in the distribution grid. Lastly, the specialization project cleaned the code and introduced a new, realistic test case to test the model.

Based on the work done in this master's thesis, an article was written and accepted (accepted 24.04.2023) for the European Energy Markets (EEM) conference this year, held in Lappeenranta, Finland. The paper will be published in IEEE Proceedings in relation to this conference. The coordination schemes showcased in Chapter 5.3 were introduced here. The paper introduced the concept of demand-side flexibility in the Day-Ahead market, to be used as a preventive measure by intermittent power producers [14]. This measure would go on to be implemented into the model for some scenarios in this master's thesis.

Since the theoretical background on the concepts of flexibility and the local flexibility market was thoroughly presented in the specialization project [11], much of this work in this thesis is an extension. Especially Chapters 2, 3, 5, 6 use much of the theoretical background presented in the project and build on this. Chapters 7 and 8 are project extensions with a somewhat different focus due to new contributions to the model and data.

1.3 Aims and Objectives

This master's thesis will further expand on the topics raised in the preliminary works. The focus will remain on DSO-LEC coordination, utilizing the realistic test case made based on data provided by a German DSO. The thesis will further investigate how demand-side flexibility can be economically beneficial and how it can aid the DSO with grid regulations. It will also focus on how these flexibility resources can support the integration of intermittent distributed energy resources. Additionally, it is a goal to provide general improvements to the model and code to make it more user-friendly.

The specific objectives can be summarized as follows:

- Further improve the code to make it more user-friendly.
- Create a realistic test case using grid and load data from a German DSO (S.W.W Wunsiedel) and flexibility data of different pilot projects and test how this demand-side flexibility can aid the DSO, by reducing operational costs and offer tools for voltage regulation and congestion management.
- Introduce a script to the model that allows realistic information communication between the market operator, DSO, and LECs, through mail exchange.
- Include distributed power generation in the distribution grid and observe how flexibility can aid intermittent power generation by simulating different generation scenarios.
- Add flexibility to the Day-Ahead optimization of the model so that power producers can utilize demand-side flexibility resources in their power generation planning.

1.4 Structure

Chapter 2 introduces the topic of flexibility by defining the concept. Some of the attributes of flexibility are presented, and the timeline of flexibility activation is discussed. Flexibility resources are then categorized based on who supplies them: supply-, grid-, and demand-side flexibility. Due to the scope of the thesis, only supply-side and demand-side flexibility is discussed further, with a particular focus on the latter. Different flexibility resources within these categories are presented. Lastly, the concept of Local Energy Communities is presented.

In Chapter 3, the benefits of including more demand-side flexibility are proposed. Some of these benefits include how flexibility resources can benefit the climate, for example, by supporting the integration of renewable energy sources, how demand-side flexibility can help the DSO with voltage regulation and congestion management, and some economic and power structure benefits. Lastly, some challenges regarding the implementation of demand-side flexibility are discussed.

In Chapter 4, the uncertainty related to integrating renewable energy sources is discussed. Here, the focus lies on wind and solar as power sources and how they are affected by unpredictable weather conditions. Some power forecasting methods and potential causes for why forecasts might deviate from actual power production are discussed.

Chapter 5 introduces the need for a new power market for exchanging flexibility. A definition of the local flexibility market is presented, and its participants are defined. Special attention is given to the new participant aggregator and market operator. Lastly, an example of how the market can be coordinated is presented, discussing the flexibility market's time frame and communication scheme.

Chapter 6 shortly introduces different types of models for the local flexibility market and different market clearing methods. The necessary general concepts for formulating the mathematical model of a flexibility market are presented, and different methods for solving these concepts are discussed. The main focus is on different decomposition techniques, as they are central to the model used in this thesis.

Chapter 7 presents the model used for this master's thesis. As the model is a continuation of earlier master's theses, the original multi-period AC/DC optimization model was developed, and the adjustments made for this thesis are presented, specifically how the model is changed to an AC/AC optimization model for DSO-LEC coordination and the ADMM algorithm. How information exchange via mail is included, how GUI is included, and how flexibility in DA is included.

Chapter 8 presents the data used for the test cases. A general introduction to the German power system is provided before a detailed description of the structure of the test grid, nodes, and lines, and relevant flexibility resources and price data are presented.

Chapter 9 presents the test cases made for this master's thesis. After that, the results of the simulations are presented and discussed.

Lastly, Chapter 10 concludes the work done in the master's thesis and points to some areas of further work that can be conducted on the topic.

2 Flexibility Resources

As mentioned in the introduction, an in-depth literature review on the topic of the flexibility concept and flexibility resources was conducted in the preliminary specialization project, and the following chapter is thus an extension of this.

Historically, the European power system has been heavily centralized, characterized by a few big power-generating units responsible for supplying power to the whole system. Thus, power has generally flown in one direction, from suppliers via the transmission grid down to the distribution networks, before reaching the end-users. However, recent changes in the power sector are reshaping this established system. Powered by the urgency of the climate crisis, growing demand for power, and technological advancements, the power system is evolving. The increasing utilization of distributed renewable energy sources (RES) such as wind and solar power [15], along with the rapid advancements of energy storage systems (ESS), new information and communication technologies (ICT), and a greater emphasis on regulating consumption patterns by end-users are introducing new opportunities, but also challenges, to the power system and power marked. Consequently, a more decentralized power system is emerging, and its market structure and participants and their respective roles are also evolving.

2.1 Definition and Categorizations

As illustrated in Figure 2.1, the power system supply and demand must continuously match to maintain the frequency balance needed for secure power delivery. Primarily, this happens in the Day-Ahead (DA) market, where power is bought and sold to plan the next day's consumption and production. However, unforeseen situations, such as faulty lines, unusually high consumption, or sudden generator outages, deviate actual power consumption and production from this initial plan. Such unforeseen events may be handled by activating flexibility resources (FR).

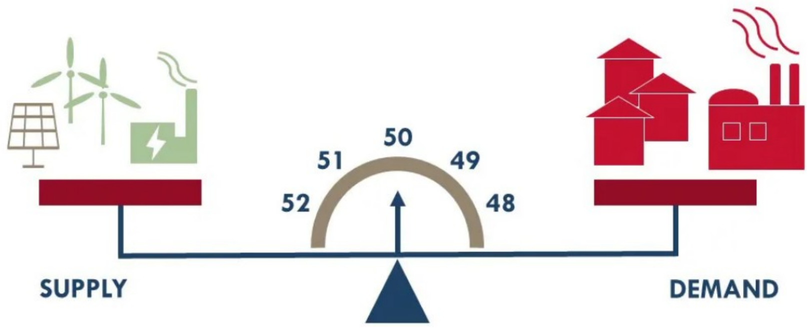

Figure 2.1: Power supply and demand has to match continuously, from [4]

The definition of power flexibility varies, depending on its intended purpose. However, in most cases, it can be defined as an altercation of power generation or consumption at a specific location in the grid for a specific amount of time [16, 17, 18]. Flexibility resources (FRs) are activated by an external request to help balance the power system and ensure satisfactory power quality and are characterized by five key attributes (see Figure 2.2): direction of power adjustment, power capacity, the duration of the adjustment, the response time, and its location [7, 17, 18]. The direction of an FR corresponds to whether it consumes or produces power. Some FRs, such as household loads, only consume power, while others, like energy storage units, may be bi-directional. Power capacity refers to the amount of power the FR can deliver. The adjustment duration refers to how long the change in generation or consumption can be endured, and the response time refers to how quickly the FR can be activated upon request. These are essential features of FRs, as flexibility needs are different. Some may need a large amount of power for a short period, while others might need less power for a longer duration. Some flexibility needs arise suddenly and thus depend on FRs with a short response time, while others can be detected earlier, and an FR activation can be planned. The location is also an important attribute, especially with new distributed technologies.

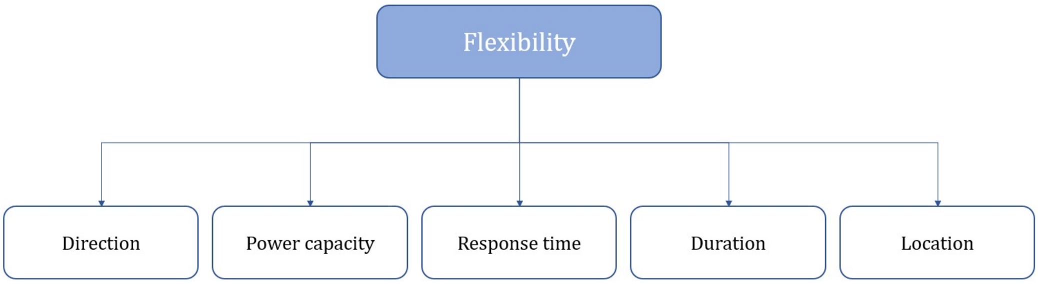

Figure 2.2: Flexibility attributes

Conventional power plants, such as hydropower or gas, have traditionally provided flexibility. However, as the penetration of renewable energy sources (RES) increases, this may no longer be sufficient. Technologies like wind and solar power have grown significantly in the last decade. In Europe, installed wind power capacity has increased by 205.9% in the last nine years, and installed solar capacity by 254.1% [19]. The increased use of such RES technologies plays a vital role in facing the climate crisis challenges. Nevertheless, integrating these technologies introduces higher uncertainty to the power system. Wind and solar forecasts are less reliable than fossil fuels, and the resources can not be stored like hydropower. Consequently, the need for flexibility in the power market is increasing to mitigate the impact of this uncertainty. Relying solely on conventional power plants to deliver this flexibility would require the construction of new power plants and expanding power infrastructure, which would result in enormous costs and contribute to more significant emissions. Therefore, alternative sources of flexibility should be explored and utilized to achieve a more sustainable power system.

The contribution of FRs to the power grid can be divided into three time periods, summarized in Figure 2.3, inspired by [20]. *Short-term flexibility* is used when unforeseen events occur, such as large deviations between forecasts and actual consumption and production, power outages, and other sudden emergencies. FRs delivering this type of flexibility must have a short response time, enabling quick activation when an event arises to help ensure power quality and reliability. *Medium-term flexibility* is used to deal with situations identified days in advance [20]. For example, if congestion problems or other discrepancies are detected after the DA market is cleared, flexibility can be bought to address these problems. This type of flexibility can also be used to shift some of the load from peak to off-peak hours or reduce it. Since the activation of medium-term flexibility is planned, the response time does not need to be as immediate as short-term flexibility. *Long-term flexibility* is used for balancing purposes, i.e., matching supply and demand [20]. As discussed, the need for flexibility for balancing purposes is increasing due to the high penetration of RES technologies, and long-term FRs can be installed as a permanent supplement to such technologies.

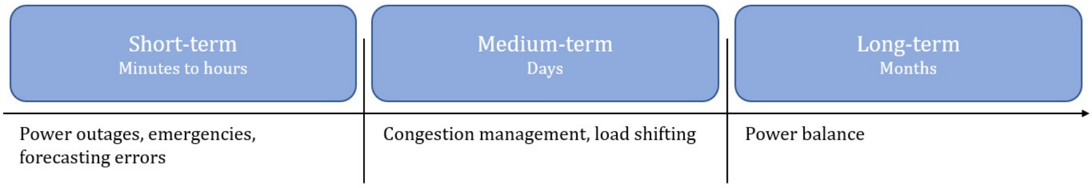

Figure 2.3: Flexibility timeline

Flexibility can also be categorized by location: supply-side flexibility, demand-side flexibility, and grid-side flexibility [7, 21]. Figure 2.4 summarizes the location of different FRs. Due to the chosen scope of this master's thesis, only supply-side and demand-side flexibility will be investigated.

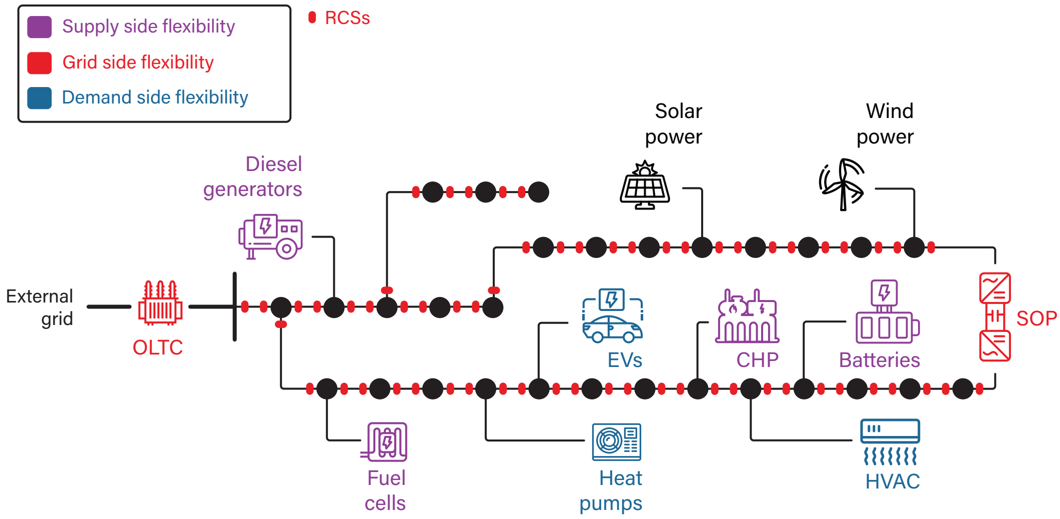

Figure 2.4: Supply-, demand-, and grid-side flexibility located in the grid

2.2 Supply-Side Flexibility

Supply-side flexibility primarily consists of the traditional FRs, namely conventional power plants [21, 22]. These power plants can be divided into three categories: baseload, peaking, and load-following power plants. Baseload power plants, such as nuclear power plants, offer little to no flexibility due to economic and technical constraints that make them highly inflexible. As the name suggests, peaking power plants are activated during peak hours when power demand is high and cannot be met solely by baseload plants. These power plants often have high operational costs and are thus only utilized when necessary. Load-following power plants can start and stop fast and have a fast response, making them highly flexible. Traditionally, these power plants have been the primary source of flexibility in the grid. Examples of load-following power plants include hydropower and gas turbines.

The conventional power plants mentioned above can be characterized as non-intermittent, as they are highly controllable. They are not affected by any external factor and can be activated when required, with the power output adjusted to the desired need within the unit's technical constraints. However, as mentioned, the power system is experiencing an increased integration of generating units relying on RES. Such RES-based generators are intermittent, meaning that they lack controllability [23]. External factors determine whether, when and to what extent these generating units can produce power. Typical examples include wind and photovoltaic (PV) generators, which depend on good wind and solar conditions to operate efficiently.

Non-intermittent generating units may appear more appealing due to their higher controllability and reliability than intermittent generating units.

However, such non-intermittent units often rely on fossil fuels such as coal or gas, increasing CO_2 emissions. As the future becomes more sustainable, such technologies are being phased out. For example, to reach the goals set by the Paris Agreement, all OECD countries should have ended their use of coal entirely by 2030 [24]. Thus, integrating intermittent generating units is vital for the shift towards lower CO_2 emissions.

To increase the reliability of intermittent generating units, they may be paired with flexibility delivered by energy storage systems (ESS). As its name implies, ESS encompasses systems for storing energy for later use. The continuous advancements in ESS technologies have been one of the driving forces for flexibility expansion [25]. ESS delivers flexibility by storing energy during low-demand periods and later utilizing this energy during peak hours. Thus, using such systems allows for the generation and consumption to be decoupled, which is beneficial for balancing purposes [15].

The largest energy storage capacities are in pumped hydro storage [15, 22, 25]. During periods of excess electricity generation, this surplus power is used to pump water from a lower reservoir back to a higher one. The pumped water may then generate more power when the demand is high. This process is repeated as necessary, thus effectively storing energy. As mentioned, hydropower plants are considered load-following plants and are thus highly suitable for balancing purposes.

Secondary/rechargeable batteries are also widely used for storing energy. Battery technologies that have proven to provide ancillary services effectively are sodium-sulfur, lead-acid, and Li-ion batteries [25]. Batteries are charged during low-demand periods and can be deployed as flexibility resources. Because of self-discharge losses, they are mainly used for short-term storage [22]. Nevertheless, their fast response time makes them highly suitable for providing flexibility, strengthening power reliability and quality, and reducing fluctuations, congestion, and transmission losses [22].

Fuel cell technology, particularly hydrogen storage, has been highly investigated recently. With hydrogen storage, an electrolyzer is used to separate water into hydrogen and oxygen. The hydrogen is then oxidized to convert the chemical energy into electric energy [22, 26]. In addition to storing energy, this process has two byproducts: water and heat, which can be utilized for district heating or other purposes. In [26], it was found that hydrogen storage can alleviate some of the uncertainty associated with wind power production and be utilized when actual wind generation deviates from the forecast. This was observed in a thermal power system characterized by high fluctuations in electricity prices, as many countries in the EU have. However, this flexibility provided by hydrogen storage was less applicable to countries with more stable price variations, such as a typical Norwegian hydropower system.

2.3 Demand-Side Flexibility

Although less conventional, demand-side flexibility is a promising approach to increasing flexibility in the power system. This type of flexibility is offered by end-users, either consumers or prosumers [7]. End-users encompass residential and commercial buildings, as well as more significant industrial buildings and parks, resulting in many users with great potential to contribute flexibility to the power system [21]. As the power market becomes more decentralized, new technologies emerge, and with an improved understanding of their consumption patterns, market power is shifting toward the end-user. By adjusting their electricity consumption or utilizing relevant technology in response to high power prices or demand, end-users can actively participate in the power market by offering flexibility to the power system.

One of the primary objectives of demand-side flexibility is reducing the stress on the power system during peak consumption periods. This is achieved by either decreasing the load (peak shaving) during these hours or shifting some load to off-peak hours (load shifting) [15]. Figure 2.5, from [5], shows the difference between the two methods, with load shifting to the left and peak shaving to the right. Load shifting involves moving load consumption from peak hours to low-demand hours; however, load shaving aims to reduce consumption during peak hours altogether.

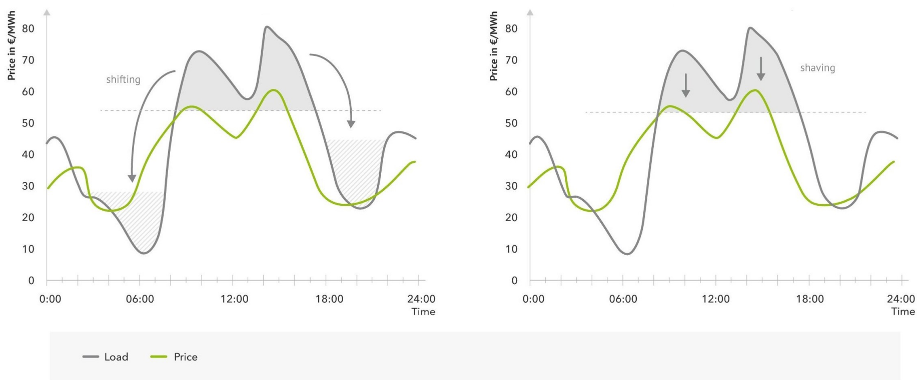

Figure 2.5: Load shifting vs. load shaving, from [5]

2.3.1 Demand Side Management

Power utility companies may implement various Demand Side Management (DSM) programs to utilize demand-side flexibility effectively. The goal of such programs is to be able to modify their customers' power consumption patterns [15, 22, 27]. They are designed to encourage customers to reduce their loads or alter their consumption patterns as a response to either power prices or other motivating incentives. DSM programs typically fall into price-based and incentive-based programs [15, 20, 22, 28]. Figure 2.6 summarizes the two categories.

Incentive-based programs (IBP) can be divided into two categories: classical IBP and market-based IBP. The classical IBP comprises two approaches, namely *direct load control* (DLC) and *interruptible/curtailable loads*. Participants of these programs are paid for their participation through a bill credit or discount rates [28]. With DLC, the power utility

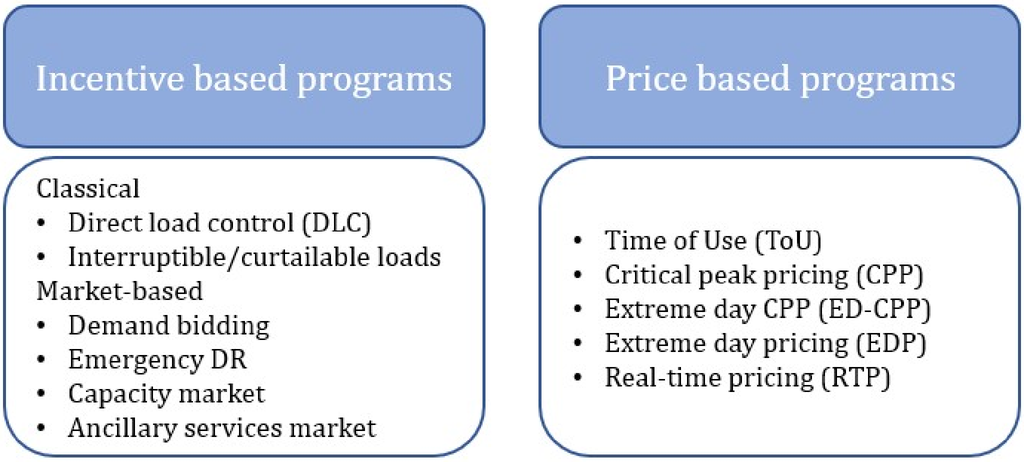

Figure 2.6: Price- and incentive-based DSM programs

company has the power to manage specific loads of the participants directly. Communication switches are installed on the customers' side, which enable the company to reduce or temporarily switch off the participants' equipment as needed to mitigate load during peak hours or in response to various problems in the power system [20, 28]. Typical loads that can be controlled include air conditioners, heat pumps, and water heaters. Programs like this face challenge due to privacy concerns, as power utility companies would have direct access to their customers' load information. Interruptible/curtailable load programs, on the other hand, involve the power utility company requesting that their customers reduce their loads to a predefined level [20, 28]. Unlike with DLC, the power utility does not directly control customer loads. Instead, it relies on the customers to respond when the request is issued. Customers may receive penalties if they fail to respond to the request.

Market-based IBPs, as the name suggests, operate based on market structures where customers offer flexibility as bids. With these types of programs, participants are not only rewarded for their participation but also based on the flexibility they provide [28]. One type of market-based IBP is *demand bidding programs*, which operates within the wholesale electricity market. Consumers submit bids on load reductions of a specified magnitude [20, 28]. Similar to the DA market, bids below the market price are accepted. If the bid is accepted, the consumer must reduce the load by the bid accepted, or else they may receive penalties. Another type is *emergency demand response programs*, designed to cope with emergency situations that may arise within the power system. Customers are paid incentives to reduce their consumption during emergencies so they can be resolved.

Capacity market programs involve pre-planned load reductions, where customers are notified the day before and can commit to reducing the load if network problems arise [20, 28]. They are penalized if they commit to this but fail to meet the load reduction. Lastly, *ancillary services market programs* are integrated into the spot market, and customers thus offer load reduction as part of operating reserves [28]. If the customer's bid is accepted, they are paid the spot price and committed to reducing the load when needed.

Price-based programs (PBP) utilize dynamic electricity pricing to encourage customers to decrease their electricity consumption [20, 28]. Pricing varies throughout the day, and customers could choose to voluntarily lower their consumption during high prices to reduce their electricity bills. Thus, the customer is not obligated to reduce the load with PBPs.

However, the power utilities rely on pricing that motivates them enough that they choose to reduce their consumption themselves. The simplest form of PBP is *Time of use* (ToU) pricing, where the price rate is divided into time blocks, with constant rates within the block but varies across blocks. In its simplest form, these programs may consist of only two price blocks: peak and off-peak, with high prices during peak hours and low during off-peak hours. Additional blocks can be added to include different pricing levels.

Critical peak pricing (CPP) is similar to ToU programs. The price is either flat or divided into blocks like with ToU during normal conditions. However, it introduces higher electricity prices when grid problems arise that can be resolved by reducing power consumption [20, 28]. The use of such pricing is limited to specific hours or days. *Extreme day pricing* (EDP) follows a similar concept, but the increased electricity prices are in effect for the entire day of grid contingencies. *Extreme day CPP* (ED-CPP) programs combine both CPP and EDP programs, using flat rates during average days and CPP rates on extreme days.

Finally, *real-time pricing* (RTP) programs encompass programs where the electricity price is varied during different intervals [20, 28]. These intervals can, for example, be hourly, like the NordPool spot price. Customers can access the prices a day in advance and then see which periods the power is expensive and when it is not.

2.3.2 Demand Response

The consumers' response to DSM programs is called demand response (DR). DR is defined by [21] as "alterations of energy consumption levels and/or patterns of end-users in response to dynamically changing prices and incentives." It thus encompasses the actions taken by the consumers when the electric utility company introduces a DSM program to avoid increased prices during peak hours.

One way end-users might offer flexibility is through controllable loads. Technological advancements have made it easier for consumers to control their loads directly and indirectly. For residential buildings, this might include wet appliances (dishwashers, washing machines, and tumble dryers), electric water heaters (EHWs) or other thermostatically controlled loads (TCLs), or EVs [9, 29]. Commercial and business buildings can utilize smart control of thermometers and ventilation systems [30]. Through smart load control, consumption can be adjusted during peak hours to enable either load shaving or load shifting to off-peak hours.

With new emerging technologies, demand-side flexibility can also be delivered through Distributed Energy Resources (DERs), which encompasses Distributed Generation (DG) and ESS [31, 32]. Like flexibility, DG has also been defined differently in different literature, but [33] aimed to find a general definition. They define a DG as "an electric power source connected directly to the distribution network or on the customer side of the meter." By this definition, one feature of DGs is that the power generation is distributed in the grid and located closer to consumption [25]. DGs include, for example, wind power, photovoltaics (PVs), micro and small gas turbines, and fuel cells.

The adoption of DGs by end-users is particularly evident in the increased installation of roof-top PVs. In Germany alone, it was projected that the number of residential solar storage systems would be as high as 667 000 by the end of 2022 [34]. By incorporating local generation, prosumers are reducing their reliance on grid power and may even supply power to the grid during high production hours. However, with DGs like PVs, there is uncertainty involved. As discussed earlier, weather forecasts are unreliable, and thus the sole use of RES power generation might also introduce new challenges to the power grid. These challenges will be explored later in this thesis.

ESS also plays an essential role in providing demand-side flexibility. Batteries can be installed independently or in addition to DGs and are used for load shifting. The demand curve can be flattened by charging batteries during off-peak or low-price hours and utilizing the stored power during on-peak hours. Additionally, if batteries are combined with PV systems, they could be charged during hours, reducing power demand.

These demand-side flexibility options contribute to what [25] defines as a flexible end-user. This individual end-user has diverse flexibility assets (DGs, ESS, load control) interconnected through a Home Energy Management System. This could be any end-user, residential, industrial, or commercial. The flexible end-user has a goal, such as reducing their carbon footprint or electricity bill and utilizing their flexibility assets to achieve this goal.

2.3.3 load-shedding

To address the most critical and severe grid problems, load-shedding can be employed as a measure of last resort. This involves intentionally shutting down electric power in specific areas or parts of a distribution system [35]. It is used when situations arise that pose significant risks to the grid that might cause serious harm and, subsequently, grid failures. Unlike other flexibility measures, load-shedding is not a deliberate action but rather an extreme measure and is only used as a last resort [36]. This thesis considers it a last resort when contingencies cannot be resolved through other flexibility options.

2.4 Local Energy Communities

The single end-user cannot necessarily offer meaningful amounts of flexibility to the power grid and has very little market power. As such, it is beneficial for the individual end-users to pool their resources together to form a local energy community (LEC), or what might also be called a virtual power plant (VPP) [25, 37, 38]. According to the European Commission, an energy community "organize collective and citizen-driven energy actions that help pave the way for a clean energy transition, while moving citizens to the fore" [39]. Thus, a LEC aims to provide demand-side flexibility through increased end-user participation in the power market.

LEC flexibility is typically derived from three primary sources: DGs, ESS, and controllable loads. The flexibility that these resources provide may primarily be utilized in two ways. Firstly, energy can be traded within the LEC. For example, a neighborhood may form a microgrid, which allows peer-to-peer (P2P) trading [40]. For instance, households equipped with roof-top solar panels can sell power during excess production to other households within the LEC. Thus, the LEC becomes more self-sufficient, and power costs may be reduced [41].

Secondly, the LEC's FRs can be utilized by delivering flexibility to the grid as a VPP. As a VPP, the combined FRs function as a single power unit through an energy management system (EMS). The system is bi-directional, and the EMS coordinates the power flow to and from units within the LEC. Several consumers and prosumers are thus represented as one united entity in the power market and can offer greater flexibility. There are two main categories of VPPs: commercial VPP (CVPP) and technical VPP (TVPP) [37, 38]. The commercial VPP focuses solely on optimizing production and demand response resources without considering the impact this will have on the distribution or transmission grid. On the other hand, the TVPP considers the DER impact on the grid in addition to the same optimization and scheduling that the CVPP does.

For the remainder of this master's thesis, only the term LEC will be used. Due to the scope of the thesis, the focus will be on how a LEC can offer flexibility to the power market as a combined entity and not flexibility trading within the community.

When the resources of several end-users are combined as a LEC, they are treated as one unified entity by the power market. The new market participant aggregator represents them. This participant will be thoroughly explained in Chapter 5.2.3. However, the primary role of the aggregator is to participate in the power market on behalf of the collective of end-users. Thus, the collective of end-users can offer more significant amounts of flexibility to the grid and impact the market more.

2.4.1 Flexibility Potential of Residential Buildings

Figure 2.7, found in [6], shows an example of what a residential LEC might include. This includes households, farms, and smaller public buildings, for example, schools.

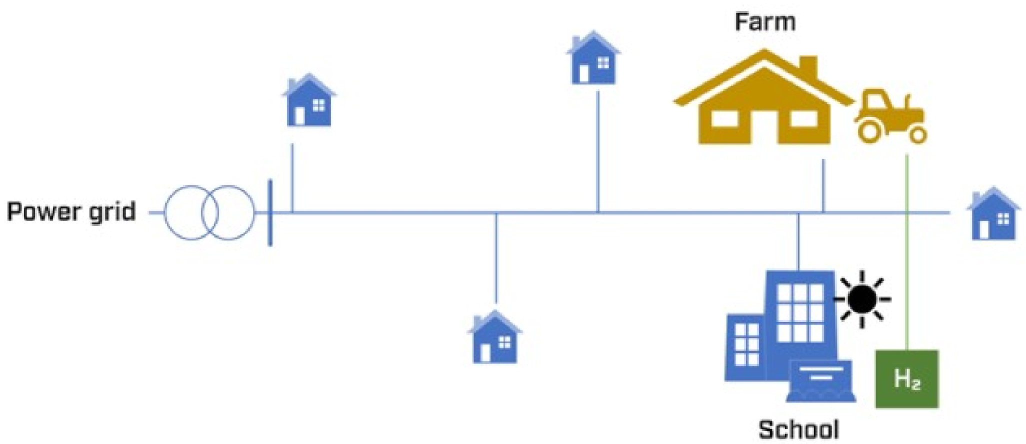

Figure 2.7: Residential local energy community, from [6]

Participants of this type of LEC might offer flexibility from several different sources. As mentioned, smart control of wet appliances is one such resource. Here end-users can, for example, define when a washing program should be finished, and the control mechanism can find the most beneficial time [9]. Such programs cannot be ended when started. EVs have a similar potential in that batteries can be charged at a beneficial time. However, the charging can be paused if needed, and the car batteries might also act as batteries for the grid as long as the battery is charged to the predefined level at the end of the charging period. Smart EHWs can have a predefined temperature interval that they might operate within. This means the power use can be turned down when needed as long as the temperature stays within the interval.

This means that residential buildings mainly offer flexibility in the form of load shifting or shaving, but EVs also have the potential to act as batteries. Through the integration of vehicle-to-grid (V2G) technologies, EV batteries can be utilized the way that has already been described (unidirectional V2G), or they can deliver power back to the grid (bidirectional V2G) [42]. In [42], V2G is defined as "the control and management of EV loads by the power utility or aggregators via the communication between vehicles and the power grid." As discussed, unidirectional V2G might offer load shifting through smart charging of the EVs. Bidirectional V2G might, in addition to this, help maintain voltage levels and support the integration of intermittent renewable energy resources.

Due to technological advancements, PV and storage systems integration has gained significant popularity in residential, public, and commercial buildings. In 2019, Norway expanded its solar capacity by 51 MW, out of which 35% was installed for private households, and approximately 60% was installed for industrial and commercial buildings [43]. By the end of 2022, Germany had a total capacity of 5.2 GWh in installed home solar power storage systems [44]. PVs are inherently intermittent and cause additional trouble for the power system. However, when combined with an ESS, they can act as an FR. By utilizing an ESS, excess solar power produced can be stored for later use. Households can then use this energy to reduce their load during peak hours or be fed back into the power grid. The latter requires a bidirectional connection to the grid.

2.4.2 Flexibility Potential of Industrial Buildings

Figure 2.8, also from [6], shows an example of an industrial LEC, consisting of larger entities like ferry charging, business and commercial buildings, and other industries. Industrial and commercial buildings might offer flexibility in many of the same ways residential buildings can. One of these ways is through controllable loads within these buildings, which allow for load shaving. For example, adjusting the building's temperature settings or ventilation systems can help manage electricity consumption during peak hours [30].

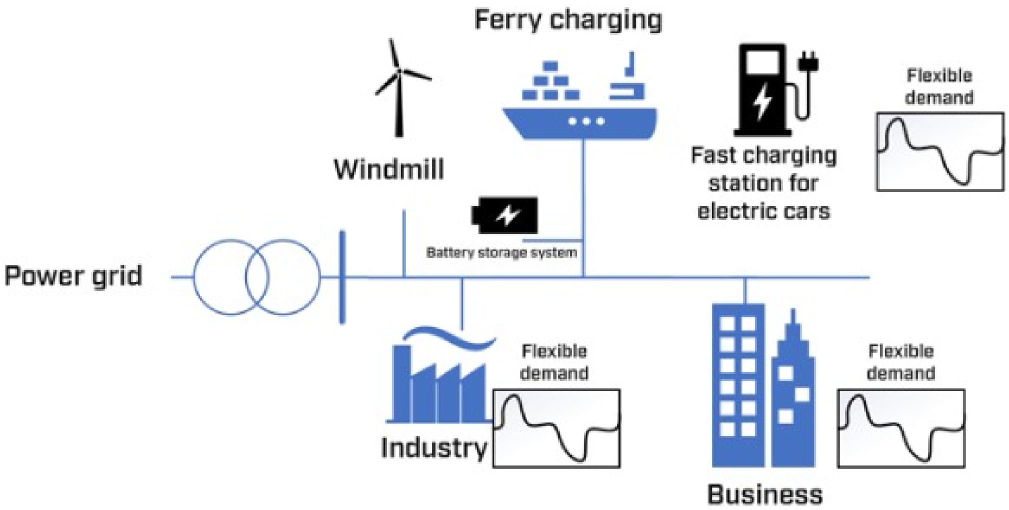

Figure 2.8: Industrial local energy community, from [6]

Integrating PV and ESS also has considerable potential within this sector. An example of this potential is an ABB installation in Lüdenscheid, Germany. Here, ABB has implemented a PV plant with the capacity to generate 100% of the required power at the site [45]. To increase the effectiveness of the plant, an associated BESS has been included for storing power. The plant is also connected to the local grid, enabling it to deliver power either during hours of excess power generation or from the stored energy of the batteries. The successful implementation of such a plant is a compelling example of how RES technologies can be integrated and utilized by the industry sector.

Ferry charging stations have the potential to provide flexibility similar to EVs, only on a larger scale. In Norway, there are ongoing investigations into the opportunities for battery switching for smaller passenger ferries. Battery switching involves installing charging stations at the dock where the ferry batteries are charged, and discharged batteries can be swiftly replaced with fully charged ones [46]. This means that the batteries at the charging stations can utilize the same smart charging techniques as EV batteries. This allows the charging to take advantage of off-peak electricity rates or periods of low demand and offers flexibility during the charging periods.

Some industrial plants also offer opportunities for demand-side flexibility through excess energy in the form of heat. Data centers, for example, generate excess heat that can be delivered to greenhouses. In 2021, the silicon company Elkem in Sørfold, Norway, opened an energy recovery plant that successfully reuses almost 28% of the electrical energy used as waste heat [47]. This is an illustrative example of how other forms of energy also can offer flexibility. However, due to limited time and resources, the scope of this thesis will be electrical energy.

Naturally, the potential for demand-side flexibility in the industrial and commercial sectors is most significant in areas and countries with a higher share of consumption. This is pointed out in [30], which investigated Northern Europe's demand side flexibility potential. They found that the industrial flexibility potential was largest in Norway, Sweden, and Finland due to "a higher share of forestry and metal processing industry." However, as this sub-chapter aims to illustrate, the potential is significant and could contribute positively to the grid.

3 Flexibility Use, Benefits, and Challenges

From the previous chapter, it is evident that there is great potential for end-users to mobilize and offer demand-side flexibility. This chapter will discuss different opportunities and benefits that the integration of such flexibility assets can provide, focusing on how it can aid the DSO with problems that may occur in the distribution grid. Lastly, some challenges regarding the integration of end-user flexibility will be discussed. This is an extension from the preliminary specialization project [11] with some adjustments and expansions.

As mentioned in Chapter 2, flexibility is an essential tool for the TSO to balance the power system's frequency. When supply and demand have to be in continuous equilibrium, and unforeseen situations arise on either side of the system, there is a need for reserves that can be utilized to maintain system balance. This is what flexibility traditionally has been used for, which is still a key driver behind the increasing need for flexibility [48].

3.1 Climate

As mentioned earlier, the integration of RES plays a crucial role in addressing challenges related to the climate crisis. In 2021, the EU 2030 Climate Target Plan proposes that GHG emissions be reduced to at least 55% below the 1990 levels by 2030[49]. One crucial strategy for achieving these emissions reductions is decreased use of fossil fuels. As noted in Chapter 2.2, all OECD countries have to end their use of coal by 2030. However, current electricity data from [50] show that many European countries are still heavily dependent on such resources. For example, in 2022, 30.9% of the electricity available in Germany came from coal, which represented almost 80% of the total emissions related to the country's electricity production. As such, the need for further RES expansion is still great. As noted in Chapter 2.1, the capacity of RES, like wind and solar power, has already increased significantly in the last decade. However, the large amounts of fossil fuels still being used underline the need for further RES expansion.

Also noted in Chapter 2.1, the growing use of intermittent power generation increases the need for flexibility in the power grid. The revealing of flexibility assets from the consumer side can be a critical contributor to this [21]. By utilizing the demand-side flexibility of the grid, the use of environmentally friendly power sources might be increased while the power quality and security of supply are maintained. If power producers utilizing RES technology can buy demand-side flexibility in the balancing market or even in the DA market, some of the uncertainty related to intermittent power production might Moreover, it reduces the dependence on building new conventional load-following power plants, benefiting the environment and climate.

A big part of facing challenges related to the climate crisis is electrification. In Norway, for instance, gas turbines have historically supplied the oil industry. However, to reduce CO_2 emissions, the industry is now moving towards importing power from land and thus renewable power [51, 52]. Additionally, there has been a significant increase in electrification in the transport sector, with a significant increase in EV production and sales. Between 2020 and 2021, the share of EVs in Europe increased from approximately 10.5% to nearly 18% [53]. This, combined with increased residential electrical needs, increases the transmission and distribution grid pressure. The result is an increased need for grid upgrades and expansions, which are time-consuming, expensive, and take their toll on the environment. Increasing the flexibility potential through end-user inclusion might delay or even eliminate some of the need for new grid infrastructure, thus minimizing the associated economic and environmental impact [22].

3.2 Aiding the DSO

As the focus of this master's thesis is on DSO-LEC coordination, it is of interest to investigate how demand-side flexibility might help the DSO deal with issues that arise in the distribution grid. Specifically, how flexibility can help reduce distribution losses, regulate voltage magnitudes, and congestion management will be investigated.

Demand-side flexibility can help reduce transmission and distribution losses [7, 8, 22, 25]. Integrating DERs in the distribution grid can minimize the need for power transfer across the transmission and distribution grid. This is achieved by having local production sites, resulting in shorter transfer distances and, as such, reduced transfer losses. In the preliminary thesis of [8], it was found that the need for active power imported from the transmission grid to the distribution grid was reduced by 40% when flexibility was included in their IEEE testing grid. Subsequently, the total active power losses were reduced by 7.5% for the considered case.

Furthermore, flexibility can be used by the DSO for voltage control purposes [7], where the aim is to keep the voltage magnitudes within its acceptable operating limits [54]. Voltage deviations occur in the distribution grid, primarily due to two reasons: fluctuations caused by a significant increase in the use of intermittent RES and over- and under-voltages during off-peak and peak hours, respectively [8, 55]. How flexibility can help solve such problems depends on the voltage levels of the grid due to the resistance to reactance (R/X) ratio of different voltage levels. This relation is observed in the voltage drop equation in Equation 1. The voltage drop is influenced by the load voltage (U_L), active and reactive power (P and Q), and short-circuit resistance and reactance (R_k and X_k). Low-voltage (LV) power grids have a high R/X ratio (higher resistance than reactance), which means that active power has a more considerable impact on such grids. Consequently, active power injections from DERs can help regulate voltage magnitudes in LV grids. However, medium-voltage (MV) power grids have a lower R/X ratio, indicating increased reactance. As a result, MV grids can benefit from active and reactive power injections to regulate the voltage.

$$\Delta U = \frac{1}{U_L} \cdot (P \cdot R_k + Q \cdot X_k) \tag{1}$$

In the preliminary work of [8], the impact of flexibility on voltage magnitudes in an IEEE test case distribution grid was tested. An under-voltage scenario was simulated, and the grid's response was analyzed, with and without demand-side flexibility. It was found that when flexibility was included, voltage magnitudes improved across all 33 nodes. In most nodes, the voltage magnitude was closer to the nominal value of 1 p.u. In contrast, without the flexibility, the nodes furthest down in the network had to resort to load-shedding to maintain voltage magnitudes within the acceptable operating limits. When flexibility was included, the need for load-shedding was eliminated.

Another issue the distribution grid might experience is congestion problems due to capacity limitations and reduced line capacity due to outages. In such scenarios, DERs could provide local power production, which reduces the need for transfer capacity. DR measures could shave or shift end-users consumption to reduce the need for power in congested areas [22].

This was also investigated in [8], where a capacity reduction in a line in the grid was introduced. Three test cases were simulated, one without flexibility or voltage control, one with flexibility and no voltage control, and one with both flexibility and voltage control. For the first test case, congestion management was achieved through load-shedding, and the voltage magnitudes were close to the lower operating limit for many of the nodes. With only flexibility and no voltage control, the need for load-shedding was eliminated, but the voltage magnitudes exceeded their upper limits for several nodes. With both flexibility and voltage control, the voltage magnitudes were all within their limits, and some load-shedding was employed. Despite the need for load-shedding when flexibility was employed, the amount of load-shedding necessary was reduced significantly. Thus, using demand-side FRs for congestion management can also be beneficial.

3.3 Shift of Market Power

The integration of demand-side flexibility and, as such, increased participation from end-users has the potential to shift the power dynamics of the market [21]. As it stands now, the TSO (see Chapter 5.2.1 for definition) controls the generation side of the grid and is responsible for maintaining the transmission grid. Below the TSO is the DSO, responsible for delivering power to end-users, who have had a relatively passive role. The power dynamic is unidirectional, with the TSO/BRP at the top, the DSO, and end-users at the bottom. Since the inclusion of demand-side flexibility depends on the greater involvement of end-users, it is natural that some of the market power is shifted towards them. Through aggregating their FRs, end-users can have a more significant impact and consequently gain greater influence in the power market. A changed power market structure would also include a more prominent role for the DSO.

3.4 Economic Benefits

The introduction of demand-side flexibility in the power market could benefit various participants economically. Firstly, as discussed in Chapter 3.2, the activation of DERs can reduce transmission and distribution losses. By generating and distributing power locally, the need for long-distance power transfer is reduced, and subsequently also, transfer losses. Such reduction naturally translates into cost savings for participants in the power market.

Moreover, the extended use of demand-side flexibility can delay or reduce the need for infrastructure expansions and upgrades, which also has significant economic benefits for both the TSOs and DSOs [21]. Investment costs of grid expansions vary depending on the size of the project and region but are generally expensive and require significant amounts of resources. Thus, a reduced need for expansions can significantly benefit the TSO and DSO. Furthermore, the grid operators can benefit economically from fewer power outages and disruptions, as demand-side flexibility is assumed to strengthen the reliability and resilience of the power grid.

End-users may also benefit economically by utilizing their flexibility. As seen in Chapter 2.3.1, participating in IBPs allows end-users to earn bill credits or discount rates, resulting in lower electricity bills. Through PBPs, they are encouraged to shift or shave their load during peak hours because of high electricity prices. By becoming more aware of their consumption patterns and prices, they can increase their energy efficiency and avoid high price periods, consequently reducing their electricity bills.

Activating demand-side FRs can also flatten the demand curve, reducing the need for peak-power plants. The need for peak power units is reduced with fewer and lower peaks in the demand curve. These units have high operational marginal costs, making them expensive to use [21, 22]. Thus, activating demand-side flexibility reduces operational costs for power producers, which subsequently impact system-wide costs. For instance, price spikes might be reduced, resulting in a lower average spot price [22], which is beneficial for end-users.

Furthermore, greater involvement from end-users can indirectly stimulate new job opportunities and economic prospects for new market players. Because demand-side flexibility is assumed to support greater integration of RES technologies, companies investing in such expansions will benefit economically. In addition, as will be discussed later in Chapter 5.2, the increased inclusion of demand-side flexibility will require new market participants. Thus, new opportunities for earning money in the power market are introduced through these new roles.

In summary, end-user FRs offer a wide range of economic benefits for various participants in the power market. By allowing end-users to adjust their power consumption or supply power to the grid in response to DSM programs, demand-side flexibility can help reduce costs, enhance reliability and resilience, and support the expansion of RES technologies.

3.5 Challenges

Despite the significant potential for demand-side flexibility to benefit the power market, several challenges must be addressed. One of the primary challenges with the implementation of demand-side flexibility is the unsuitable market structure that is currently being employed [21]. The power market still remains highly centralized, with the BRP and TSO on top, while the end-user still has a relatively passive role. This market structure makes the integration of demand-side flexibility difficult. Consequently, a more significant shift towards a decentralized market is necessary, which requires novel ways to coordinate the participation of different participants in the market. This includes a greater inclusion of the DSOs, power utility companies, and, most importantly, the end-users.

However, the transition to such a market structure presents its own set of challenges. Firstly, these structural changes will require significant investments [21]. Even though the activation of demand-side flexibility can potentially reduce the need for infrastructure expansions, upgrading existing technology will still be necessary. With the integration of demand-side FR options like ESS and DGs, the power system has to be able to handle bi-directional power flow, which deviates from the traditional unidirectional flow of the present system [33]. Additionally, the DSO needs more technology and resources for managing its grid based on DER technologies.

Addressing such challenges will require comprehensive solutions and adaptations in the power market structure and the grid operators' technological resources. This will require significant investments, upgrades, expansions, and great coordination efforts between participants to move towards a decentralized power system suitable for demand-side flexibility.

3.5.1 Seasonal variations

The availability and flexibility potential of certain demand-side FRs may be subject to seasonal variations, with the most significant differences occurring between summer and winter. For example, FRs such as TCLs and EVs are influenced by consumption patterns that vary across seasons. In colder countries that rely on electric heating, power demand will be higher during the cold winter months. Consequently, there is "more" flexibility, but the willingness to supply this flexibility might be lower due to comfort-related reasons. In contrast, warmer countries have higher use of air conditioning during summer periods, leading to more flexibility available during these months. Again, the willingness to offer this flexibility depends on each end-user's comfort requirements.

In the case of EVs, their battery performance is typically poorer in winter compared to other seasons. This results in increased power consumption from EV charging during winter, as batteries need to be recharged more frequently [56]. This consumption might be less flexible because of poor battery performance.

On the other hand, some end-user FRs are not significantly affected by seasonal variations. The consumption patterns of other controllable loads, like, for example, wet appliances, remain relatively static and are thus available during all seasons. Still, seasonal variations pose a challenge for aggregators or power utility companies, as the DSM program design has to consider such seasonal variations.

3.5.2 Technological Challenges

As pointed out earlier, the use of intermittent DGs as flexibility assets on their own is challenging as weather forecasts are unreliable, and the ability to control power production as needed is limited. With the increased utilization of DERs, more accurate forecasting tools are necessary to operate such resources effectively [21]. With improved and more accurate forecasts, operators can more easily predict power generation and optimize the use of DERs, and as such, boost the flexibility of the system.

In addition to improved forecasting tools, better Information and Communication Technologies (ICTs) are essential for utilizing demand-side flexibility. Precise communication of flexibility needs and potentials between end-users and their aggregator is essential, as well as between aggregator and flexibility buyers. Accurate communication is also vital for the correct activation and deactivation of FRs. Therefore, the deployed technology must facilitate precise and effective communication so that demand-side flexibility can be utilized optimally.

The integration and operation of V2G also present specific technical challenges. In [57], three main problems were identified: battery degradation, charger and communication efficiency, and aggregation. With V2G, the more frequent charging and discharging cycles result in more rapid battery degradation than regular use, impacting the vehicle's capacity range. Charger efficiency refers to the power loss during power transfer between the grid and the vehicle. With bidirectional power flow, such losses might increase.

The communication challenges are related to developing standardized communication protocols between EVs, charging stations, and the power grid. Good ICTs are required for precise monitoring and control of power flows and for managing the charging and discharging in response to grid conditions. The aggregator challenge relates to developing good algorithms that optimize charging schedules that balance the flexibility demand and the needs of EV owners.

These technological requirements and challenges may pose economic challenges for integrating some demand-side FRs. While significant advancements have been made in different technologies in the last decade, there is still work to be done, which can be costly for several participants. The end-user has to invest in appliances that can be controlled to be able to offer flexibility, the aggregator/power utility company has to invest in the development and installment of good ICTs, and the DSO and TSO need a power grid that tolerates the bi-directional nature of some DERs. Consequently, economic challenges still need to be addressed for the full integration of demand-side FRs.

3.5.3 Need For a Good Framework For End-User Inclusion

The implementation of new ICTs in the power market introduces potential issues related to privacy and security [21]. As data communication between end-users and power utility companies increases, concerns about privacy regarding this data might arise. This could discourage some end-users from participating in DSM programs.

With the shift of market power towards end-users, other participants might lose some of their influence which can result in conflicts of interest regarding the implementation of demand-side flexibility [21]. With the current market structure, traditional power producers offer flexibility in the balancing/reserve market. However, with the increased penetration of demand-side flexibility alternatives, these producers may experience a decrease in sales and may therefore oppose the inclusion of other FRs.

The greater involvement of end-users in the power market might impose problems. The integration of demand-side flexibility relies heavily on end-user behavior, which can be highly variable and challenging to predict [21]. Different end-users will naturally have differing priorities and motivations, which makes it hard to design a DSM program that encourages all end-users to participate. Without adequate incentives, participation in DSM programs might not be beneficial enough for end-users, thus limiting the overall success of integrating demand-side flexibility.

Successfully integrating demand-side flexibility requires significant changes to the existing power market structure or, most likely, the development of an entirely new market model (see Section 5). This introduces additional challenges that must be addressed [58]. One such challenge regards the roles and objectives of the different participants. With a new market design and structures, existing participants may need to assume new roles or entirely new participants might emerge. Moreover, the objectives of the market and the participants need to be clearly defined. The stakeholders might have different perspectives on how demand-side flexibility should be distributed. All participants cannot have all their wishes granted, and a compromise must be made. A challenge is thus to find a satisfactory solution for all participants, encouraging their active participation in the market.

4 Uncertainty of RES

As discussed in Chapter 2.1, the use of distributed RES is increasing significantly. Due to their intermittent nature, there is a higher degree of uncertainty related to such power production compared to more traditional energy sources like gas, coal, or hydropower [59]. Because of this uncertainty, RES power production can be categorized as *stochastic power generation*. "Stochastic" refers to a random probability pattern that may be analyzed but not accurately predicted [60]. By this definition, RES power generation is unpredictable over longer time frames. For shorter time frames, uncertainty may cause smaller deviations as well.

The cause of this uncertainty is the RES dependency on external factors. Wind power is heavily dependent on weather conditions. The most apparent factors are wind speed and direction, where for example, strong gusts of wind can cause sudden generation spikes or calm winds resulting in little to no generation. However, other factors like terrain, humidity, air pressure, date, and time of day also impact the production [61]. Similarly, solar power is dependent on the availability of sunlight for production. Weather conditions like cloud coverage and solar irradiance determine how much electricity can be generated [62].

The intermittency of wind and solar power introduces uncertainty in energy planning and management. Power producers utilizing RES are thus tasked with analyzing their available data to find the best possible prediction. To participate in the power market, they need to know how much power they can produce and, thus, how much they can offer. To mitigate this, grid operators rely on sophisticated forecasting models that utilize weather data and historical patterns to estimate power generation levels. Such methods are crucial to decrease uncertainties and will, for example, make it easier to determine optimal maintenance and dispatch [63].

4.1 Forecasting

[63] divides wind power forecasting models into four categories: persistence methods, physical methods, time series models, and artificial neural networks (ANNs). Solar power forecasting also utilizes methods based on these approaches [62]. With persistence methods, future power production is assumed to be equal to the current measured power. As such, these methods are straightforward and are usually just used as a reference. Physical methods are, as the name suggests, dependent on physical data. Here, wind turbines or solar panels are modeled, and numerical weather prediction (NWP) data are used to determine, for example, wind speed. The related wind turbine power curve is then used to forecast wind power based on the predicted speed. These models depend heavily on accurate weather forecasts for correct input data.

Time series models and ANNs are statistical methods and are "based on developing the non-linear and linear relationships between NWP data and the generated power" [63]. Historical model prediction data is compared to the actual measured power to tune the models. After it has been tuned, the model can use upcoming NWP forecasts to predict how much power the turbines can produce.

Specifically, time series-based methods generate mathematical models that "develop the model, estimate parameters, and check simulation characteristics" [63]. Such methods include different regression models like the autoregressive (AR) model and the AutoRegressive

Moving Average (ARMA) model [62]. ANN methods have the ability to uncover non-linear associations between input and output, making it one of the most commonly employed wind power prediction methods [63]. Such models usually comprise an input layer, one or more hidden layers, and an output layer, where historical data is used for training, as described for the general statistical methods. Within the layers, neurons act as interconnected processing units through weighted connections. During the tuning, these weighted connections are adjusted.

Physical methods were found to be more suitable for medium- to long-term predictions [63]. However, they are models that require large amounts of computational resources. Statistical methods performed better for short-term to medium-term projections and were easier to model. Hybrid models combining these different approaches were found to be promising as well.

4.2 Demand-side flexibility for Production Planning

Advancements in data availability and quality, better weather forecasts, and increased computational power have led to significant accuracy improvements in forecasting methods. However, even with better forecasting tools, some deviation between forecasts and actual production is expected when analyzing intermittent processes. The most significant source of error is the unpredictability of weather, with minor changes in, for example, wind speed or direction or cloud cover and movements significantly impacting power production.

Due to this inherent uncertainty, RES power producers must rely on flexibility measures and, as such, might benefit from utilizing demand-side flexibility, as discussed in Chapter 3.1. A helpful tool for determining what flexibility is needed is generating scenarios [59]. With good input and statistical/historical data, it is possible to anticipate different scenarios for the various variables that determine power production. This could, for example, include imagining sudden weather changes and the probability that such events will occur.

With good scenario simulations, it might be possible for producers to anticipate their potential flexibility needs, which can then be incorporated into the planning phase. In [14], demand-side flexibility was included in the DA and FM markets. With flexibility added to the DA market, RES power producers could buy flexibility based on their anticipated needs if a different scenario should occur. This was also described in Figure 5.4 in Chapter 5.3. As such, power producers can increase their ability to respond to potential deviations between forecasts and production, contributing to the power system's more efficient and reliable operation.

5 The Local Flexibility Market

As mentioned in the introduction, also this chapter is an extension of the preliminary specialization project [11]. Some adjustments and expansions have been added, as this thesis also focuses on the integration of distributed power generation. As such, the role of the power producer has been included and has been added to the coordination scheme that is introduced and discussed in Chapter 5.3.

5.1 Market Definition

As discussed in Chapter 3.5, integrating demand-side FRs introduces the need to modify the existing power market structure. The market's current structure for trading flexibility is designed to primarily cater to a few large generating entities and not smaller, locally distributed FRs. As such, it is designed to be less accepting of price deviations compared to the bids in the DA market [64]. This highlights the need for a new, more modern market model that caters to several different FRs. The traditional structure where one entity owns most of the components is unsuitable in this context. Instead, a new market structure is necessary, incorporating new participants and roles for trading flexibility. A Local Flexibility Market (LFM) can be defined as a geographically limited platform that facilitates the trading of flexibility [7]. The geographical limitation can range from a small neighborhood to a somewhat larger area in the form of small cities. The platform includes multiple participants who offer flexibility, want flexibility or are tasked with controlling and clearing the market. As such, the LFM has a defined structure, assigned roles, and mechanisms for clearing the market.

5.2 Market Players

Traditionally, the power system has included the participation of the grid operators TSOs and DSOs, the Balancing Responsible Party (BRP), power producers, and the passive role of the end-user. However, in the LFM, two new additional roles are introduced. These are the roles of the Aggregator and the LFM operator (LFMO), who represent the end-users and operate and clear the market, respectively [7]. As this thesis mainly focuses on the coordination between the DSO and LECs, the TSO and BRP are only briefly introduced.

5.2.1 Grid Operators

To fully understand how flexibility can be utilized and who will benefit from it, it is vital to understand the roles of different participants in the power system. Two of the most well-established participants are the TSO and DSO. The TSO and DSO are the backbones of the power distribution grid infrastructure. They are responsible for managing and maintaining the grid, which consists of the Main grid (EHV), Regional grid (HV), HV Distribution network (MV), and LV Distribution Network (LV) [65].

Transmission System Operator TSOs are responsible for operating, managing, and maintaining the transmission system, which predominantly consists of high voltage grids [66]. This part of the power grid is where most of the conventional power generation occurs, and there are generally few consumers directly connected to this grid [67]. Formerly referred to as EHV or HV grid, this part of the grid plays an essential role in ensuring the reliable transmission of electricity.

In the context of this thesis, DSOs can be considered the TSOs' main consumers. The primary objective of the TSO is to ensure the security and stability of the power supply, ensuring that the grid can meet demand at all times. The TSO will often participate actively in the LFM, as demand-side flexibility could benefit congestion management within the transmission grid. However, due to the specific focus of this thesis, the TSO falls outside of the scope and will not be discussed further going forward.

Distribution System Operator *DSOs* can be defined as the distribution system's operators, managers, and maintainers. Their primary focus is on the MV and LV parts of the power grid, which connect directly to end-users. Traditionally, the DSOs have not been directly connected to power-generating units but import power from the connection to the transmission grid.

According to article 2, point 29, in the European Legislation, the role of the DSO is defined as: "a natural or legal person who is responsible for operating, ensuring the maintenance of and, if necessary, developing the distribution system in a given area and, where applicable, its interconnections with other systems, and for ensuring the long-term ability of the system to meet reasonable demands for the distribution of electricity" [66],

On a day-to-day basis, the DSO performs various administrative tasks, such as collecting electricity bills, planning and supervising the MV and LV grid maintenance, and responding to client complaints related to power outages or voltage problems [3]. As discussed in Chapter 3.5, the DSO could utilize demand-side flexibility to deal with problems related to congestion, voltage irregularities, and distribution losses. Furthermore, several economic benefits related to demand-side FR utilization were discussed in Chapter 3.4, such as possible delays in the need for infrastructure expansions.

Coordination between TSO and DSO The need for optimal coordination between TSO and DSO is well documented in the literature as one of the most crucial steps in integrating RES power generation into the power system in a seamless manner. This has been the focus of the preliminary works of both [8] and [12]. Furthermore, the importance of this coordination is highlighted in a report by the European Distribution Operators (EDSOs) [68]. As the power becomes increasingly complex and unpredictable, the efficient sharing of information and coordinated action concerning said information will only become more critical. When properly implemented, such coordination could significantly benefit both TSO and DSO [8].

Future role of DSO In the future, the responsibilities of the DSO will become increasingly vital to optimizing the rapidly evolving decentralized grid. As illustrated in [3], the DSO will assume new roles and responsibilities in addition to the ones they have had historically. The efficient implementation of such responsibilities is crucial for the prospect and effect of the evolving power grid on the quality of life for all participants, especially end users. These responsibilities may include the procurement of DERs to maintain grid stability by reducing voltage violations or helping alleviate congestion in the grid. The continuous integration of ICTs will bring more control and complexity to the tasks of the DSO. As previously mentioned, effective and accurate information sharing between the two is crucial to TSO-DSO coordination. This could also be extended to the entire market, as this coordination should facilitate newer market players to enter the market [68].

5.2.2 Power producer

As the name suggests, the primary role of the power producer is to generate electricity and participate in the power market by selling their produced energy. Traditionally, power generation has been dominated by conventional resources like gas, coal, nuclear power, or hydropower. However, as discussed in Chapter 2.1, the capacity of RES technologies like wind and solar power has increased dramatically in the last decade. This expansion has been realized by traditional large-scale power producers that have shifted some of their production to RES, and new producers solely focused on RES.

Large-scale power producers have traditionally dominated the power system. For instance, in Norway, the largest power producer, Statkraft, has a yearly power production of approximately 60 TWh, accounting for almost 35% of the country's total power generation [69, 70, 71]. The majority of this capacity comes from large hydropower plants, and as such, power production is centralized, situated far away from the actual power consumption.

However, as discussed earlier, there is a shift towards decentralized power generation, and it is no longer limited to these large-scale power producers. With the increasing availability of cost-effective small-scale and on-site renewable power generation through RES technologies, electricity production is moving closer to consumption. A good example of this is the ABB site, mentioned in Chapter 2.4.2, where a local PV plant makes it possible to generate power on-site. During excess power production, the power is sold to the grid. This example demonstrates the decentralization of power generation and highlights the entry of new types of power producers into the market.

5.2.3 Aggregator

Due to their location, size, and limited capacity, smaller generating units controlled by conventional consumers need more market power to compete effectively with the traditional market players. This has led to the emergence of a new type of market player, the Aggregator.

The concept of the Aggregator is relatively new in the power market, only becoming a noticeable market participant alongside the emergence of LFMs. As a result, several various definitions of the concept have been proposed to accommodate different stakeholders' needs [1]. Consequently, one clear, universal definition that encompasses every need has yet to be established. However, similar characteristics arise; an aggregator is responsible for trading flexibility from the consumer side, either by selling or controlling it, to help relieve stress during peak demand periods or provide economic advantages for consumers [1].

One possible definition of an aggregator is a market participant providing the necessary platform for trading, facilitating information sharing, flexibility exchange, and scheduling flexible devices [72]. Ikäheimo, Evens, and Kärkkäinen proposed a well-rounded definition of the Aggregator; "An aggregator is a company who acts as an intermediator between electricity end-users, who provide distributed energy resources, and those power system participants who wish to exploit these services" [73]. This is widely accepted in the literature as one of the most comprehensive and accurate definitions of the Aggregator.

5.2.4 Who Can Be the Aggregator?

Depending on the specific market structure and clearing methods, the Aggregator can assume various forms within the LFM. In their thesis, Juffermans presented six configurations of aggregators, shown in Figure 5.1 [1]. The different configurations are adapted to fit various market structures and meet the different needs of market participants within the LFM. The six possible configurations combined with the Aggregator's main activities described in Chapter 5.2.3, the aggregator role can be categorized into two main types: combined and independent [1, 2].

The combined Aggregator is when an already established market player, such as the DSO, assumes the aggregator role. Here, the task is to trade with the end-users to ensure they utilize their demand-side flexibility, like load shifting or shaving. The primary objective is thus to optimize the consumption patterns of the end-users. On the other hand, the independent Aggregator operates as a separate entity that provides end-users with a platform to trade their demand-side flexibility with the rest of the power market [74].

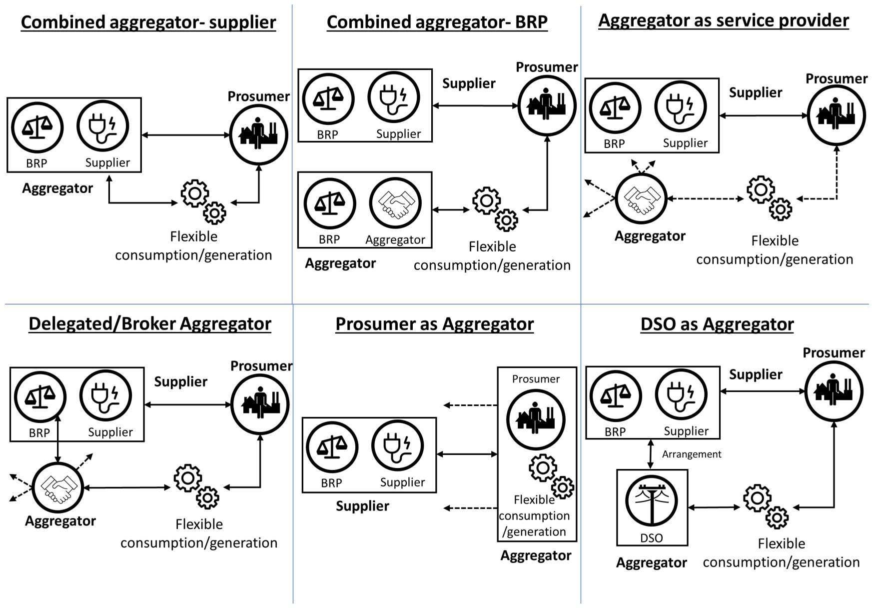

Figure 5.1: Types of aggregator configurations for LFM, from [1]

Current market player as Aggregator The first category of aggregators is the combined Aggregator, where the aggregator role is combined with one or more existing market roles. This is the most common type of Aggregator in today's power system, as little to no legislative changes are required since the market participant is already integrated into the LFM [75]. As shown in Figure 5.1, the aggregator configurations included in this category are Aggregator with BRP, Aggregator with supplier, and Aggregator with DSO. Juffermans's thesis explains these three configurations and a description, and the most prominent features are presented in Table 5.1 [1].

Aggregator configurations	Description	Key features
Aggregator-BRP	Aggregator is responsible for balancing the LFM combined with the traditional BRP for the supplier. This leads to increased complexity in the market as communication becomes more essential.	Prosumer has contract with both supplier and aggregator separately Aggregator sells flexibility at own risk, they purchase it from end-users before balance
Aggregator-Supplier	Aggregator provides the prosumer with a proposition that allows them to access both conventional supply as well as flexibility resources. In this configuration the Aggregator is also undertaking market balancing responsibilities, and is therefore a defacto BRP	Prosumer has contract with aggregator to cover all demand Aggregator fulfills roles of BRP, supplier and flexibility coordinator
Aggregator-DSO	DSO provides the prosumer with the ability to commercialize their flexibility through the DSO. In this configuration, the DSO is responsible for communicating with the BRP/LFMO on when flexibility is to be used so that imbalance does not occur	DSO in control of DERs More convenient for DSO as they can utilize DERs for congestion management more actively Opens for less competition in the flexibility market

Table 5.1: Description of configurations of Aggregator with current market players [1]

Independent actor as Aggregator The second category of aggregators is the independent Aggregator. Here, the Aggregator is an entity independent from any other market role, resulting in an increased number of market participants. From Figure 5.1, the three configurations in this category are Aggregator as a service provider, delegated/broker aggregator, and prosumer as Aggregator. These configurations are third-party aggregators with no predefined role or tasks in the market [2]. Definitions and key features of the three configurations are presented in Table 5.2.

Aggregator configurations	Description	Key features
Aggregator-Prosumer	This type of aggregator arises when the prosumer themselves broker a portfolio of their flexibility.	Many more aggregators Only self-owned flexibility to be used by each aggregator More realistic for larger scale prosumers
Aggregator-Service provider	This type of aggregator primarily works by providing the platform for the flexibility from a prosumer to be traded.	Little to no risk for the aggregator as they do not own the power at any point Less active in the traditional market
Aggregator-Broker	This type of aggregator acquires the flexibility from the prosumer and trades in on behalf of them.	Aggregator trades at own risk More collaboration between aggregator and BRP is needed

Table 5.2: Description of configurations of Aggregator as a third-party entity [1, 2]

5.2.5 LFM Operator

In the LFM, the LFMO plays a crucial role in coordinating the activities of the other participants in the market. Their primary responsibility is to provide a platform that facilitates the trading and exchange of flexibility. Their tasks include gathering market bids and offers, clearing the market, and communicating information between the market participants. Either the TSO or the DSO can fulfill the operator role, or it can be a collaborative effort between them both [8]. Alternatively, a new independent party can assume the role, fulfilling the responsibilities of the LFMO without having any preexisting role in the market.

Efficient coordination between all market players is crucial for the optimal functioning of the LFM [76]. Therefore, it is required that the LFMO operates the market optimally. As mentioned, an essential part of this is good communication flow between participants. As shown in Figure 5.2, based on [8], all information between the participants passes through the LFMO. Rather than communicating with each other directly, the TSO, DSO, and Aggregator convey their flexibility demand and supply to the operator. By gathering and analyzing all relevant information from the other participants, the LFMO can effectively clear the market and allocate the FRs optimally. As such, the LFMO is the entity that is most influential in the operation of the LFM.

In addition to the coordinating role, the LFMO is responsible for establishing and enforcing regulations and guidelines in the market, verifying the accuracy of bids and offers, and facilitating development and improvements to the market. Overall, the LFMO is crucial for a well-functioning LFM.

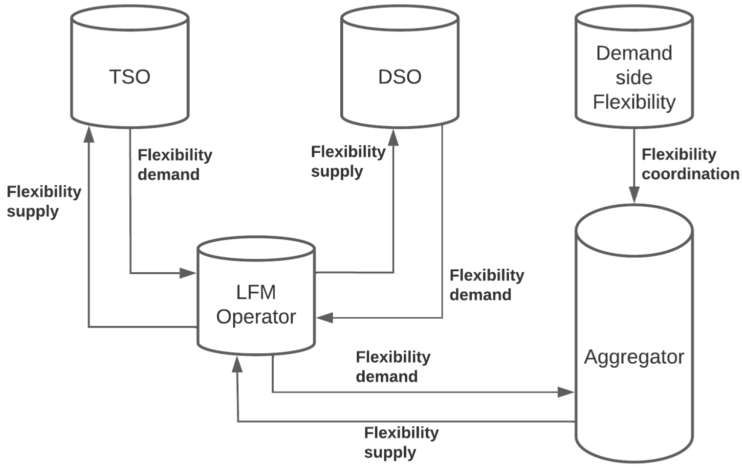

Figure 5.2: Flow of flexibility in the LFM when the Aggregator is a separate entity from the DSO

5.3 Market Coordination

In order to effectively manage the flow of demand-side flexibility, a well-defined coordination scheme is necessary. This coordination scheme serves as the platform for communication and interaction among the participants involved, and it operates based on a defined set of rules and procedures. The market design and coordination sets a framework for communication, establishes rules and procedures, and defines when flexibility is traded, how flexibility needs are prioritized, how and when flexibility is activated, and how and when payments are made. As such, the coordination scheme ensures that the exchange of flexibility is carried out in a structured and organized manner.

In the preliminary specialization project, the coordination scheme presented in Figure 5.3 by [7] and a more elaborate scheme by [8] was introduced and discussed. The scheme includes four participants, the BRP/TSO, DSO, LFMO, and Aggregator, and consists of three phases: planning, operation, and settlement. However, as the focus of the master's thesis is to include intermittent producers in the FM, these models have been expanded to include this participant. For producers to utilize demand-side flexibility to support the integration of RES technology, they need to be included in the market coordination.

The coordination scheme's first phase, the planning, is shown in Figure 5.4. The producer is added to this scheme based on the planning scheme presented in [8]. The planning phase starts right after the DA market is cleared, and, similarly to the DA market, the planning extends to the following day. The goal of this phase is to ensure the efficient utilization of FRs. During the planning phase, the Aggregator accumulates the available demand-side flexibility from end-users and communicates this to the operator. Firstly, the LFMO communicates the available flexibility to the DSO. The DSO evaluates its flexibility needs through OPF simulations of different scenarios and reserves the necessary flexibility. The OPF results are also shared with the TSO for balancing purposes.

Once the DSO has reserved the required flexibility, the remaining available flexibility is presented to the TSO, which also assesses its flexibility needs and reserves the flexibility it deems necessary. Lastly, the remaining available flexibility is offered to the producer, who

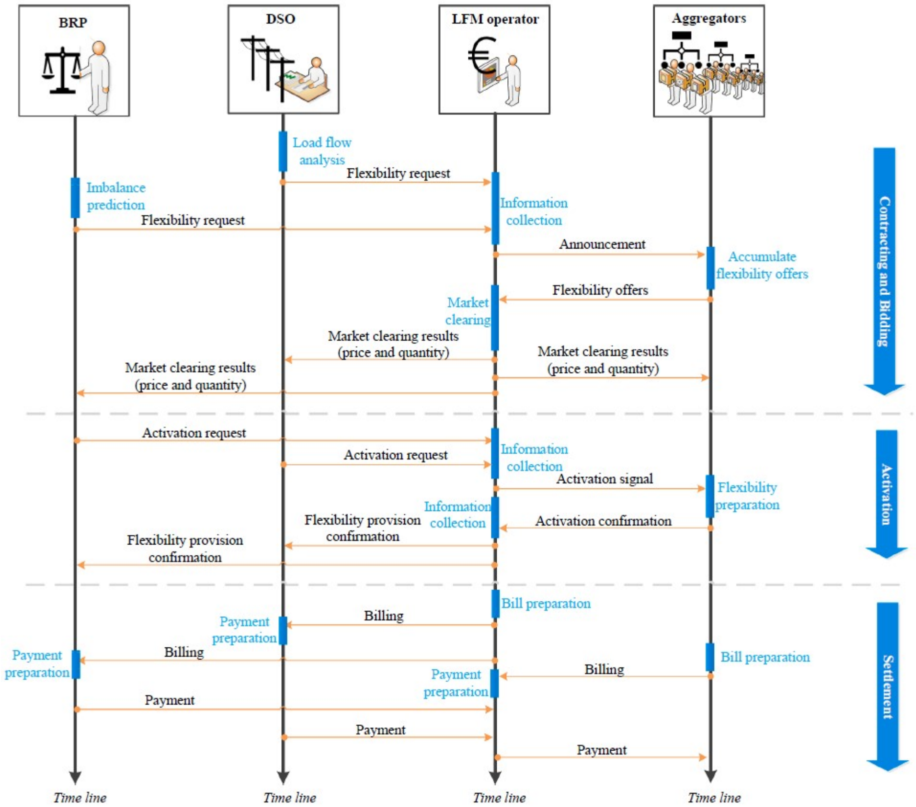

Figure 5.3: Timeline of a LFM, from [7]

reserves the flexibility they predict they might need based on their estimated forecasting errors. Once all the flexibility reservations are completed, the LFMO schedules the operation based on the total flexibility needed, which is communicated to the Aggregator. This market-clearing has to consider all the flexibility reservations and ensure that the flexibility activation does not violate any potential grid constraints.

The operation phase, depicted in Figure 5.5, starts at 00:00 the following day. While the flexibility activation is planned, there is always some uncertainty related to these plans. The rolling-horizon technique can be employed to address this uncertainty, dividing the operation into shorter time slots that are solved sequentially [77]. For this LFM coordination, each hour is split into 15-minute time slots.

During each time slot, the DSO uses its latest available data to conduct new OPF simulations, which provide updated information about its flexibility needs. Simultaneously, the producer monitors their operations and re-evaluates their flexibility need. The DSO and producer communicate their updated information to the LFMO, who then re-evaluates and adjusts the flexibility activation schedule, if necessary. The potential changes are communicated to the Aggregator and TSO. The Aggregator activates the requested flexibility, and the TSO performs the necessary balancing actions to maintain system stability. This process is then repeated every 15 minutes during the whole day. The settlement process is conducted at the end of the day, where the Aggregator receives payment for their flexibility activation.

The rolling-horizon technique allows for real-time adjustments, making it possible to address uncertainties and quickly adapt to changing conditions. The iterative process ensures that

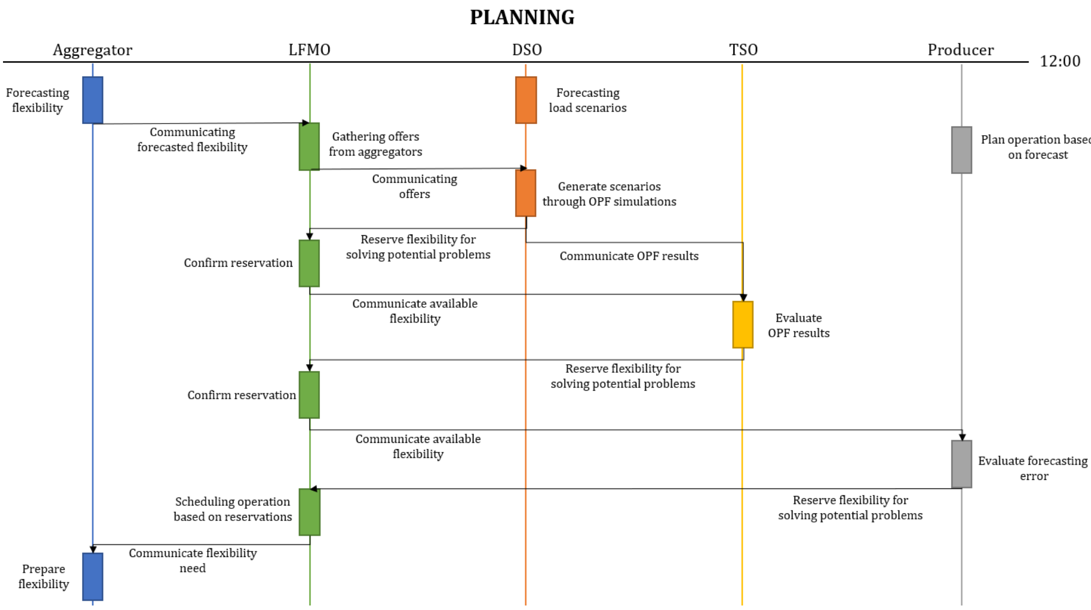

Figure 5.4: LFM planning phase, based on [8]

the demand-side flexibility is activated as effectively as possible and maintains grid reliability while fulfilling the participants' demands throughout the day.

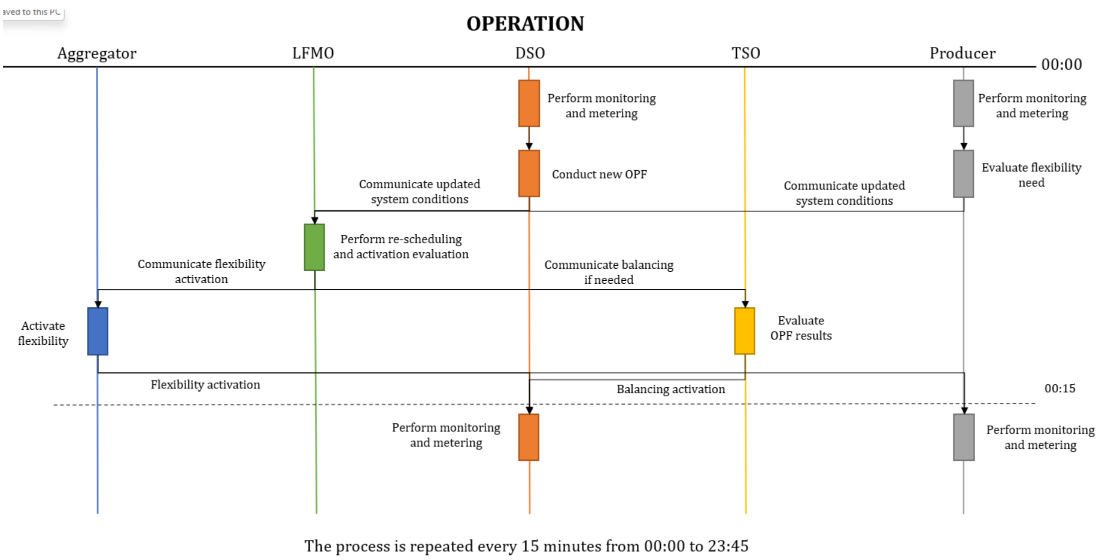

Figure 5.5: LFM operation phase, based on [8]

As both Figure 5.4 and Figure 5.5 show, the DSO is prioritized in this model. It has the first opportunity to reserve flexibility for their needs, then the TSO and the producer. Favoring the DSO in this way may not be a good solution for the real-life implementation of such a market. As discussed in Chapter 3.5, one of the challenges regarding the implementation of end-user FRs is the differing motives and goals of the participants. With a model that prioritizes the DSO, the TSO and producers might not want to participate as they cannot utilize the demand-side flexibility in a meaningful way.

6 Market clearing

As with the previous chapters, this part is also an extension of the preliminary specialization project [11]. As the different market clearing methods are not part of the main focus of this thesis, this chapter has yet to be modified or expanded in any way from the project. Even if it is not the main focus, it is included in the master's thesis as well, as it gives a theoretical introduction to some of the concepts used later in Chapter 7.

In order to gain a better understanding of the LFM and how it can be expressed mathematically, further elaboration of the concept is necessary. The LFM is a marketplace for trading flexibility as a balancing resource [7]. While the market and the resources are available for most traditional market participants, it is beneficial for the TSO and DSO regarding different aspects discussed in Chapter 3.2. This includes, among others, issues related to voltage regulation and congestion management. This results in a complex market structure, as multiple parties have competing objectives, which requires extensive and effective communication [1, 78].

As described in [7], the LFM can be expressed in different layers, each addressing a distinct market aspect. These layers include market participants, control, communication, and the physical grid. All these components are crucial for establishing a market structure suitable for all participants and encouraging their participation [78]. For this master's thesis, the layers of the market and communication are of particular interest. The market layer, modeled in Chapter 7, focuses on the interaction among market participants. In [7], four different market models were presented. These are summarized in Figure 6.1. These models will be briefly introduced in the following chapter. This chapter should be prefaced by mentioning the work of Jin et al. [7] in consolidating the information from other literature regarding this topic. Most of this chapter draws information from their works.

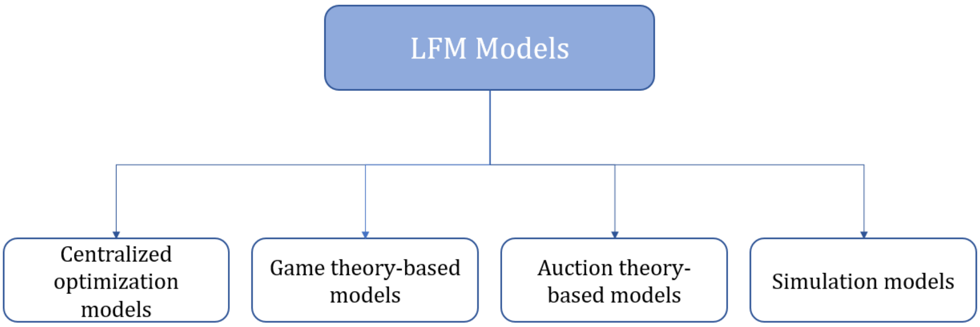

Figure 6.1: Figure showing the four concepts for modeling the LFM that are most prominent [7]

6.1 Models for the LFM

As previously mentioned, there are four main modeling approaches for the LFM, each offering unique perspectives. A comprehensive understanding of each is beneficial when deciding how to model the market. As such, all four are introduced in this chapter, in addition to arguments for what model was selected.

The first model that will be presented is the centralized optimization model, which is the most straightforward approach. Even though the market contains several participants, as discussed in Chapter 5.2, this model considers the market as seen by only one of these participants. Although the other participants still provide information and constraints, the centralized optimization only considers the objectives of the chosen participant [7]. As the model optimizes the system for the single participant, the excluded participants are operated for their benefit. A typical main objective of such optimization is minimizing operational costs. These models are generally simple to solve, as the complexity is reduced by only considering one participant's perspective. However, this simplicity comes at the expense of scalability, where the complexity and need for computational power increase significantly with the growing size of the problem.

The second market model considers the market a game, where each participant is viewed as a player. This model type is based on game theory and introduces a more competitive market model [7]. Such models suit markets with power imbalances, as described in [79]. In this report, game-theoretic markets are assumed to have utterly voluntary participation, with perfect information and rationality. It is also assumed that none of the participants would deviate from this perfect behavior for personal gain. The game represents the interaction between several individuals in a setting with strategic independence [80]. The game could thus become either cooperative, where participants have collective objectives, or non-cooperative, where each participant acts based on their own best interest [7, 80].

In the third model, auction theory is introduced. This is a thoroughly studied concept in market modeling, where the market is modeled as a bidding game between supply and demand. Bids are placed for supply and demand, and the market is cleared. This finds the clearing price and thus determines the amount of power a bidder has procured or sold. Suppliers whose bid is below this clearing price can sell their power, and the demand bids above the clearing price can buy this power [7]. There are two primary types of auction theory: single-sided and double-sided auctions. With single-sided auctions, there is a single supplier and many buyers, or vice versa. As such, the single unit, whether a supplier or a buyer, is monopolistic and determines the clearing price. However, a double-sided auction model is more appropriate for LFMs, as multiple suppliers and buyers are competing with each other [7, 81]. This resembles the Nordic electricity market, where bids are placed from both sides and influence the clearing price [65].

The last model concept for the LFM is simulation models, which involve multiple agents that interact with each within the defined environment. Such models are well-suited for complex socio-technical problems [82]. The agents of the markets can alter their behavior based on changes to the environment they are placed in [7]. Due to the LFM's complexity and number of participants that rely on effective communication and coordination, this is regarded as a suitable model approach [82].

The model of this master's thesis is an operational cost minimization model, which can be categorized as a centralized model. This method was chosen due to the size of the problem being relatively small. For future work, it might be necessary to change this approach if there is a desire to expand the model. How the model is implemented in Chapter 7 allows for integrating many medium size networks.

6.2 Clearing Methods for the Models

Having introduced the various modeling concepts for the LFM, a brief introduction to different clearing methods will now be presented. There are numerous strategies for clearing the different models, and which strategy is best depends on the formulation of the model. The different methods were summarized in [7]. This thesis will introduce these methods, but they will only be described briefly. Instead, the main focus will be on the methods utilized in the model described in Chapter 7. A summary of the concept for solving the LFM models is shown in Figure 6.2.

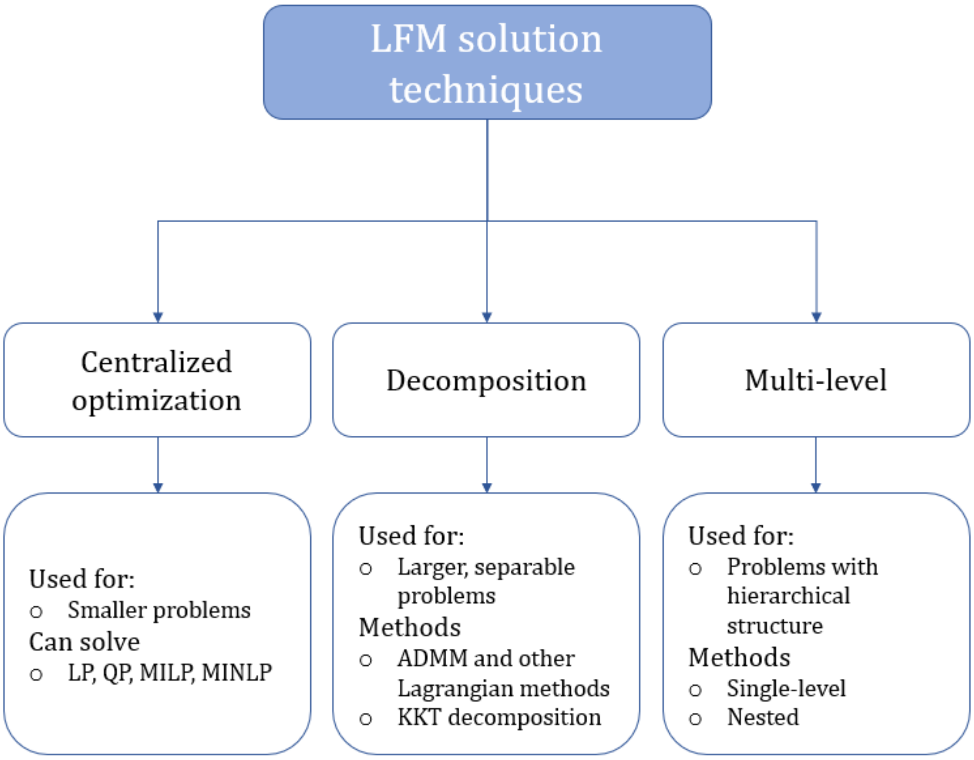

Figure 6.2: A figure showing the different solution techniques, based on the information from [7]

The first type of clearing method is the centralized optimization, presented in Chapter 6.1. Here, the market clearing is formulated as a unified system with a specific time horizon [7, 83]. These methods are typically utilized in systems that are small in both size and complexity, as they are inconvenient when applied to more significant problems. General algorithms and solvers for standard mathematical programming models, such as LP, MILP, and QP problems, are commonly used in centralized optimization models [7]. This approach is naturally well-suited for centralized optimization models.

On the other hand, decomposition models can be utilized when dealing with more complex LFM models. An example would be to relax the problem into a centralized form and solve it similarly to the centralized optimization models. Decomposition methods involve isolating portions of the model into smaller segments that are easier to solve. As demonstrated in [84], these techniques are particularly relevant in the context of emerging DERs and flexibility. Decomposition methods are often applied to larger, more complex centralized optimization models [7].

When optimizing an LFM, which can contain numerous participants, it is preferable to choose a relatively easy method to implement and can handle an increasing number of players. One such algorithm is the Alternating Direction Method of Multipliers (ADMM). ADMM is an algorithm for decomposing more significant convex mathematical problems into smaller, more manageable subproblems through iterations. The algorithm is a powerful tool for solving complex distributed convex optimization problems. The main principles of the algorithm are based on [85] and will be outlined in Chapter 7.2.1. However, it is beneficial to gain some understanding of ADMM mechanisms before the mathematical description is provided, and as such, a simplified version will be presented here.

The ADMM algorithm is used for larger problems with a separable objective. This means that the variables of the problem allow it to be split, and each subproblem is then solved separately by locking the other variable and regarding it as a parameter for that iteration. The variables are locked in an alternating order, where the unlocked variable is solved with the most recent updated value for the other variable. A convergence criterion is checked in each iteration. An optimal approximation to the complete problem has been found when this criterion is reached. As ADMM combines the method of dual ascent, which has great approximation abilities, and the method of multipliers, which has excellent convergence criteria, it achieves high accuracy in this area [85].

Using the ADMM algorithm for analyzing how DERs influence the power market has been thoroughly documented in the literature. The algorithm has proved to be highly effective when addressing the complexity of LFM market modeling [86], especially regarding voltage control [87]. Chapter 7.2.1 will present a summary of the algorithm as explained in [85], with slight adjustments to conform to the model used in the thesis.

Several other algorithms are also available for decomposing problems, like the LFM, with various attributes that make them applicable to different cases. Some standard methods include ATC, APP, PMP, and OCD[7]. However, these fall outside of the scope of this master's thesis and will therefore not be explained.

Lastly, markets with a hierarchical structure, i.e., where one participant leads, and the others follow this, even when they have their objectives in the market [88]. Such market structures can utilize bi-level optimization tools, where the optimization is divided into two layers, one nested within the other. This is most commonly used for markets following clear hierarchical structures [7].

Lastly, when the market formulations are hierarchical formed, i.e., one participant leads the market, and others follow their lead, even though all participants have their own goals in the market [88]. This leads to the need for bi-level optimization. In bi-level optimization, one has two layers of optimization, where one is nested within the other [88]. Bi-level optimization is commonly used when solving LFM formulations where a clear hierarchical structure is present [7].

7 Modeling

With the presented theory and literature in mind, the thesis will now explain the modeling section of the project. This thesis started with a model presented in [11], which was an adaptation of the work done by [8]. The original version of this model was created to solve a TSO-DSO connection DC/ACOPF problem with the integration of flexibility. The model was further developed by [12] and [13] in order to account for more DSOs and even include LECs. Due to this model being implemented over several years, the model is seen as quite robust and well-tested. As mentioned in Chapter 1.3, one of the goals of this thesis is to create and simulate a more realistic test case. This test case will be more detailed in Chapter 8. For the modeling part, the model used in this thesis is an AC/AC-OPF model aimed at solving a grid with the operational costs of running the grid for 24 hours. The AC/AC-OPF model will be solved by utilizing the ADMM algorithm. Later in this chapter, the methodology for solving this problem will be presented in more detail. However, first, the mathematical formulations itself is going to be introduced.

7.1 Multi-Period AC/AC Optimization Model

In this chapter, the model's whole mathematical formulation will be presented. As mentioned, the model operates over a 24-hour period, where the model first solves the DA market before the 24 hours and later solves the FM as a balancing of the DA results. The constraints of the model are going to be discussed, as well as presenting the different variables and parameters, beginning with showing Equations 2-19 from the DA model before going on to explain Equations 22-39 from the FM model.

Day-Ahead model

Minimize:

$$\sum_{t \in T} \left(\sum_{m \in TM} P_{mt}^{G,DSO} \cdot c_{mt} + \sum_{n \in N} P_{nt}^{G,LEC} \cdot c_{nt} \right) \tag{2}$$

Subject to DSO constraints:

$$P_{mt}^{L,DSO} - P_{mt}^{G} = -\sqrt{2} u_{mt} \cdot \sum_{j \in k(m)} G_{mjt} + \sum_{j \in k(m)} (G_{mjt} R_{mjt} - B_{mj} I_{mjt}) \tag{3}$$

$$Q_{mt}^{L,DSO} - Q_{mt}^{G} = -\sqrt{2} u_{mt} \cdot \sum_{j \in k(m)} B_{mjt} + \sum_{j \in k(m)} (B_{mjt} R_{mjt} - G_{mjt} I_{mjt}) \tag{4}$$

$$2 u_{mt} u_{jt} \geq R_{mjt}^2 + I_{mjt}^2 \tag{5}$$

$$R_{mjt} \geq 0 \tag{6}$$

$$u_{mt} = \frac{V_1^2}{\sqrt{2}} \tag{7}$$

$$u_{mt} \geq 0 \tag{8}$$

$$P_{mt}^{G,DSO,min} \leq P_{mt}^{G} \leq P_{mt}^{G,DSO,max} \tag{9}$$

$$Q_{mt}^{G,DSO,min} \leq Q_{mt}^{G} \leq Q_{mt}^{G,DSO,max} \tag{10}$$

Subject to connection constraint:

$$P_{mt}^{G,DSO} - P_{nt}^{G,LEC} = -\sqrt{2} u_{mt} \sum_{j \in k(m)} G_{mjt} + \sum_{j \in k(m)} (G_{mjt} R_{mjt} - B_{mjt} I_{mjt}) \tag{11}$$

Subject to LEC constraints:

$$P_{nt}^{L,LEC} - P_{nt}^{G,LEC} = -\sqrt{2}u_{nt} \cdot \sum_{o \in k(n)} G_{not} + \sum_{o \in k(n)} (G_{not}R_{not} - B_{not}I_{not}) \tag{12}$$

$$Q_{nt}^{L,LEC} - Q_{nt}^{G,LEC} = -\sqrt{2}u_{nt} \cdot \sum_{o \in k(n)} B_{not} + \sum_{o \in k(n)} (B_{not}R_{not} - G_{not}I_{not}) \tag{13}$$

$$2u_{nt}u_{ot} \geq R_{not}^2 + I_{not}^2 \tag{14}$$

$$R_{not} \geq 0 \tag{15}$$

$$u_{nt} = \frac{V_1^2}{\sqrt{2}} \tag{16}$$

$$u_{nt} \geq 0 \tag{17}$$

$$P_{nt}^{G,LEC,min} \leq P_{nt}^{G} \leq P_{nt}^{G,LEC,max} \tag{18}$$

$$Q_{nt}^{G,LEC,min} \leq Q_{nt}^{G} \leq Q_{nt}^{G,LEC,max} \tag{19}$$

All constraints in 3-19 are subject to:	$t \in T$
Constraints 3,4,9,10, are subject to:	$m \in M$
Constraints 5,6 are subject to:	∀ (m,j) lines
Constraint 7 is subject to:	$m = 1$
Constraint 8 is subject to:	$m \in M \backslash 1$
Constraint 11 is subject to:	$P_{nt}^{G,LEC} = P_{mt}^{L,DSO} if m_{DSO} = n_{LEC}, m \in M, n \in N, t \in T$
Constraints 12,13,18,19, are subject to:	$n \in N$
Constraints 14,15 are subject to:	∀ (n,o) lines
Constraint 16 is subject to:	$n = 1$
Constraint 17 is subject to:	$n \in N \backslash 1$

DA model The DA model aims to find the optimal dispatch for the grid hourly. The objective function, shown in Equation 2, is to minimize the operational costs for both the DSO and LECs with the given resources, which for the DA market model consists of generating costs. The model solves for all hours in the set T, for all the nodes in the DSO grid M, and for all the nodes in the LECs grid N. This model aims to solve for 2 while satisfying Equations 3-19. Equations 3 and 4 represent the power balance of the system in the DSO part of the grid. These ensure that the demand is met at all nodes for all hours. Equation 5 is the inequality that ensures that the problem will converge towards one OPF solution as the iterations are run [8]. The model also has two variables, R and u, with non-negativity constraints, shown in Equations 6 and 8. The variable u is also defined as a set value for the slack node in the system, given by Equation 7. The upper and lower limits of the active and reactive power generation are given by Equations 9-10, ensuring that the system does not become unbounded with regard to power generation. For the Equations 12-19, they correspond to Equations 3-10, only that the constraints apply for the LEC part of the grid, and will therefore not be explained further. Lastly, Equation 11 represents the active power balance between the DSO part of the grid, M, and the LEC part of the grid, N. This constraint applies where n=m, meaning the node is the connection node between the two grids.

Flexibility market model

Minimize:

$$\sum_{t\in T}\sum_{u\in U}\Bigg(\sum_{m\in M} P_{mtu}^{slack,DSO}\cdot c_{mtu}^{slack,DSO} + \sum_{n\in N}(P_{ntu}^{load-shedding,LEC}\cdot c_{ntu}^{load-shedding,LEC} \tag{20}$$

$$+P_{ntu}^{G,Flex,LEC}\cdot c_{ntu}^{G,Flex,LEC} + P_{ntu}^{L,Flex,LEC}\cdot c_{ntu}^{L,Flex,LEC} \tag{21}$$

$$+(P_{ntu}^{discharge,LEC} - P_{ntu}^{charge,LEC})\cdot c_{ntu}^{battery,LEC})\Bigg) \tag{22}$$

Subject to DSO constraints:

$$P_{mtu}^{L,DSO} - P_{mtu}^{G,DSO} = -\sqrt{2}u_{mtu}\cdot\sum_{j\in k(m)} G_{mjtu} + \sum_{j\in k(m)}(G_{mjtu}R_{mjtu} - B_{mj}I_{mjtu}) \tag{23}$$

$$Q_{mtu}^{L,DSO} - Q_{mtu}^{G,DSO} = -\sqrt{2}u_{mtu}\cdot\sum_{j\in k(m)} B_{mjtu} + \sum_{j\in k(m)}(B_{mjtu}R_{mjtu} - G_{mjtu}I_{mjtu}) \tag{24}$$

$$2u_{mtu}u_{jtu} \geq R_{mjtu}^2 + I_{mjtu}^2 \tag{25}$$

$$R_{mjtu} \geq 0 \tag{26}$$

$$u_{mtu} = \frac{V_1^2}{\sqrt{2}} \tag{27}$$

$$u_{mtu} \geq 0 \tag{28}$$

$$P_{mtu}^{G,DSO,min} \leq P_{mtu}^{G,DSO} \leq P_{mtu}^{G,DSO,max} \tag{29}$$

$$Q_{mtu}^{G,DSO,min} \leq Q_{mtu}^{G,DSO} \leq Q_{mtu}^{G,DSO,max} \tag{30}$$

Subject to connection constraint:

$$P_{mtu}^{G,DSO} - P_{ntu}^{G,LEC} = -\sqrt{2}u_{mtu}\sum_{j\in k(m)} G_{mjtu} + \sum_{j\in k(m)}(G_{mjtu}R_{mjtu} - B_{mjtu}I_{mjtu}) \tag{31}$$

Subject to LEC constraints:

$$P^{L,LEC}_{ntu} - P^{G,LEC}_{ntu} = -\sqrt{2}u_{ntu} \cdot \sum_{o\in k(n)} G_{notu} + \sum_{o\in k(n)} (G_{notu}R_{notu} - B_{notu}I_{notu}) \tag{32}$$

$$Q^{L,LEC}_{ntu} - Q^{G,LEC}_{ntu} = -\sqrt{2}u_{ntu} \cdot \sum_{o\in k(n)} B_{notu} + \sum_{o\in k(n)} (B_{notu}R_{notu} - G_{notu}I_{notu}) \tag{33}$$

$$2u_{ntu}u_{otu} \geq R^2_{notu} + I^2_{notu} \tag{34}$$

$$R_{notu} \geq 0 \tag{35}$$

$$u_{ntu} = \frac{V_1^2}{\sqrt{2}} \tag{36}$$

$$u_{ntu} \geq 0 \tag{37}$$

$$P^{G,LEC,min}_{ntu} \leq P^{G}_{ntu} \leq P^{G,LEC,max}_{ntu} \tag{38}$$

$$Q^{G,LEC,min}_{ntu} \leq Q^{G}_{ntu} \leq Q^{G,LEC,max}_{ntu} \tag{39}$$

All constraints in 23-39 are subject to:	$t \in T, u \in U$
Constraints 23,24,29,30, are subject to:	$m \in M$
Constraints 25,26 are subject to:	∀ (m,j) lines
Constraint 27 is subject to:	$m = 1$
Constraint 28 is subject to:	$m \in M\backslash 1$
Constraint 31 is subject to:	$P^{G,LEC}_{nt} = P^{L,DSO}_{mt} if m_{DSO} = n_{LEC}, m \in M, n \in N, t \in T$
Constraints 32,33,38,39, are subject to:	$n \in N$
Constraints 34,35 are subject to:	∀ (n,o) lines
Constraint 36 is subject to:	$n = 1$
Constraint 37 is subject to:	$n \in N\backslash 1$

FM model Now that the DA model has been introduced, the following paragraph will explain the FM model. The FM model is the mathematical formulation of the grid operations cost minimization during the response market with flexibility or the flexibility market. The objective of this market is to minimize the imported power in the DSO and minimize the costs of utilizing the different flexibility resources the market has access to, shown in Equation 22. The market can access load shedding, batteries, load control, and flexible generation as its flexibility resources for this model. The rest of the equations that define this market perform a similar purpose as the corresponding ones in the DA market model, the main difference being that the FM model includes time-steps for each hour. The time-step set, U, defines how much each hour will be split into. For a U=4, each hour is divided into four 15-minute segments. The model then optimizes for each hour, time-step, and node in the system. One other difference from the DA model is that in Equation 32, the variable $P_{ntu}^{G,LEC}$ includes all the flexibility resources shown in Equation 22. For readability, these are not written out.

7.2 Algorithmic Methods

The aim of the model presented in Chapter 7.1 was to solve the LFM to optimality when considering multiple flexibility trading LECs connected to a DSO. This resulted in the models in Chapter and Chapter . These mathematical problems are written as SOCP problems, which are relaxed versions of non-convex problems. This method was applied because it is a tool to make the problem solvable in polynomial time by relaxing the non-linear constraint that made the problem non-convex [89]. The model still is not as easily solved for large cases. Considering that this problem could grow into a large, hard-to-solve problem, the alternating directions method of multipliers (ADMM) algorithm was applied as a solution tool. The ADMM algorithm works on convex mathematical optimization problems, such as the resulting model presented in earlier chapters. The implementation of the ADMM algorithm was first done in earlier works [12] and [13], and was improved in this thesis. The ADMM algorithm will be introduced in the following chapter, along with modifications and convergence criteria.

7.2.1 ADMM algorithm

To address problems characterized by unfavorable structure, such as the general problem depicted in 40, the ADMM algorithm can be employed. The ADMM algorithm assumes that f and g are convex functions and that $x \in R^n$, $y \in R^m$, $A \in R^{p \times n}$, $B \in R^{p \times m}$ and $c \in R^p$ [85].

$$\begin{aligned} minimize f(x) + g(y) \\ s.t. Ax + By = c \end{aligned} \tag{40}$$

The algorithm decomposes problems like Equation 40 by relaxing the complicating constraint that involves both variables x and y, allowing for the creation of two independent sub-problems. The algorithm then applies the dual variable to this constraint, λ, and the Lagrangian parameter, ρ, to move the constraint into the objective function of the sub-problems for x and y. The resulting Equation 41 is the Lagrangian function representing the relaxed problem.

$$L_p(x, y, \lambda) = f(x) + g(y) + \lambda^T(Ax + By - c) + (\rho/2)||Ax + By - c||_2^2 \tag{41}$$

The λ and ρ sections of Equation 41 are to punish any deviations from the relaxed constraint. Following this, the algorithm has three update functions; the x-minimization, the y-minimization, and the dual variable update.

$$x^{k+1} := \underset{x}{\text{argmin}}\, L_\rho(x, y^k, \lambda^k) \tag{42}$$

$$y^{k+1} := \underset{y}{\text{argmin}}\, L_\rho(x^k, y, \lambda^k) \tag{43}$$

$$\lambda^{k+1} := \lambda^k + \rho(Ax^{k+1} + By^{k+1} - c) \tag{44}$$

The Lagrangian penalty parameter, ρ, in Equation 42, 43 and 44 defined as a non-negative parameter for all iterations of the algorithm. The parameter will is for traditional variants of ADMM set as a constant close to 1, as this provides stability [85].

7.2.2 ADMM Convergence

The model is set to end at the point where either a set amount, in this case, 100, of iterations have been performed, or if convergence is achieved by satisfying the following equations:

The algorithm is defined to have a finite amount of iterations, meaning that there is a maximum allowed iterations. In this thesis that maximum is set to 99 iterations. The algorithm will either end if maximum iterations are reached or if Equation 47 is satisfied.

$$E^{pri} = \sqrt{\rho_{i,t}} * e^{absolute} + e^{relative} * argmax\Big((y_t^{gen} + y_t^{BQ})^2, (-x_t^{gen} - x_t^{slack})^2\Big) \tag{45}$$

$$R^{pri} = \Big| y_t^{gen} + y_t^{BQ} - x_t^{gen} - x_t^{slack} \Big| \tag{46}$$

$$R^{pri} <= E^{pri} \tag{47}$$

Equations 45, 46, and 47 are updated for each iteration of the algorithm. The index i determines what LEC it is, index t is what hour, and parameters e are predetermined convergence bounds. The algorithm will converge when this set of constraints is true for each LEC and each hour in the market. This is implemented for both the DA market and the FM market separately.

Figure 7.1 highlights the general flowchart for the ADMM algorithm, showing how the algorithm proceeds between iterations and in what order each step is performed.

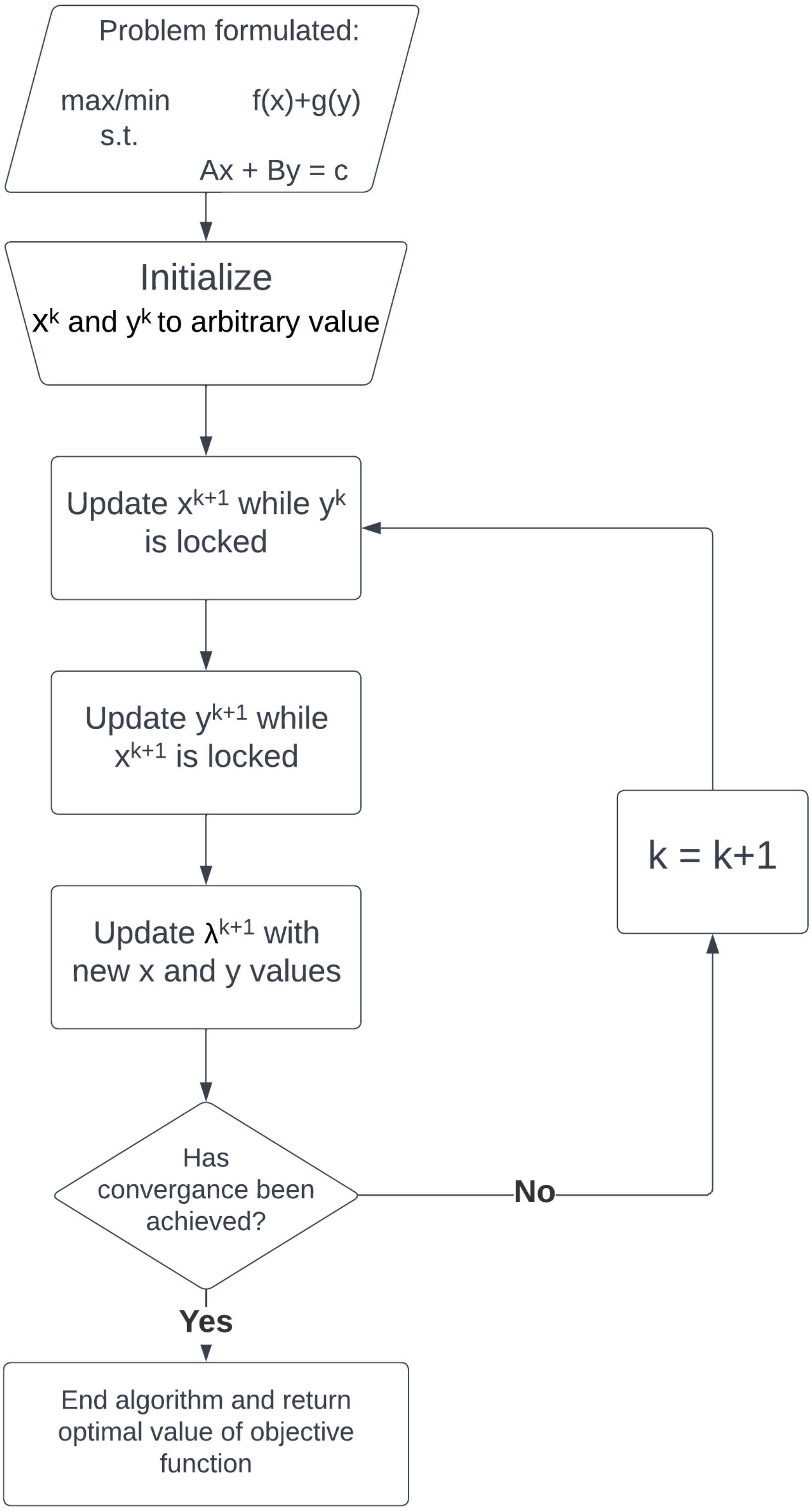

Figure 7.1: Flowchart showing the general steps of the ADMM algorithm

7.2.3 ρ update

The Lagrangian penalty parameter ρ, also known as the step-length of the algorithm, defines how far the algorithm changes into the next iteration in the direction that it has chosen. A large ρ will entail a significant change, and a small ρ will result in a slower change. In the literature, a smaller ρ is often chosen as the ADMM algorithm already possesses a rapid approach toward convergence. However, this is not always the case. In cases where the ADMM algorithm does not tend to converge fast, a technique that changes the ρ value for each iteration to facilitate convergence could be introduced. The convergence of ADMM with ρ update function can be hard to prove, but the method assumes that ρ becomes fixed at a point, which allows for convergence [85].

The scheme for the ρ update varies based on the specific problem. However, a general scheme is presented in [85], and is as follows:

$$\rho_{i+1} = \begin{cases} \rho_i \cdot \tau & \text{if far from convergence, and moving fast} \\ \frac{\rho_i}{\tau} & \text{if far from convergence, and moving slow} \\ \rho_i & \text{if close to convergence} \end{cases}$$

Here, τ is a constant that indicates the rate of change in the step-length. This is often set to be a smaller number between 1 and 3. A modification of this was applied to the market operator section of the model, which is responsible for driving the ADMM algorithm. In this modification, the τ parameter is set to be 1.6 for the DA market and 1.55 for the flexibility market.

7.3 Application of ADMM to the Model

The ADMM algorithm described in Chapter 7.3 has been applied to the model presented in Chapter 7.1. This has resulted in creating a set of sub-problems that structurally is much easier to solve. These sub-problems provide the results that the ADMM algorithm uses to achieve convergence. These sub-problems will be introduced to more accurately show how the problem is implemented into the model. As mentioned, the optimization model has been decomposed into four sub-problem groups, one for DA-DSO, DA-LEC, FM-DSO, and FM-LEC. Each DSO and LEC presented in the simulation will have its own sub-problem within their respective DA and FM sub-problem groups. The structure of the sub-problems in each group is shown in Equations 48-83. This decomposition has been achieved by relaxing the complicating constraints for both the DA and FM models, shown in Equations 11 and 31. These constraints include both DSO and LEC variables, which make the original problems much larger than the sub-problems that are going to be presented in the following chapter. The complicating constraints have been moved to the objective functions of the sub-problems as the Lagrangian equation shown in Equation 41. To be specific, this model consists of two separate ADMM algorithms. The DA ADMM algorithm solves the system in the DA market, and the FM ADMM algorithm solves the system for the FM. This also means that any given ADMM algorithm only manages two separate sub-problems, which is done to simplify each sub-problem as much as possible.

7.3.1 Decomposed DA model

As mentioned in the previous chapter, the AC/AC OPF model for the DA market was decomposed into two sub-problems, one for the DSO and one for the LECs. Since the objective function of the DA model is to minimize the operating costs for both the DSO and LECs, the objective function could be split into sub-problems, where each sub-problem minimizes its operational cost. When decomposing the DA model that is shown in Equations 2-19, Equation 11 stands out as the complicating variable. Decomposing this model by relaxing that constraint allows the model to be solved as a set of smaller sub-problems. These sub-problems will now be explained, along with their constraints.

DA DSO sub-problem Minimize:

$$\sum_{t\in T}\sum_{m\in M}\Bigg(P^{G,DSO}_{mt}\cdot c_{mt}+\sum_{i\in I}\Bigg(\lambda_{it}\Bigg(P^{G,DSO}_{mit}+(-\sqrt{2}u_{mit}\cdot\sum_{j\in k(m)}G_{mjit}+ \sum_{j\in k(j)}(G_{mjit}R_{mjit}-B_{mjit}I_{mjit}))\Bigg)+\frac{\rho_i}{2}\Bigg\|P^{G,DSO}_{mit}+ (-\sqrt{2}u_{mit}\cdot\sum_{j\in k(m)}G_{mjit}+\sum_{j\in k(j)}(G_{mjit}R_{mjit}-B_{mjit}I_{mjit}))-P^{G,LEC}_{nit}\Bigg\|^2\Bigg)\Bigg) \tag{48}$$

Subject to:

$$P^{L,DSO}_{mt}-P^{G}_{mt}=-\sqrt{2}u_{mt}\cdot\sum_{j\in k(m)}G_{mjt}+\sum_{j\in k(m)}(G_{mjt}R_{mjt}-B_{mj}I_{mjt}) \tag{49}$$

$$Q^{L,DSO}_{mt}-Q^{G}_{mt}=-\sqrt{2}u_{mt}\cdot\sum_{j\in k(m)}B_{mjt}+\sum_{j\in k(m)}(B_{mjt}R_{mjt}-G_{mjt}I_{mjt}) \tag{50}$$

$$2u_{mt}u_{jt}\geq R^2_{mjt}+I^2_{mjt} \tag{51}$$

$$R_{mjt}\geq 0 \tag{52}$$

$$u_{mt}=\frac{V_1^2}{\sqrt{2}} \tag{53}$$

$$u_{mt}\geq 0 \tag{54}$$

$$P^{G,DSO,min}_{mt}\leq P^{G}_{mt}\leq P^{G,DSO,max}_{mt} \tag{55}$$

$$Q^{G,DSO,min}_{mt}\leq Q^{G}_{mt}\leq Q^{G,DSO,max}_{mt} \tag{56}$$

All constraints in 49-56 are subject to:	$t \in T$
Constraints 49,50,55,56, are subject to:	$m \in M$
Constraints 51,52 are subject to:	$\forall$ (m,j) lines
Constraint 53 is subject to:	$m = 1$
Constraint 54 is subject to:	$m \in M \backslash 1$

DA DSO sub-problem The DSO sub-problem in the DA section of the model consists of the constraints for the DSO grid that in the original formulation were shown in Equations 3-10. The main change appears in the objective function, seen in Equation 48. The objective function has been amplified to be in the form of Equation 41, where $f(x)$ is the original objective function from the DSO perspective of minimizing operational costs, meaning the costs of generating active power. The relaxed constraint is also included in this new objective function, to ensure that the constraint is satisfied by punishing deviations in it. The LEC variables are, as in the constraint in Equation 11, only the values for the connected nodes where the node of the LEC and DSO are in the same node. The LEC variables are set to input parameters for this model. The value of the LEC parameters is determined by either an initial guess, for the first iteration, or by the result from the update function in Equation 43, which finds the solution from the previous iteration of the LEC sub-problem. The model has three sets, I, T, and M, representing the LECs, hours, and nodes in the distribution grid respectively. It aims to minimize Equation 48 while being subject to Equations 49-56.

DA LEC sub-problem
Minimize:

$$\sum_{t\in T}\sum_{n\in N}\left(P^{G,LEC}_{nt}\cdot c_{nt}+\sum_{i\in I}\left(\lambda_{it}\Big(-P^{G,DSO}_{mit}\Big)+\frac{\rho_i}{2}\left\|P^{G,DSO}_{mit}+\right.\right.\right.$$
$$\left.\left.\left.(-\sqrt{2}u_{mit}\cdot\sum_{j\in k(n)}G_{njit}+\sum_{j\in k(j)}(G_{njit}R_{njit}-B_{njit}I_{mjit}))-P^{G,LEC}_{nit}\right\|^2\right)\right) \tag{57}$$

Subject to:

$$P_{nt}^{L,LEC} - P_{nt}^{G,LEC} = -\sqrt{2}u_{nt} \cdot \sum_{o \in k(n)} G_{not} + \sum_{o \in k(n)} (G_{not}R_{not} - B_{not}I_{not}) \tag{58}$$

$$Q_{nt}^{L,LEC} - Q_{nt}^{G,LEC} = -\sqrt{2}u_{nt} \cdot \sum_{o \in k(n)} B_{not} + \sum_{o \in k(n)} (B_{not}R_{not} - G_{not}I_{not}) \tag{59}$$

$$2u_{nt}u_{ot} \geq R_{not}^2 + I_{not}^2 \tag{60}$$

$$R_{not} \geq 0 \tag{61}$$

$$u_{nt} = \frac{V_1^2}{\sqrt{2}} \tag{62}$$

$$u_{nt} \geq 0 \tag{63}$$

$$P_{nt}^{G,LEC,min} \leq P_{nt}^{G} \leq P_{nt}^{G,LEC,max} \tag{64}$$

$$Q_{nt}^{G,LEC,min} \leq Q_{nt}^{G} \leq Q_{nt}^{G,LEC,max} \tag{65}$$

All constraints in 58-65 are subject to:	$t \in T$
Constraints 58,59,64,65, are subject to:	$m \in M$
Constraints 60,61 are subject to:	$\forall$ (m,j) lines
Constraint 62 is subject to:	$m = 1$
Constraint 63 is subject to:	$m \in M \backslash 1$

DA LEC sub-problem The LEC sub-problem for the DA model aims to solve the LEC grid by minimizing the operational costs of generating active power, while still satisfying all constraints. Equation 57 the objective function in the DA LEC model, with the relaxed constraint added with the punishing parameters λ and ρ. This is subject to Equations 58-65. The DSO variable is set as an input parameter that is, like in the DA DSO model, based either on an initial guess for the first iteration or a result of the Equation 42 after solving the last iteration of the DA DSO sub-problem. After this sub-problem is solved, the λ update from Equation 44 is performed, and the algorithm either converges or performs another iteration.

7.3.2 Decomposed FM model

Like the DA model, the FM model is separated into two sub-problems to make it easier to solve. The constraint in Equation 31 is relaxed into the objective functions of each sub-problem, and to ensure that its restrictions are still satisfied, the punishing parameters λ and ρ are applied to punish deviations. The structure of the FM model and the DA model is very similar, with the main differences being that the FM model is performed for U time-steps in each hour and includes the flexibility and battery resources in the load balance equations for the LEC grid.

FM DSO sub-problem

Minimize:

$$\sum_{t\in T}\sum_{u\in U}\sum_{m\in M}\Bigg(P^{slack,DSO}_{mtu}\cdot c^{slack,DSO}_{mtu}+\sum_{i\in I}\Bigg(\lambda_{itu}\Bigg(P^{G,DSO}_{mitu}+(-\sqrt{2}u_{mitu}\cdot\sum_{j\in k(m)}G_{mjitu}+$$
$$\sum_{j\in k(j)}(G_{mjitu}R_{mjitu}-B_{mjit}I_{mjitu}))\Bigg)+\frac{\rho_{iu}}{2}\Bigg\|P^{G,DSO}_{mitu}+$$
$$(-\sqrt{2}u_{mitu}\cdot\sum_{j\in k(m)}G_{mjitu}+\sum_{j\in k(j)}(G_{mjitu}R_{mjitu}-B_{mjitu}I_{mjitu}))-P^{G,LEC}_{nitu}\Bigg\|^2\Bigg)\Bigg) \tag{66}$$

Subject to DSO constraints:

$$P^{L,DSO}_{mtu}-P^{G,DSO}_{mtu}=-\sqrt{2}u_{mtu}\cdot\sum_{j\in k(m)}G_{mjtu}+\sum_{j\in k(m)}(G_{mjtu}R_{mjtu}-B_{mj}I_{mjtu}) \tag{67}$$

$$Q^{L,DSO}_{mtu}-Q^{G,DSO}_{mtu}=-\sqrt{2}u_{mtu}\cdot\sum_{j\in k(m)}B_{mjtu}+\sum_{j\in k(m)}(B_{mjtu}R_{mjtu}-G_{mjtu}I_{mjtu}) \tag{68}$$

$$2u_{mtu}u_{jtu}\geq R^2_{mjtu}+I^2_{mjtu} \tag{69}$$

$$R_{mjtu}\geq 0 \tag{70}$$

$$u_{mtu}=\frac{V_1^2}{\sqrt{2}} \tag{71}$$

$$u_{mtu}\geq 0 \tag{72}$$

$$P^{G,DSO,min}_{mtu}\leq P^{G,DSO}_{mtu}\leq P^{G,DSO,max}_{mtu} \tag{73}$$

$$Q^{G,DSO,min}_{mtu}\leq Q^{G,DSO}_{mtu}\leq Q^{G,DSO,max}_{mtu} \tag{74}$$

All constraints in 67-74 are subject to:	$t \in T, u \in U$
Constraints 67,68,73,74, are subject to:	$m \in M$
Constraints 69,70 are subject to:	$\forall$ (m,j) lines
Constraint 71 is subject to:	$m = 1$
Constraint 72 is subject to:	$m \in M \backslash 1$

FM DSO sub-problem The DSO sub-problem in the FM market operates the same as the DSO sub-problem for the DA market, as the main change is the introduction of the time-steps U. It still has its objective to minimize costs. However, the power generation in the objective function is replaced with the $P_{mtu}^{slack,DSO}$ variable, resulting in the objective function seen in Equation 66. This is the power imported from the TSO in order to balance inaccuracies from the DA market. The DSO can also utilize the LECs to balance these inaccuracies, which has the possibility to be a cheaper option for the nodes closer to the LEC. The DSO does not have access to flexibility, therefore it can only use the slack production or the LECs production to balance the system.

FM LEC sub-problem

Minimize:

$$\sum_{t\in T}\sum_{u\in U}\sum_{n\in N}\Bigg(P_{ntu}^{load-shedding,LEC}\cdot c_{ntu}^{load-shedding,LEC}+P_{ntu}^{G,Flex,LEC}\cdot c_{ntu}^{G,Flex,LEC}$$
$$+P_{ntu}^{L,Flex,LEC}\cdot c_{ntu}^{L,Flex,LEC}+(P_{ntu}^{discharge,LEC}-P_{ntu}^{charge,LEC})\cdot c_{ntu}^{battery,LEC}$$
$$+\sum_{i\in I}\Bigg(\lambda_{itu}\Big(-P_{nitu}^{G,LEC}\Big)+\frac{\rho_{iu}}{2}\Bigg|\Bigg|P_{nitu}^{G,LEC}+ \tag{75}$$
$$(-\sqrt{2}u_{mitu}\cdot\sum_{j\in k(n)}G_{njitu}+\sum_{j\in k(j)}(G_{njitu}R_{njitu}-B_{njitu}I_{mjitu}))-P_{nitu}^{G,LEC}\Bigg|\Bigg|^2\Bigg)\Bigg)$$

$$P_{ntu}^{L,LEC} - P_{ntu}^{G,LEC} = -\sqrt{2}u_{ntu} \cdot \sum_{o \in k(n)} G_{notu} + \sum_{o \in k(n)} (G_{notu}R_{notu} - B_{notu}I_{notu}) \tag{76}$$

$$Q_{ntu}^{L,LEC} - Q_{ntu}^{G,LEC} = -\sqrt{2}u_{ntu} \cdot \sum_{o \in k(n)} B_{notu} + \sum_{o \in k(n)} (B_{notu}R_{notu} - G_{notu}I_{notu}) \tag{77}$$

$$2u_{ntu}u_{otu} \geq R_{notu}^2 + I_{notu}^2 \tag{78}$$

$$R_{notu} \geq 0 \tag{79}$$

$$u_{ntu} = \frac{V_1^2}{\sqrt{2}} \tag{80}$$

$$u_{ntu} \geq 0 \tag{81}$$

$$P_{ntu}^{G,LEC,min} \leq P_{ntu}^{G} \leq P_{ntu}^{G,LEC,max} \tag{82}$$

$$Q_{ntu}^{G,LEC,min} \leq Q_{ntu}^{G} \leq Q_{ntu}^{G,LEC,max} \tag{83}$$

Flexibility and Battery Constraints:

$$P^{load-shedding,LEC}_{ntu} \leq P^{L,LEC}_{ntu} \tag{84}$$

$$P^{G,Flex,LEC,min}_{ntu} \leq P^{G,Flex,LEC}_{ntu} \leq P^{G,Flex,LEC,max}_{ntu} \tag{85}$$

$$P^{L,Flex,LEC,min}_{ntu} \leq P^{L,Flex,LEC}_{ntu} \leq P^{L,Flex,LEC,max}_{ntu} \tag{86}$$

$$\sum_{t\in T}\sum_{u\in U}\sum_{n\in N/1} P^{L,Flex,LEC}_{ntu} = 0 \tag{87}$$

$$P^{B,state,LEC,min}_{ntu} \leq P^{B,state,LEC}_{ntu} \leq P^{B,state,LEC,max}_{ntu} \tag{88}$$

$$P^{B,charging,LEC,min}_{ntu} \leq P^{B,charging,LEC}_{ntu} \cdot (1-\delta_{ntu}) \leq P^{B,charging,LEC,max}_{ntu} \tag{89}$$

$$P^{B,discharge,LEC,min}_{ntu} \leq P^{B,discharge,LEC}_{ntu} \cdot \delta_{ntu} \leq P^{B,discharge,LEC,max}_{ntu} \tag{90}$$

$$P^{B,state,LEC}_{n,1,1} = P^{B,state,LEC,initial}_{n} + P^{B,charging,LEC}_{n,1,1} \cdot \eta^{charging} - \frac{P^{B,discharge,LEC}_{n,1,1}}{\eta^{discharge}} \tag{91}$$

$$P^{B,state,LEC}_{ntu} = P^{B,state,LEC}_{nt,u-1} + P^{B,charging,LEC}_{ntu} \cdot \eta^{charging} - \frac{P^{B,discharge,LEC}_{ntu}}{\eta^{discharge}} \tag{92}$$

$$P^{B,state,LEC}_{nt,1} = P^{state,LEC}_{n,t-1,U} + P^{B,charging,LEC}_{nt,1} \cdot \eta^{charging} - \frac{P^{B,discharge,LEC}_{nt,1}}{\eta^{discharge}} \tag{93}$$

$$P^{B,state,LEC}_{n,T,U} = P^{B,state,LEC,initial}_{n} \tag{94}$$

All constraints in 76-94 are subject to:	$t \in T, u \in U$
Constraints 76,77,82-94, are subject to:	$n \in N$
Constraints 78,79 are subject to:	∀ (n,j) lines
Constraint 80 is subject to:	$n = 1$
Constraint 81 is subject to:	$n \in N \backslash 1$

FM LEC sub-problem The sub-problem representing the FM LEC model is the most complex in the set of sub-problems, as it includes flexibility. This model has the objective of minimizing the cost of flexibility activation and import from the DSO while still satisfying the loads in the grid. Equations 84-87 represent the flexibility constraints, and Equations 88-93 are the battery constraints. These constraints dictate how the LEC can utilize its flexibility and battery resources in order to assist in satisfying the load of the grid, as well as export to the DSO. Equation 84 restricts the load shedding of a given node to be, at most, the same as the load in the node. Equations 85 and 86 restrict the altering of flexible generation and flexible load in the system. Equation 87 ensures that the total load of the system stays the same. Equation 88 provides maximum and minimum charges for the batteries in the given nodes. The maximum charge and discharge of each battery are given by Equations 89 and 90. The charge for the first hour and time-step is given by Equation 91, and for the first time-step of each hour is given by Equation **??**. Otherwise, the state of the battery for the next time-step is given by 92. The battery begins and ends the day with an initial charge, given by Equation 94. For readability, the flexibility and battery resources are embedded in the term $P^{G,LEC}_{ntu}$ in the load balance constraints. However, it is still written out in the LEC objective function to highlight the resources available.

DA LEC sub-problem with flexibility The LEC sub-problem, when introducing flexibility, operates much like the FM LEC sub-problem, only that instead of being a model that aims to balance the response, it aims to plan the use of flexibility. For the sake of this thesis and the arguments made, this is not considered its own sub-problem; rather, it is a variation of the DA LEC sub-problem. This means that the mathematical formulation is much like the one presented in Equations 22-94. The main difference is that there are no units; it solves over T hours and the N nodes, not the U units. Other changes are that the LEC cannot plan to use load shedding or voltage control, as these are direct response resources. This allows the LEC to plan for the dispatch of some of the flexibility it possesses, although the amount of flexibility is reduced compared to the FM LEC model, as the LEC is not assumed to have access to all the flexibility the day before. This implementation was the focus of [14], and a full mathematical formulation can be found there.

7.4 Implementation of the Model

The presented mathematical formulation is constructed as a set of Python scripts that run to solve the market as the sub-problems presented in 7.3.1 and 7.3.2. As well as performing all the other tasks, such as reading input data, executing the ADMM algorithm, and saving results. The mathematical models were formulated using the Python package Pyomo and the solver Gurobi. One of the aims of this thesis was, as in the specialization project [11], to improve the script that is used to solve the model. In addition to the improvements made to the model implementation in the specialization project, further emphasis has been put on making each variable and function intuitive and understandable. Improvements to the resource efficiency of the script were also a focus, leading to many unnecessary parts of the script being either removed or altered to a more efficient form.

7.4.1 Realistic communication

The previous iterations of the script that is used to solve the model that is shown in 7.3 from the specialization project [11] worked in a way that necessitated that every part of the code was on the same computer. This was seen as a limitation to the use of this code, and such new methods were introduced. To simulate a more realistic communication flow between the DSO and LEC, two new scripts were introduced that allow for the necessary information to be sent and received by mail. This was done to simulate a system where the data from each market participant was not kept in the same location, and only the critical data needed for the LFMO to balance the market was traded. This includes the security of sensitive information for each market participant is kept in mind, in addition to the anonymity that is provided by the ADMM algorithm. More directly, this was done by utilizing the Python packages email, smtplib, imaplib, and base64. Email is a package in Python that deals with emails. SMTP and IMAP are both protocols for handling mail, where SMTP, short for simple mail transport protocol, is for sending, and IMAP, short for internet mail access protocol, is for retrieving. This interaction can be shown in Figure 7.2. The reason for choosing IMAP over other mail access protocols is its ability to permit the user to access only one part of the multipart MIME message [90]. This allows for the mail-reading script to ignore any text in the mail. Since it only needs to read a file with the relevant data. The data is then formatted and returned to the ADMM algorithm for solving.

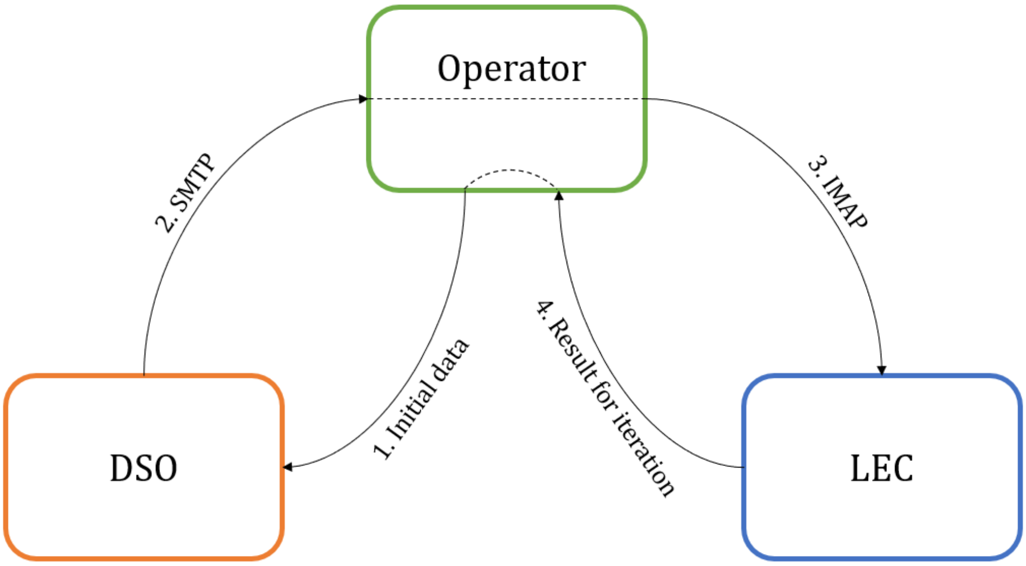

Figure 7.2: Sketch highlighting how the mail script alters the information flow of the main script. Previously the lines were connected to the dotted lines, which now are replaced with the Operator.

7.4.2 GUI

One additional goal of this thesis was to make the script more accessible to users. This led to adding a graphic user interface (GUI) to the script used to run the model. A GUI is a way for the script to convey information to the user without the user having to work on the script itself. The GUI works by utilizing multi-thread processing, which means that the GUI works on a separate thread from the model script, allowing them to work in parallel. Multi-threading as a concept falls outside the scope of this thesis and will, therefore, not be discussed in detail. The introduction of the GUI has increased ease of use as there is no longer any need to change the actual script between each simulation. The GUI provides information regarding what cases can be run, asks the user to choose what case to run, and asks for a parameter defining the generating capacity of any DGs in the DSO grid. After these inputs have been provided, the GUI will wait for the user to execute the script by either pressing Enter on the keyboard or pressing the "Start" button on the GUI.

After the script is executed through the GUI, the interface will change and show a set of four graphs. These graphs will update for each iteration of the ADMM algorithm, resulting in further insight into how the algorithm is approaching convergence. The graphs will show the average difference between the control parameters, E_{pri} and R_{pri}, that was presented in 7.2.2, for each iteration of the ADMM algorithm. A preliminary sketch for the GUI is shown in 7.3.

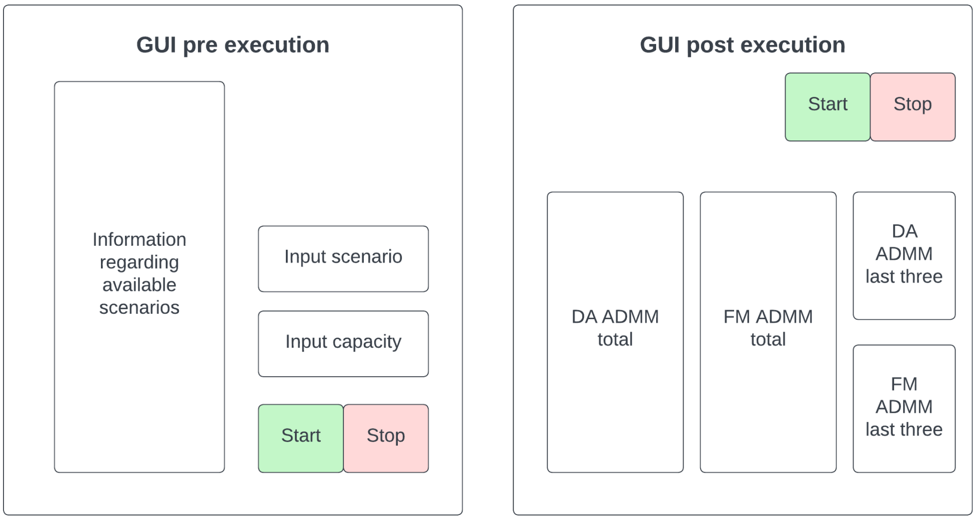

Figure 7.3: Reference image for the GUI

8 Test grid

As described in Chapter 7.1, the model used in this thesis was first developed to fit a TSO-DSO coordination, which was later expanded with the ADMM algorithm to handle several DSOs. Later, the model was altered to fit the coordination of DSO and several LECs. This coordination is also the focus of this master's thesis. The model has been tested with IEEE test cases, with fictional grids and data on loads and flexibility in all the preliminary theses. This includes a 9-node meshed transmission grid, a 33-node and a 38-node distribution grid, and a 23-node LEC. For the preliminary specialization project and this master's thesis, a practical test case has been made based on grid and load data provided by the German DSO S.W.W. Wundsiedel. This test case has been altered and further developed in this thesis to make it more realistic. As such, the robustness of the model will be tested with more realistic scenarios.

8.1 German Power Grid

As this part of the thesis focuses on a test case from the German distribution grid, it is beneficial to understand how the German power grid is structured. The grid consists of two main components; The transmission grid and the distribution grid. The transmission grid includes voltage levels above $220kV$ and is primarily managed by the four German TSOs; TenneT, 50Hertz Transmission, Amprion, and TransnetBW [91]. On the other hand, the distribution grid is responsible for the LV and MV grids and some HV grids below $220kV$ and is operated by various DSOs. Approximately 883 different DSOs are tasked with operating and maintaining the German distribution grid for different municipal areas [92].

Since there are many DSOs, there is a need for effective coordination mechanisms within the power grid. This introduces the upstream DSO, which bridges the smaller DSOs in an area, and the TSO [68]. As such, they play a crucial role in the optimal coordination and information exchange between the grid operators.

8.2 Distribution Grid

In order to conduct a more realistic test case, data from the distribution grid in Wundsiedel, Eastern Germany, was provided and utilized. However, due to limited time and resources during the period of this master's thesis, and the size of the complete grid, it was decided to select only a few parts of the grid as the primary focus. The complete grid can be found in Appendix A.

The chosen areas of interest are Schönbrunn and Tröstau, two smaller areas outside Wunsiedel in Eastern Germany. Figure 8.1 illustrates this specific grid part. It is a 20 kV grid comprising 21 nodes, 11 connected to end-users. Node 1, J01, is the node connected to the upstream DSO, where power is imported from the TSO. The remaining nodes consist of an MV node directly connected to the distribution grid. A transformer and an LV node are connected to these MV nodes representing the buildings in that area. The building mass primarily consists of residential buildings and some local business buildings. This is true for all nodes except node 8 (Heizwerk Schönbrunn), a CHP plant.

Table 8.1 shows the node numbers, which area they belong to, and the active load in the

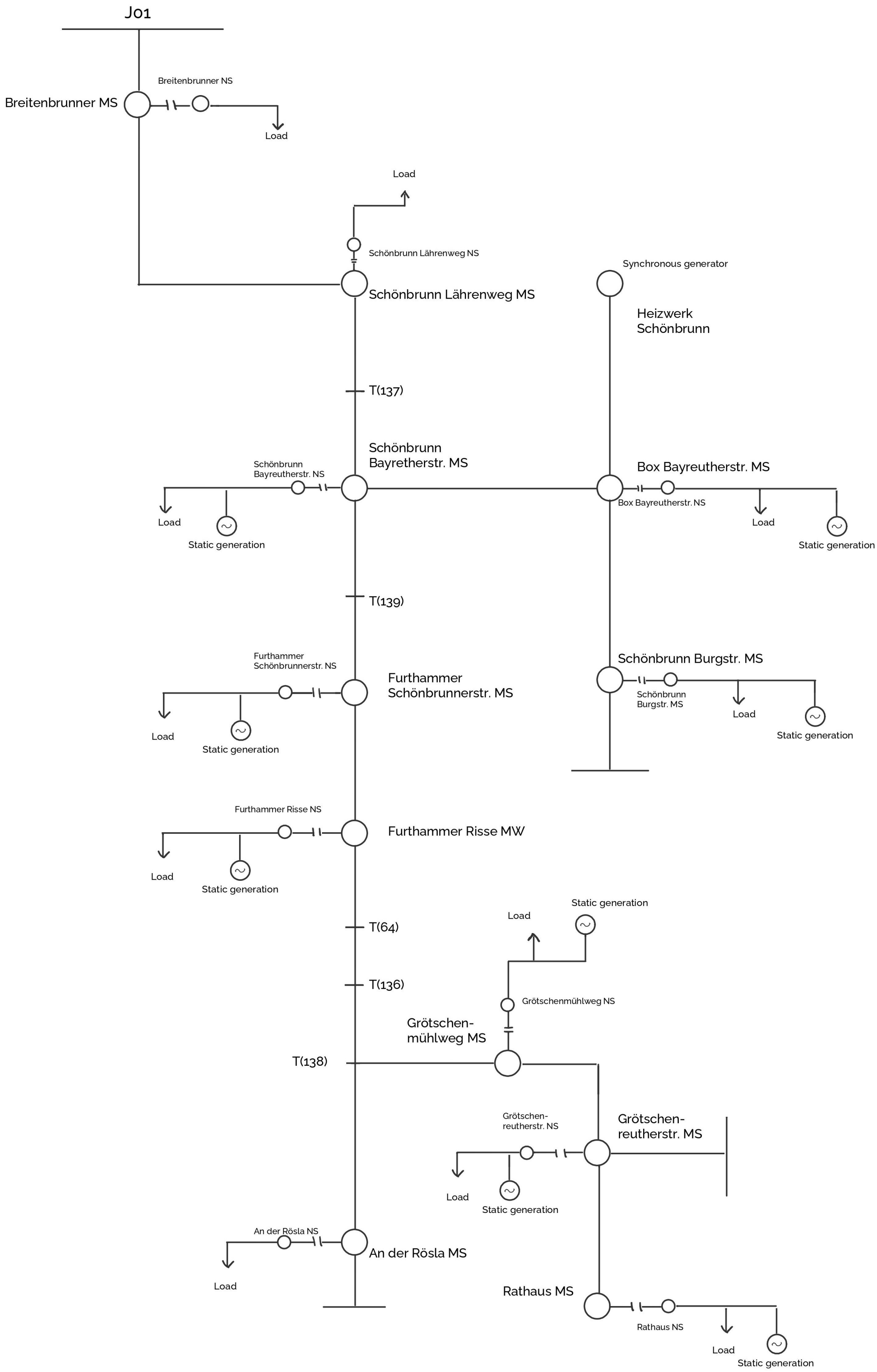

Figure 8.1: Grid of Schönbrunn and Tröstau

node. The missing nodes are the terminal nodes, which are only included in the line data as lines on either side of such a node are different.

Node number	Node name	Area	P
1	J01	Schönbrunn	-
2	Breitenbrunner	Schönbrunn	27.75
3	Schönbrunn Lährenweg	Schönbrunn	259.00
5	Schönbrunn Bayreutherstr.	Schönbrunn	56.50
7	Box Bayreturherstr.	Schönbrunn	62,35
8	Heizwerk Schönbrunn	Schönbrunn	-
10	Schönbrunn Burgstr.	Schönbrunn	179.00
12	Furthammer Schönbrunnerstr.	Schönbrunn	81.06
13	Furthammer Risse	Schönbrunn	144.5
17	An der Rösla	Tröstau	106.25
18	Grötschenmühlweg	Tröstau	42.75
19	Grötschenreutherstr.	Tröstau	100.75
21	Rathaus	Tröstau	36.25

Table 8.1: Nodes included in the DSO data set

Table 8.2 shows the line data with terminal nodes included. There are a total of 20 lines considered in this test case. The table also shows the terminal nodes that have to be included due to different line data on each side of these nodes. This is, for example, seen between nodes 3 and 5 in lines 3 and 4. Other than for the line data, the terminal nodes have no effect on the test grid. The table includes the length of the lines, in km, and the resistance and reactance, given in Ω/km. All the lines are cables except those connecting the two areas, namely lines 14, 15, and 16, which are overhead.

8.2.1 Load Profiles

Load profiles for the areas were made using a typical load profile provided by the German DSO, shown in Appendix B. The table shows the average quarter-hourly output expected if the customer consumes 1000/kWh annually in kW. The profile chosen was a Sunday during the summer period. The load data shown in Table 8.1 was used to find the average power consumption for the whole area. Then all the nodes' variation from said average was found, which was then multiplied by the typical load profile to find each node's load profile. To create additional variation, each hourly consumption was multiplied by a random number between 0.9 and 1.1 (±10%). This resulted in a unique load profile for each node.

Figure 8.2 shows the resulting active DA load profiles. Note that the load of node 7 and node 10 are not included, as these are the nodes with LECs connected. Loads of these nodes are thus divided between the nodes of their respective LEC. The profiles have two spikes during the day, with the first starting in the morning between 06:00 and 07:00. The demand increases until approximately 11:00, which is the highest demand during the entire day. After this, it decreases until approximately 17:00 before spiking again around 19:00. There is a decline during the rest of the day. Node 3 has the highest power consumption, as seen in Table 8.1, while node 2 has the lowest.

In addition to the active DA load profile, a reactive DA load profile and an active, reactive

Line	From node	To node	Length [km]	R [Ω/km]	X [Ω/km]	Type
1	1	2	0.460	0.097	0.056	Cable
2	2	3	2.294	0.485	0.280	Cable
3	3	T(137)	1.067	0.225	0.130	Cable
4	T(137)	5	0.171	0.036	0.020	Cable
5	5	T(62)	0.121	0.025	0.013	Cable
6	T(62)	7	0.289	0.061	0.035	Cable
7	7	8	0.362	0.076	0.044	Cable
8	7	T(63)	0.172	0.036	0.018	Cable
9	T(63)	10	0.293	0.062	0.036	Cable
10	5	T(139)	0.172	0.036	0.021	Cable
11	T(139)	12	0.313	0.066	0.038	Cable
12	12	13	0.321	0.068	0.039	Cable
13	13	T(64)	0.145	0.031	0.018	Cable
14	T(64)	T(136)	0.596	0.355	0.229	Overhead line
15	T(136)	T(138)	0.155	0.092	0.060	Overhead line
16	T(138)	17	0.238	0.142	0.091	Overhead line
17	T(138)	18	0.312	0.066	0.038	Cable
18	18	19	0.578	0.122	0.071	Cable
19	19	T(140)	0.216	0.058	0.022	Cable
20	T(140)	21	0.142	0.030	0.017	Cable

Table 8.2: Line data for the Schönbrunn and Tröstau area

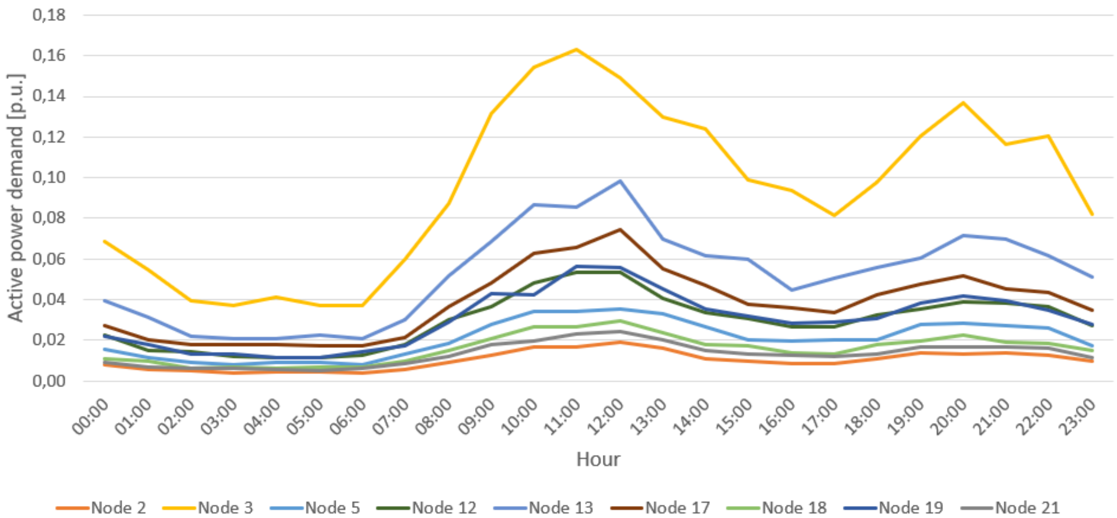

Figure 8.2: DA load profile of the distribution grid

FM load profile were generated for each node. They were all generated based on the active load profile, and it was therefore chosen not to include these in the thesis.

8.3 LEC

As the scope of the thesis is on DSO-LEC coordination, two LECs were designed to be included in the Schönbrunn area, namely nodes 7 and 10. For simplicity and lack of realistic grid structure at this voltage level, a 13-node LEC was developed based on the preliminary work of [13]. The grid topology is shown in Figure 8.3. Within the LEC, there is load consumption situated in nodes 3, 5, 7, 9, 11, and 13. It was reported that the LV nodes referenced in Chapter 8.2 had a voltage level of 400 V, which was thus used for these LECs.

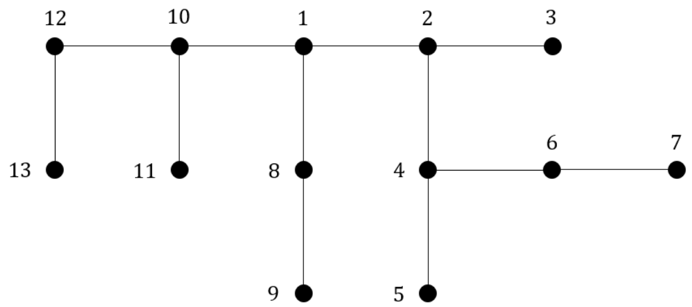

Figure 8.3: LEC grid

Table 8.3 shows the line data of the LEC, which are also derived from the IEEE test case presented in [13]. There are four different types of lines based on resistance and reactance characteristics. No information about the length of the lines was provided.

Line	From node	To node	R [Ω]	X [Ω]
1	1	2	1.010	0.191
2	2	3	0.152	0.029
3	2	4	1.010	0.191
4	4	5	0.152	0.029
5	4	6	1.010	0.191
6	6	7	0.152	0.029
7	1	8	1.010	0.191
8	8	9	0.152	0.029
9	1	10	0.308	0.058
10	10	11	0.091	0.017
11	11	12	0.308	0.058
12	12	13	0.091	0.017

Table 8.3: LEC line data

8.3.1 Load profiles

The same 13-node grid was used for both LECs. However, their load profiles differ, as the load consumption in nodes 7 and 10 differ. For each distribution grid node, the total load for each time slot was divided by six and distributed between the load-consuming nodes in the LEC. The resulting active DA load profiles for both nodes are shown in Figure 8.4. The trend of both load curves is the same as the load profiles presented in Figure 8.2, as they were made the same way. The load consumption is highest in LEC 2, with the largest gap occurring during the peak consumption hours. The reactive DA and FM load profiles are not included for the same reasons discussed in Chapter 8.2.

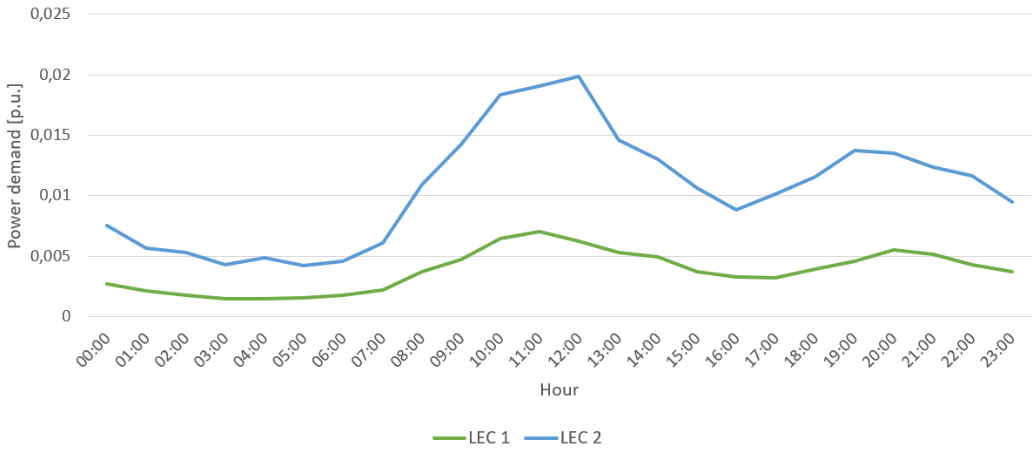

Figure 8.4: DA load profile of a LEC node in LEC 1 and LEC 2

8.3.2 Flexibility and costs

It was, as mentioned, decided to include the LECs in the Schönbrunn area of the test grid, namely nodes 7 and 10. The first FR that was included was a PV and battery combination. As discussed in Chapter 2.3.2, rooftop solar panels have become a popular addition to residential and commercial buildings, and combined with battery technologies, they can be used to deliver flexibility in different ways. Domestic solar PV systems typically have a capacity range of 1-4 kW [93]. Therefore, the two capacities chosen were 2 kW for node 9 and 4 kW for node 5. Battery capacities were found in [94], with the largest option being 3.3 kWh. As such, a 2 kWh capacity was chosen for the 2 kW PV of node 9 and a 3.3 kWh capacity for the 4 kW PV of node 5. All values were converted to p.u. to fit the model input structure.

Costs for the PV-battery system were generated using data provided by the German DSO, shown in Appendix C. The figure shows that small rooftop PVs have operational costs ranging between 8 and 11 €-cents/kWh, while the battery has operational costs between approximately 8 and 20 €-cents/kWh.

In addition to the DG and ESS combination, load control was added to all load-consuming nodes of the LECs. The load control data was generated based on results from the LINEAR project [9]. The project included a 36-month-long pilot where residential FRs were tested in real-life conditions. Five smart appliance types were included, namely dishwashers, washing machines, tumble dryers, smart EWH buffers, and EVs, installed in 239 households.

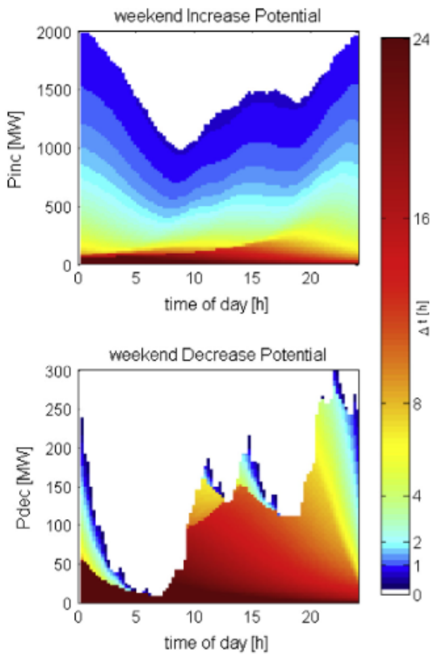

Figure 8.5: Flexibility potential of postponable wet appliances for the Belgian population, from[9]

The dishwashers, washing machines, and tumble dryers are defined as postponable appliances. As the name indicates, this means that the start of the appliance can be postponed, where a predefined time interval determines the period when the appliance should be used. However, once it is started, it cannot be stopped and restarted again. Figure 8.5, from [9], shows the total load control potential of the postponable wet appliances for the Belgian population for an average weekend day. The figure was used to find the average potential for a household. The flexibility potential was extracted for each hour and divided by the assumed total number of households, which is 4.6 million. It was then converted to p.u. and adjusted some to fit the load profiles of the grid. The different colors of the figure indicate how long the increase or decrease can be sustained. This is not accounted for in this thesis.

Water heaters and EVs were defined as buffered appliances. The water heaters can adjust their load as long as the water temperature is kept within a predefined temperature interval. The EV load consumption was controlled through smart charging. An end-time is defined by the user at which the vehicle has to be fully charged. The smart charger can adjust the charging during the plug-in period to deliver flexibility and ensure that the vehicle is fully charged when needed. Similar graphs as Figure 8.5 were presented for the EWH and EV flexibility potential and the data was extracted and adjusted for these as well. The three potentials were added and included as the potential for load increase and decrease for each load-consuming node in the LECs.

9 Simulations

9.1 Test Cases

As mentioned in Chapter 1.3, the aims of this thesis are to test the robustness of the model with the realistic test case, include realistic communication between market participants to the code, and introduce stochastic power generation to the distribution grid. To realize these goals, different test cases were generated. To test the functionality of the realistic communication implementation detailed in Chapter 7.4.1, all of the following test cases were simulated using said mail communication.

9.1.1 Economic Optimization

Firstly, some simple economic optimization test cases will be conducted to showcase the potential economic benefits of including demand-side flexibility. Three different economic optimization cases will be simulated with different flexibility combinations. For the first simulation, load control is included in all nodes with consumption. For the second simulation, the two batteries in nodes 5 and 9 are included. Lastly, all flexibility options will be included, namely load control in all nodes, DGs, and batteries. The flexibility data available was presented in Chapter 8.3.2.

9.1.2 Voltage Regulation

To illustrate how end-user flexibility can aid the DSO with operational tasks, test cases with voltage disruption were generated. Under-voltage problems are created by increasing load consumption during peak hours, thus causing a voltage drop (see Equation 1 in Chapter 3.2). The load was increased in nodes 17, 21, and 22, during the on-peak period at 11:45, 12:00, and 12:30. The loads were increased by 100%. In addition to potential help from FRs, the code has the option of including voltage management in the form of a voltage constraint that keeps the magnitude within predefined lower and upper limits. Said voltage management is included in all other test cases.

Three different simulations were designed for these test cases. Firstly, the voltage drop is simulated with neither voltage management nor FRs included, making a base case for comparison. Second, voltage management is included, but still without FRs. Lastly, FRs are included in addition to voltage management. Based on similar test cases conducted in the preliminary work of [8] and [12], it is expected that the model will have to resort to load shedding when FRs are not included but that this will be unnecessary when FRs are included.

9.1.3 Integration of RES

Lastly, test cases were made to test how demand-side flexibility can help integrate RES. A DG is included in node 8 to simulate some small on-site generation. Data from urban wind energy systems provided by [95] were used to generate the DG capacity used in the test cases.

Three different power generation scenarios are included. The first case will be simulated with 100% generation capacity, meaning that perfect weather conditions were assumed. Secondly, a generation capacity of 80% was simulated, and lastly, a test case with only 40% generation capacity was simulated. It is assumed that these reduced capacities are due to forecasting errors to see whether power producers can utilize demand-side flexibility to reduce the power delivery unreliability. In addition, the 100% and 40% generation capacity test cases were simulated without including flexibility to see the flexibility activation's effect better. For the 100% capacity test case, flexibility and battery resources were introduced into the DA market to see if they could provide economic benefits.

9.2 Results

9.2.1 GUI

Figures 9.1 and 9.2 show that the GUI turned out as desired with regard to the sketch in Figure 7.3. The GUI provides the user with minimal need to access the script in between each scenario.

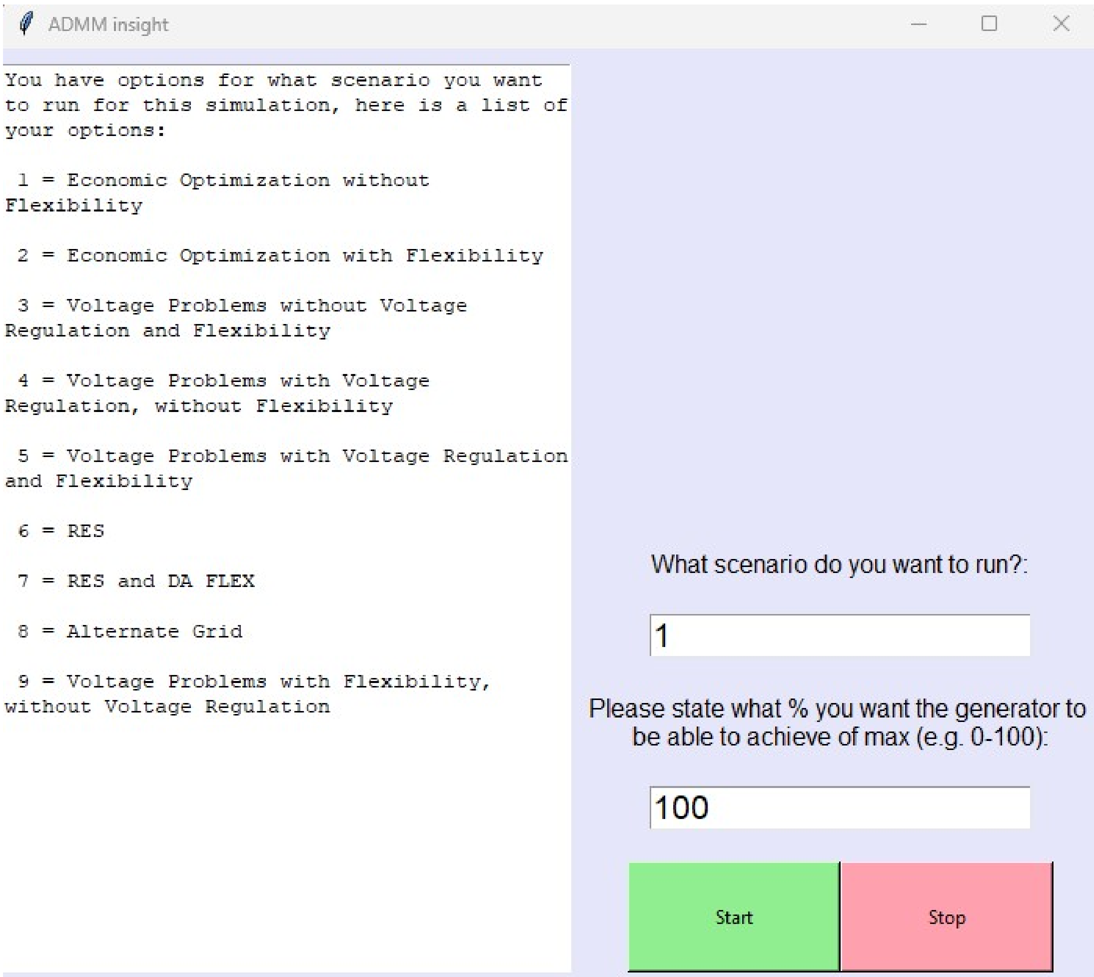

Figure 9.1: Screenshot of the GUI before selecting scenario

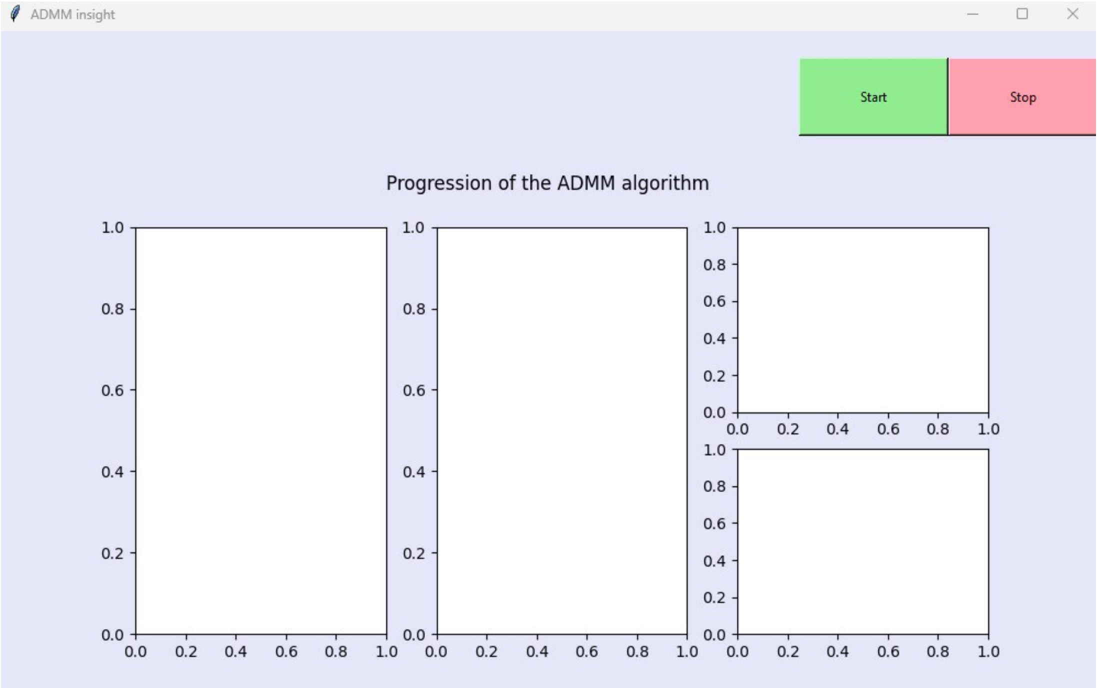

Figure 9.2: Screenshot of the GUI after selecting scenario, showing the graphs that will give insight into the convergence of ADMM

9.2.2 Economic Optimization

The goal of the economic optimization test cases was to strengthen further the belief that the inclusion of demand-side flexibility can positively affect operational costs, also with a more realistic base case.

Table 9.1 shows the operating cost of the economic optimization without flexibility. The high FM operational costs of LEC 2 are due to the load shedding involved. This is shown in Figure 9.3. The load shedding occurs in node 7 of the LEC. As the figure shows, load shedding occurs during hours of high demand, between 09:00 and 14:00 and between 19:00 and 21:00.

DA	Objective value [€]
DSO	72 908.57
LEC 1	13 490.22
LEC 2	39 644.41
Total	126 043.21

FM	Objective value [€]
DSO	70 452.28
LEC 1	13 675.61
LEC 2	257 035.74
Total	341 163.63

Table 9.1: Total operating costs for the economic optimization without flexibility.

Table 9.2 shows the operating cost of the economic optimization test case with flexibility. Compared to the test case without flexibility, the total operational costs are decreased by 74%. LEC 1 has negative operational costs, as the FR activation is high enough that the community delivers more flexibility back to the grid than it consumes power. The largest decrease is in LEC 2, as load shedding is no longer necessary in the community.

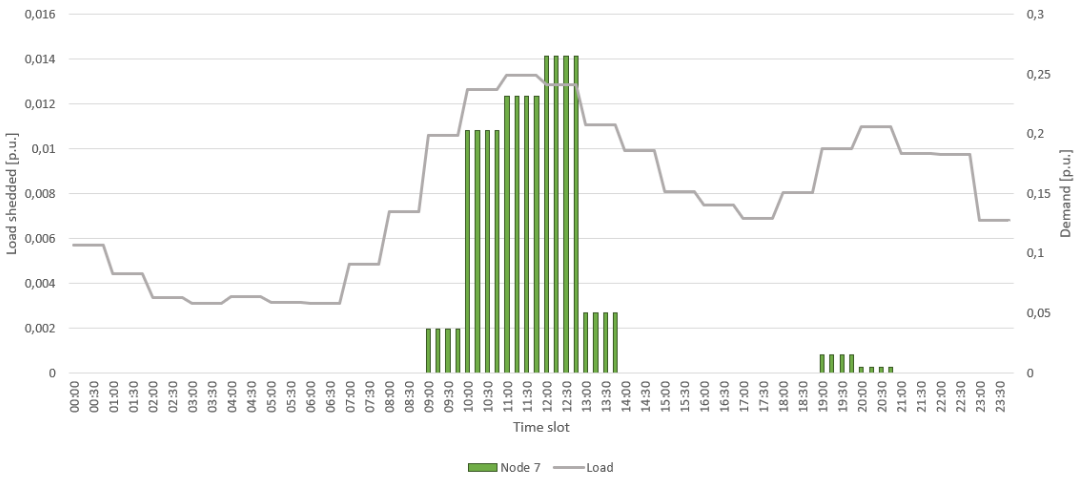

Figure 9.3: load shedding in LEC 2 for the economic optimization test case without flexibility.

DA	Objective value [€]	FM	Objective value [€]
DSO	72 908.57	DSO	69 531.91
LEC 1	13 490.22	LEC 1	-1 239.86
LEC 2	39 644.41	LEC 2	19 454.92
Total	126 043.21	Total	87 746.97

Table 9.2: Total operating costs for the economic optimization test case with flexibility.

Figure 9.4 shows the flexibility activation for the economic optimization test case. During off-peak hours, the batteries are charged, and the load increases. During on-peak hours, the opposite occurs, where the load decreases and batteries discharge. In addition to this flexibility activation, the flexible generation of both LECs runs at 100% capacity during the whole simulation period. In addition, flexible generation is utilized at full capacity during the simulation period in both LECs.

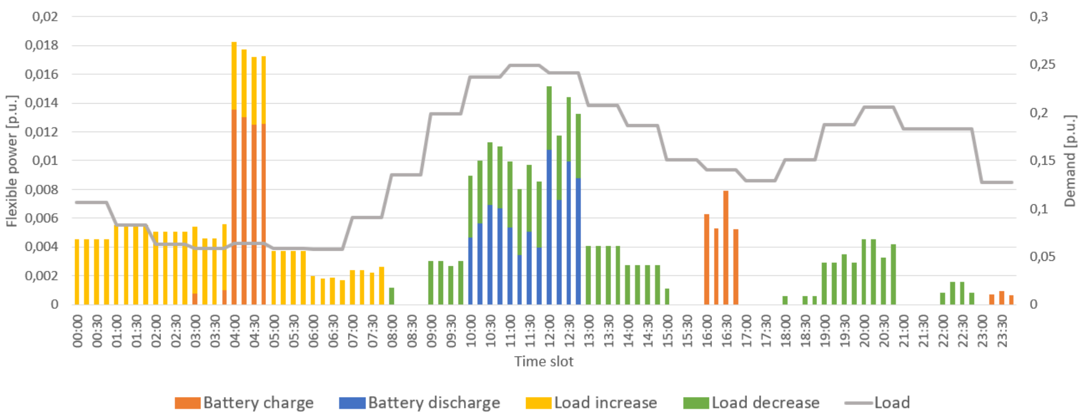

Figure 9.4: Flexibility activation for the economic optimization test case with flexibility.

Figure 9.5 shows the transfer losses in the grid, with and without flexibility. With flexibility included, the need for imported active power is reduced by approximately 54%, and the transfer losses are reduced by 45%.

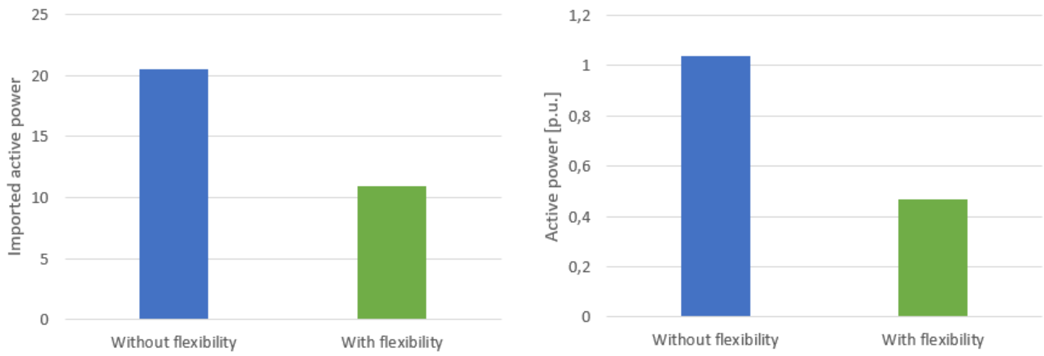

Figure 9.5: Imported active power from the TSO and transfer losses in the distribution grid, with and without flexibility.

Figure 9.6 compares the voltage magnitudes of all nodes at 10:00 without and with flexibility. All magnitudes are above the 0.9 voltage limit for the economic optimization test cases. With flexibility included, the magnitudes are closer to the nominal value of 1 p.u.

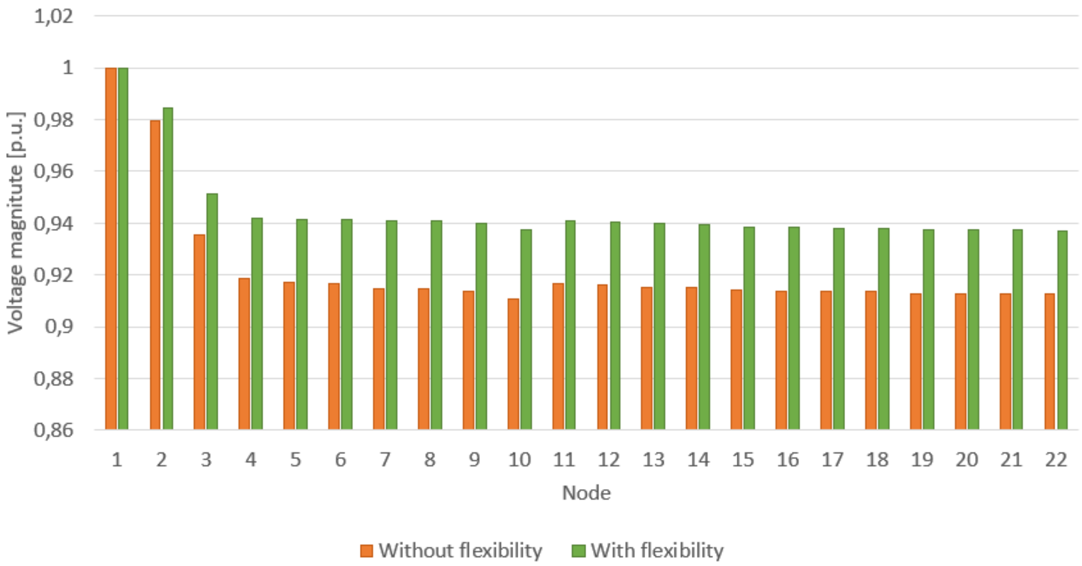

Figure 9.6: Voltage magnitudes for the economic optimization test case without and with flexibility.

9.2.3 Voltage Regulation

The goal of the voltage disruption test cases was to test the robustness of the model and how demand-side flexibility can aid the DSO with voltage regulation with a realistic test case. The voltage drop was induced at 11:45, 12:00, and 12:30, and all voltage magnitudes depicted in this sub-chapter are at 12:00.

Figure 9.7 shows the voltage magnitudes of the economic test case without flexibility and the voltage drop test case without voltage regulation or flexibility. Without the voltage drop, the magnitudes are above the 0.9 limits set for the economic test case but well below the

0.95 limits set for the voltage regulation test cases. With the voltage drop, the magnitudes are well below the voltage limits for all nodes except two. Even with a lower limit of 0.9, most voltage magnitudes would still be below this. The voltage level is lowest in node 10, the node with the largest LEC connected.

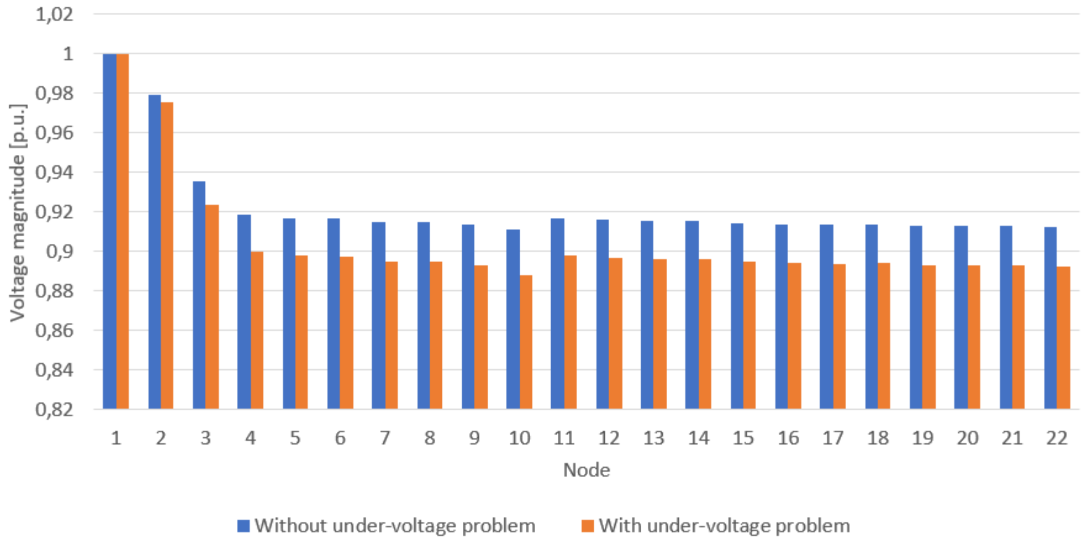

Figure 9.7: Voltage magnitudes for the voltage drop test case, without voltage management or flexibility.

Figure 9.8 shows the voltage magnitudes of the voltage drop test case with voltage regulation but without flexibility and the test case with voltage regulation and flexibility. The voltage magnitudes of all nodes, except nodes 1-3, are barely above or at the voltage limit of 0.9 p.u., with the magnitudes worsening further out in the grid. With flexibility, the voltage magnitudes are not improved for any nodes except for a small increase in nodes 9 and 10.

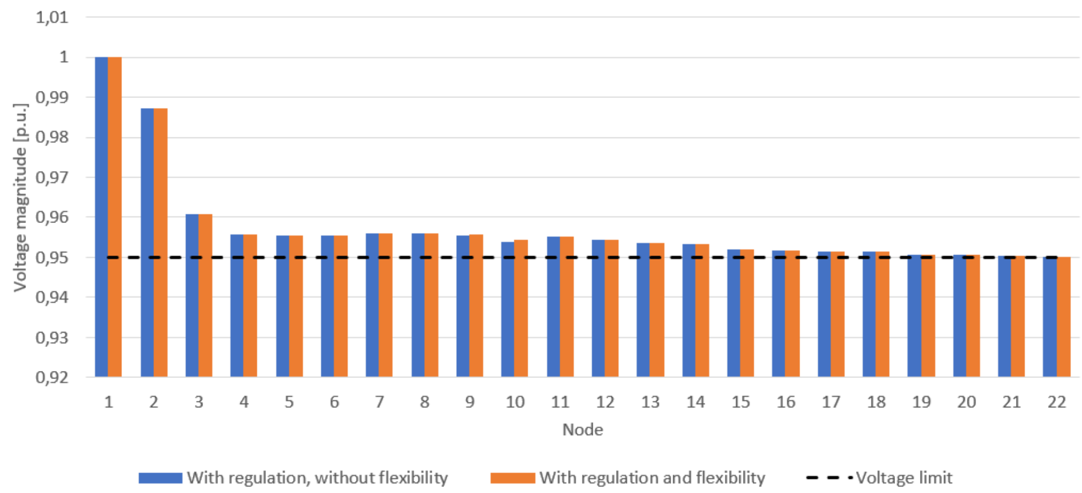

Figure 9.8: Voltage magnitudes for the test cases with voltage regulation, without and with flexibility.

Figure 9.9 shows the resulting load shedding for the test case with voltage regulation and no flexibility activation. All the load shedding occurs in LEC 2. With strict voltage regulation, it is only between 01:00 and 08:00 there is no load shedding. Load shedding is the highest during peak hours and the voltage drop, but there is also load shedding during the rest of the day.

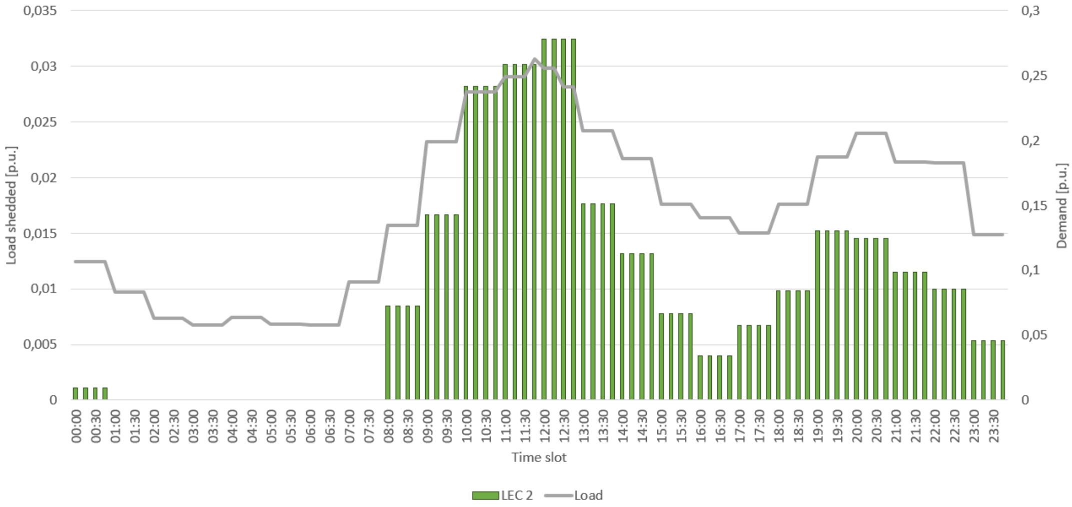

Figure 9.9: Load shedding for the test case with voltage regulation and no flexibility.

Figure 9.10 shows the flexibility activation for the voltage drop with voltage management and flexibility. The activation more or less follows the same pattern as the economic optimization test case, with load increase and battery charging during low-demand hours and load decrease and battery discharging during high-demand hours. The activation is highest during the voltage drop at 11:45, 12:00, and 12:15.

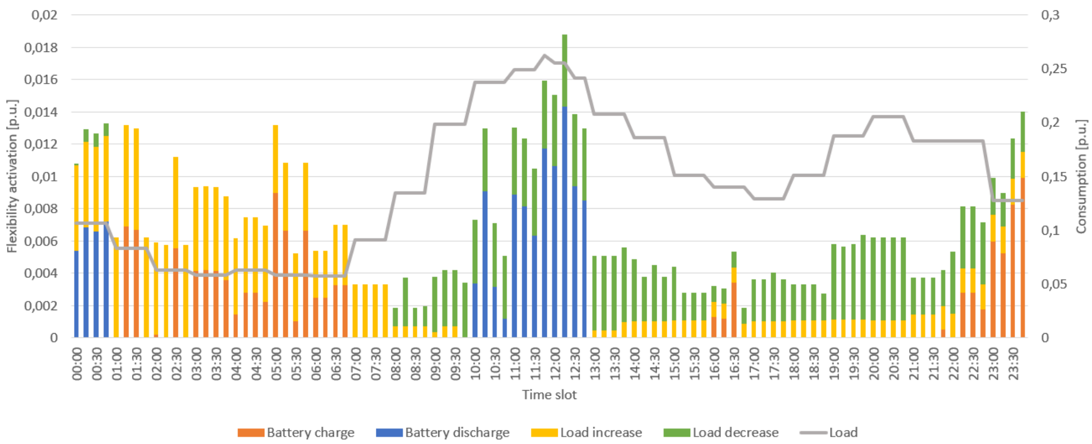

Figure 9.10: Flexibility activation for the voltage drop test case, with voltage management and flexibility.

Figure 9.11 shows the DG power generation for the voltage drop test case with regulation and flexibility. both LECs operate both their DGs at almost full capacity (0.6 total per LEC) during the entire day.

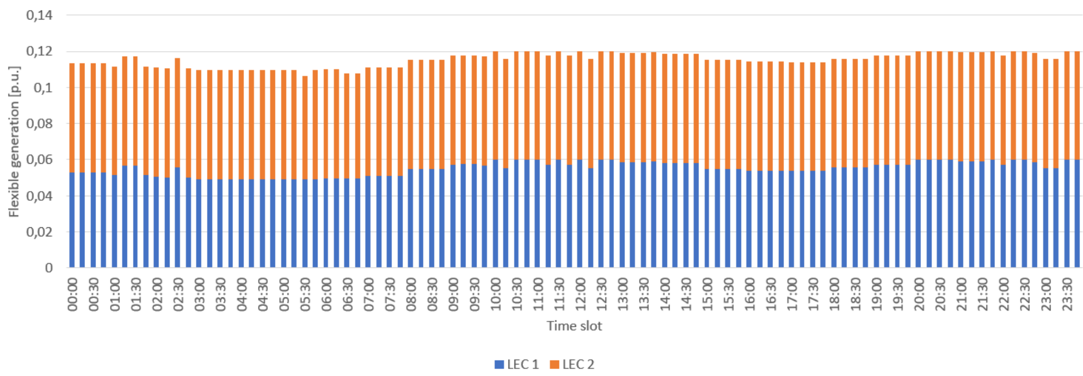

Figure 9.11: DG power generation for the voltage drop test case with voltage management and flexibility.

Figure 9.12 shows the imported active power from the TSO and the transfer losses in the distribution grid for all the voltage drop test cases with voltage regulation. With flexibility, the need for imported power is reduced by 54% and the transfer losses by 15%.

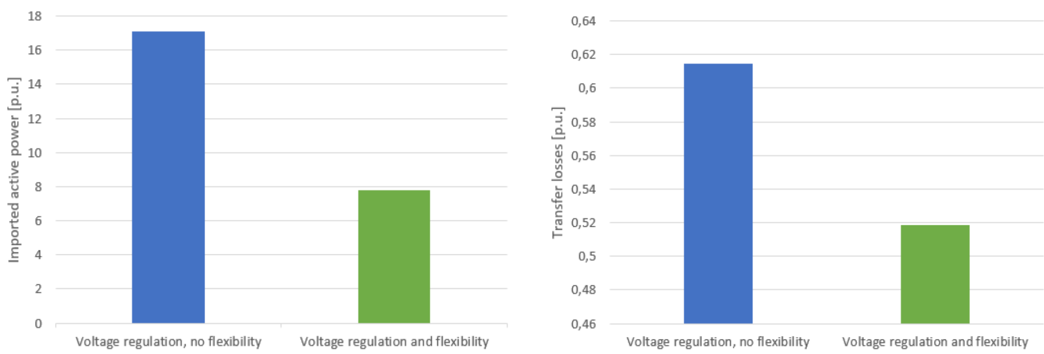

Figure 9.12: Imported active power from the TSO and transfer losses in the distribution grid, for the voltage drop test cases with voltage regulation.

9.2.4 RES Integration

For these test cases, the objective was to see how demand-side flexibility can be utilized when intermittent distributed power generation is added to the grid and how this utilization can aid the power producer when the predicted production capacities deviate from actual power production.

Table 9.3 shows the DA objective values for the test case with 100% generation capacity and flexibility included in the DA market. The results are lower than the DA objective values of the economic optimization test case with flexibility. The LEC 1 objective value has become negative, as in the FM of the same economic optimization test case.

DA	Objective value [€]
DSO	69 542.10
LEC 1	-1 264.83
LEC 2	13 743.26

Table 9.3: Objective values for the DA optimization, with 100% DG capacity and flexibility

Table 9.4 shows the operational costs of the test cases with 100% and 40% generation capacity, without flexibility included. The LECs have relatively unchanged operational costs compared to the economic optimization test case without flexibility. However, the DSO's operational costs are reduced when the DG is included.

100%	Objective value [€]
DSO	37 785.69
LEC 1	13 214.59
LEC 2	255 772.95

40%	Objective value [€]
DSO	56 406.56
LEC 1	13 456.09
LEC 2	254 435.58

Table 9.4: Total operating costs for the economic optimization test case with flexibility.

Table 9.5 shows the three scenarios' operational costs. The DSO's operational costs are lowest at 100% RES generation capacity and steadily increase when the generation capacity is reduced. The operational costs of LEC 1 decrease when the capacity is reduced to 80% but increase a little when it is reduced to 40%. The operational costs of LEC 2 increase each time the capacity is reduced.

100%	Objective value [€]
DSO	37 448.23
LEC 1	-871.92
LEC 2	18 861.51

80%	Objective value [€]
DSO	42 101.51
LEC 1	-1 074.91
LEC 2	19 023.17

40%	Objective value [€]
DSO	54 881.22
LEC 1	-1 047.37
LEC 2	19 227.81

Table 9.5: Total operating costs for all three RES generation scenarios.

Figure 9.13 shows the DG power generation for the three scenarios. The power production is low during the low-demand hours of 01:00 to 07:00. At 00:00 and 07:00, the power production is equal for the three scenarios. From 08:00 and throughout the rest of the day, the DG runs at maximum capacity for the 40% capacity scenario. For the 80% and 100% capacity scenario, the DG runs at maximum during the high-demand hours and is lowered some during low-demand hours.

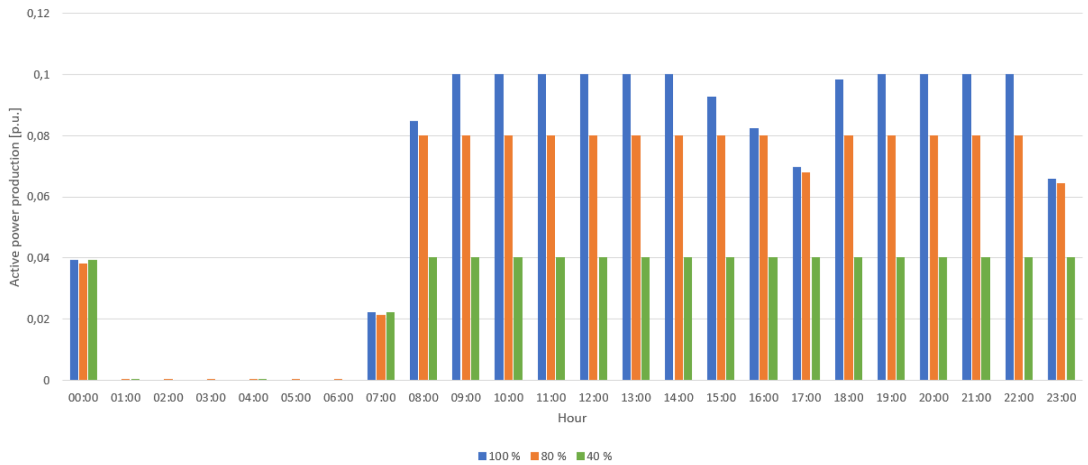

Figure 9.13: DG power generation for the three different RES generation scenarios.

Figure 9.14 shows the flexibility activation for the 100% RES scenario. During the low-demand hours, load increase and battery discharge are utilized to avoid over-voltage problems. During high-demand hours, load decrease and battery discharge are utilized to avoid under-voltage problems.

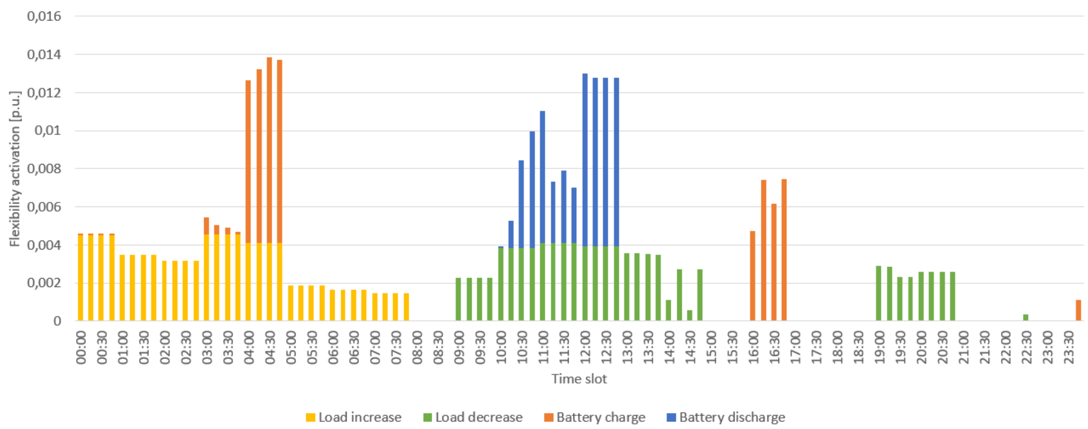

Figure 9.14: Flexibility activation for the 100% RES scenario.

Figure 9.15 shows the flexibility activation for the 80% RES scenario. The activation pattern is similar to the 100% capacity scenario, only with a higher amount of flexibility delivered to the grid. The same is true for Figure 9.16, which shows the flexibility activation for the 40% capacity scenario.

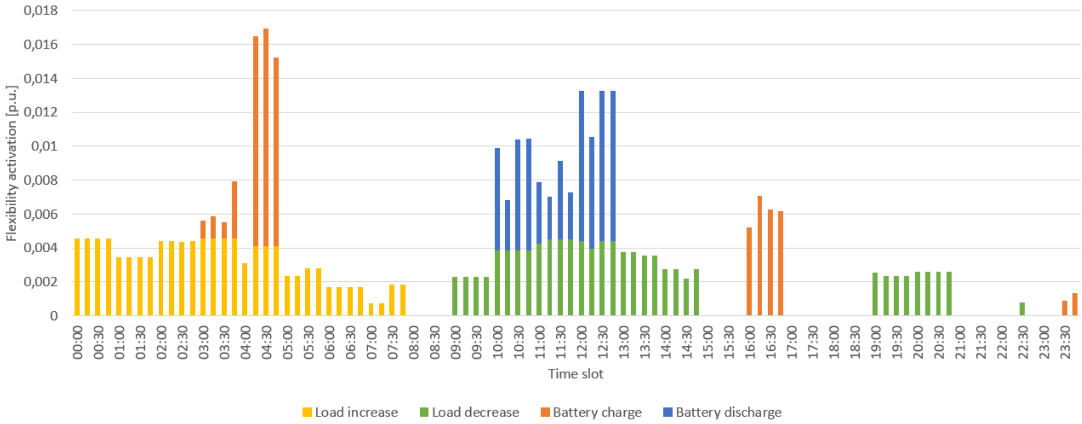

Figure 9.15: Flexibility activation for the 80% RES scenario.

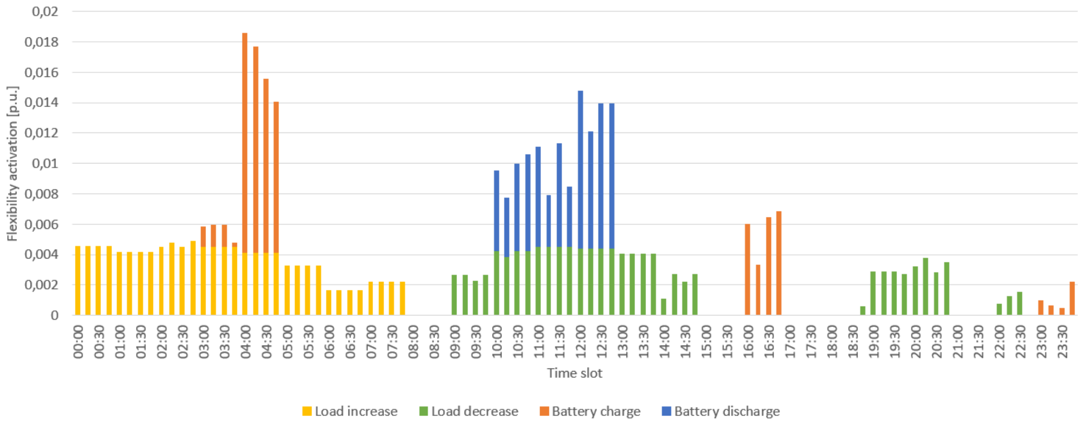

Figure 9.16: Flexibility activation for the 40% RES scenario.

Figure 9.17 shows the imported active power from the TSO and the transfer losses in the distribution grid for the three different RES generation scenarios. The need for imported power increases as the capacity decreases. Subsequently, the transfer losses increase as well, with the largest change occurring between the 80% scenario and 40% scenario.

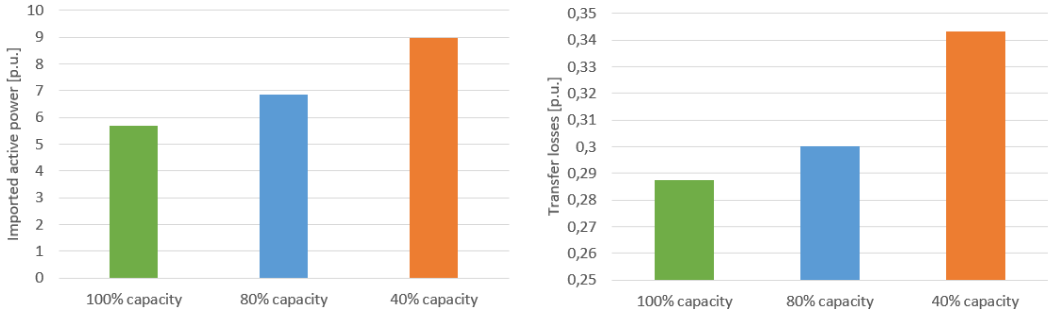

Figure 9.17: Imported active power from the TSO and transfer losses in the distribution grid for the three different RES generation scenarios.

Figure 9.18 compares the test cases' imported active power and transfer losses with and without flexibility. When flexibility is included, the need for imported power is reduced by 60% for the 100% capacity test case and 43% for the 40% capacity test case. The transfer losses are reduced by 50% and 44%, respectively.

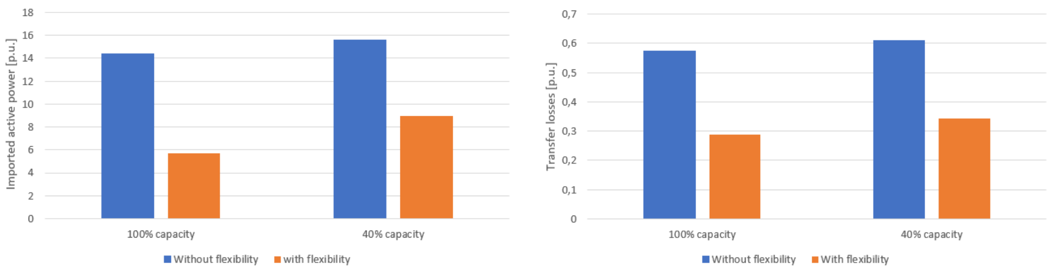

Figure 9.18: Imported active power from the TSO and transfer losses in the distribution grid for the 100% and 40% test cases without and with flexibility included.

9.2.5 Model performance

	Objective values	
	New Model	Old Model
DA DSO	78304,65	78450,86
DA LEC1	13242,82	12729,36
DA LEC2	13242,82	12564,09
FM DSO	81286,97	81265,8
FM LEC1	13432,47	12980,33
FM LEC2	13432,47	12822,24

Table 9.6: Objective functions of the old and new models, with the test case used in the specialization project

Table 9.6 shows the resulting objective values of the new model and the old model for the DSO and each of the LECs for the test case used in the specialization project. Highlighting that for the old and new models, the objective function values are slightly different.

	DA iterations	FM iterations	Total time spent until convergence [seconds]
New model	6	4	610.86
Old model	18	6	636.34

Table 9.7: Convergence data between the old and new model

Table 9.7 highlights the convergence data for the old and new models with the data used in the specialization project. The table shows that the new model converges much faster concerning iterations, however, each iteration takes more time.

	Objective values	
	New model	Old model
DA DSO	72897,81	64320,64
DA LEC1	13489,59	10550,82
DA LEC2	39643,49	32834,02
FM DSO	69561,31	71301,73
FM LEC1	-1174,08	-5692,17
FM LEC2	19553,02	14329,06

Table 9.8: Objective functions of the old and new models, with the test case created for this thesis

Table 9.8 shows the objective function values of the new and old models with the new test case used for this thesis. This shows that the models have moved towards a similar solution; even though they are different the magnitude of the results are similar.

	DA iterations	FM iterations	Total time spent until convergence [seconds]
New model	9	9	828,21
Old model	99	87	3176,97

Table 9.9: Convergence data between the old and new model with the new test case

Table 9.9 highlights the convergence data of the new and old model with the new test case, showing that the new model achieved convergence in 828.21 seconds, while the old model reached the maximum iterations of 99, using 3176.97 seconds.

9.3 Discussion

9.3.1 Realistic Communication

The integration of realistic communication that was described in Chapter 7.4.1 showed that the model could be utilized in a more decentralized way than before. Figure 9.7 highlights the main drawback of this implementation, as it shows that each iteration tends to use much more time than without the implementation. There was no change in accuracy due to the mail integration.

9.3.2 Economic Optimization

Without flexibility included, load shedding occurs in LEC 2. This is due to under-voltage problems in the community, as the consumption is greater than the grid can handle. Even though the LECs are structured the same way, the load demand differs. This is illustrated in Figure 8.4, in Chapter 8.3.1. As the load in LEC 2 is significantly higher than that of LEC 1, this community does not experience the same under-voltage problems. The load profiles were made using realistic data, and the grid structure was based on the IEEE test case of [13]. As such, it may not be a suitable grid for this load profile. More realistic grid data at this voltage level would have improved the test case and probably given better results.

Due to load shedding, the operational costs of the grid without flexibility are very high. This is due to the high load shedding costs, specifically 50 000 € in the data set, to illustrate how this is a last resort when the grid is experiencing problems. With flexibility included, the need for load shedding is eliminated. This, combined with the lower operational costs of FRs, results in a 74% decrease in the FM's operational costs.

Even though most of this reduction is due to eliminating load shedding, it still illustrates how demand-side FRs can reduce operational costs. LEC 1 reduces operational costs significantly and even achieves a negative operational cost when flexibility is included. It means that enough flexibility is sold back to the DSO so that they make money during the 24-hour simulation period. This results from high generation capacities and low load consumption in this community. As discussed in Chapter 8.3.2, the two LECs were given the same FRs and capacities. This might not be as realistic as desired, but it was done due to limited access to data and time during this thesis. However, it is an illustrative example of how extensive expansion of LEC flexibility can make a community self-sufficient.

The flexibility activation follows a natural pattern based on the load demand during the day. The load increases at night and morning, and the batteries are charged. During off-peak hours the grid is in danger of experiencing over-voltage problems, which the increased load and battery charging helps prevent. The battery charging also occurs during the period of the lowest costs of importing power from the TSO. During on-demand hours, the load decreases, and batteries are discharged to prevent under-voltage problems in the grid. As Figure 9.6 shows, all nodes' voltage magnitudes are improved. This was true for all time slots, not only at 10:00, as shown in the figure. This indicates that demand-side flexibility can improve voltage magnitudes, even with problems.

Flexible generation is used excessively for the economic optimization test case with flexibility included. This is due to the operational costs of the DGs being much lower than the cost of importing power from the TSO. In the input data, these capacities are defined as constant even though they are considered intermittent power sources like solar panels. As such, the capacities would realistically vary during the day based on weather conditions. This was, however, not included in this thesis due to restricted time and limited resources. Without these intermittent capacities, less generation would occur during less optimal operating conditions. With less flexible generation, more power would be imported from the TSO, resulting in higher operating costs and transfer losses. It could also result in more activation of other FRs during high-demand hours.

In general, these test cases show that the utilization of demand-side flexibility can have great economic benefits for several participants in the market. They have also shown that with extensive FR expansion, the LECs can become self-sufficient and deliver more power back to the grid than they consume, thus gaining a positive net revenue.

9.3.3 Voltage Regulation

Even without the simulated under-voltage problem, the voltage magnitudes are below the 0.95 limits for the voltage regulation test cases. However, with the voltage problem, the magnitudes are poorer for all nodes except the slack node and drop below the 0.9 limits for nodes 4-22.

There is a large increase in the need for load shedding with the stricter voltage limit and voltage drop compared to the economic optimization test case without flexibility. Much of this increase is due to the stricter voltage limit, as the load shedding starts before the voltage problem and continues for the remainder of the day. As such, it could have been advantageous to simulate the economic optimization test case without flexibility with this stricter voltage limit to see how much the voltage drop contributes to the load shedding. However, these test cases aimed to observe whether flexibility could aid the DSO with voltage regulation. As such, the fact that the grid is designed so that load shedding is needed without any voltage problem directly included is a test of this. Both in the economic optimization test cases and these voltage regulation test cases, the need for load shedding was eliminated when flexibility was included. For the economic optimization test case, the magnitudes were also improved. This indicates that demand-side flexibility can maintain and improve voltage magnitudes closer to nominal values and aid when problems are causing low or high voltage magnitudes in the grid.

The flexibility activation of the last voltage drop simulation is generally high. This increased use is also largely attributed to the stricter voltage limits of this test case compared to the economic optimization. Load control is utilized throughout the day, with the load increasing during low-demand hours and decreasing during high-demand hours. During the voltage drop, the discharging of batteries is the most prominent FR used. Flexible generation still runs at almost maximum capacity for the entire 24 hours. This results in decreased imported active power and lower transfer losses. The generation is high enough that the distribution grid delivers power back to the TSO between 00:00 and 08:00. As a result, the imported active power is reduced by over 50% when flexibility is included. The transfer losses are subsequently reduced since the need for imported power is reduced. This is an additional indication that demand-side flexibility reduces transfer losses due to distributed power generation and the utilization of resources locally.

These test cases aimed at illustrating how demand-side flexibility can aid the DSO with managing voltage magnitudes of the grid. With an under-voltage problem and strict voltage limits, the demand-side flexibility could not improve the voltage magnitudes during the under-voltage problem. However, the need for load shedding in LEC 2 was eliminated. This indicates that demand-side FRs greatly benefit voltage regulation in the distribution grid.

9.3.4 RES Integration

With flexibility added to the DA market, the objective values decrease compared to the original DA market results without flexibility. The LEC 1 objective value has become negative, which has been the case for many test cases with flexibility included. This indicates that the model can use demand-side flexibility in the planning. Comparing the results from the RES simulation with DA flexibility to the economic optimization with flexibility, it can be observed that the objective values for the DSO and LEC 1 stay around the same value. However, LEC 2 has its optimal value reduced, as this grid has benefited from introducing flexibility in the planning stage, due to its higher loads. The capacities of the flexibility resources in the DA flexibility case are, as mentioned in Chapter 7.3, reduced compared to the FM. This could be one of the causes for the increase in the DSO objective value, as it could not utilize as much flexibility as it would need to balance the segment of the grid that the LECs are present in.

When RES generation is included, the FM operational costs of the DSO are halved compared to the economic optimization test case without flexibility. However, the LEC operational costs are relatively unchanged. This is also the case when the generation capacity is reduced, as only the DSO operational costs are significantly changed. This might be due to the location of the DG. It is located in node 17, far from the LECs in nodes 7 and 10. As such, the DG would have a larger impact on the LECs if it was located in Schönbrunn rather than the Tröstau area. The operational costs of LEC 2 are still high due to the load shedding that is still needed in the community.

Just as the DSO's operational costs were most affected by the inclusion of DGs, the LECs gain the largest economic benefits of including flexibility in the test cases. The operational costs of LEC 1 also become negative here, meaning that they sell more power than they consume. The operational costs of LEC 2 are decreased significantly due to the elimination of load shedding. For the DSO and LEC 2, the operational costs increase when the RES capacity is reduced. For LEC 1, however, they decrease when going from 100% to 80% RES capacity. This indicates that the community has unrealized flexibility potential in the 100% test case, which is needed when capacity is reduced. With proper capacity expansions, the LEC can aid the power producer when the production capacity is lower than expected.

As the generation capacity decreases, the need for imported active power naturally increases. Subsequently, the transfer losses and operational costs of the DSO also increase. The increase becomes bigger as the capacity reduces. As illustrated by the comparison of generation capacities with and without flexibility included, the difference between the test case with and without flexibility is lower for the 40% capacity test case than the 100% capacity test case. This could result from the 40% test case having to deal with more load shedding than the 100% capacity test case. Even though the operational costs show that the DG affects the DSO the most, there is still some effect on LEC 2, meaning that the load shedding is reduced with the DG included.

In summary, the test cases show that with a significant expansion of demand-side flexibility, the end-users can aid the power producer when power generation is lower than forecasted. The inclusion still lowers the need for imported active power and transfer losses, reducing operational costs for several participants.

9.4 The Model

In this section of the discussion, the focus will be taken on the performance of the model, not the results. This is due to the time spent working on the model and adapting it to achieve results, giving perspectives on how it performs and its drawbacks.

9.4.1 Time used to achieve convergence

To gather a perspective on how the model has been improved, the grid used in the specialization project was used to make a benchmark test. The results of this test are highlighted in Table 9.6 and Table 9.7.

As seen in Table 9.7, the new model achieves convergence in far fewer iterations. However, this has not led to a significant reduction in overall time usage. This is because there is a time delay in sending and receiving the data through mail to ensure that the script does not run faster than the mail-protocols can mail server can operate. This gives the setup used in this thesis a total DA delay per iteration of 4 seconds; for FM, the delay is 10 seconds. This does not account for the time it takes to run the sending and receiving scripts, which also adds time. When considering this, the improved efficiency of the new model with ρ update is significant.

Table 9.9 shows that the results of the new and old models are close. The results were expected to differ somewhat due to the ρ update function added to the new model. However, this deviation could likely be reduced further by improving the ρ update function to take into account more information. However, due to the focus of this thesis, emphasis was not put on this.

The data presented in Table 9.6-9.9 show that the new model improves the convergence time significantly, especially with the more realistic grid. This time saved comes at a slight loss of accuracy, as shown in Table 9.6. The new, realistic test grid could not converge without the improvements made to the model, especially the ρ update function, as shown in Table 9.8.

9.4.2 Limitations of the model

The model struggles with data where the load sent across the DSO grid is smaller, i.e., the model works better for larger grid sizes. This is highlighted well in Chapter 9.4.1, where the old grid, which was much larger, is shown to converge quickly even with the old model. However, the model struggles compared to the new grid, which is much more realistic but smaller. The model is even shown to be unable to find convergence for the DA market part, as it reached 99 iterations, the maximum allowed. This indicates that if the flow in the DSO grid is small, the model is slow to update the lambda values, giving slower convergence.

How the ρ update function was implemented could also be a limitation, as it does not account for slowing down the algorithm when convergence is close. This was dropped because the algorithm tended to overshoot the convergence and could not achieve it. With a more sophisticated implementation, this could be avoided.

Another significant limitation of the model today is that troubleshooting and debugging it is tedious. As mentioned earlier in this Chapter, the algorithm performs better for larger grids. This became a problem when testing the new grid, which could often not be solvable in the model for some cases. Modifications such as the ρ update function aided somewhat in this regard. However, the model is still limited by the lack of transparency regarding what part of a grid is not solvable.

10 Conclusions and Further Work

10.1 Conclusion

The work on this master's thesis consisted of several parts, one of which was the work done on the optimization model and the code that was written to simulate it. The work done on the model further strengthened the position of the ADMM algorithm within the LFM field, as it provided good results with the simulations in this thesis. The model was improved by reducing resource usage within the code itself by removing unnecessary code and by introducing more adaptive step length in the algorithm. This has made the model much more efficient at finding the optimal solution.

This thesis addresses four distinct objectives related to the topic of the LFM. The first objective of this thesis was to create a more realistic test case with data provided by industry. From this realistic test case, the objective was to see how the SoC AC/AC-OPF with the ADMM modification would solve it. This is the basis for all the results shown in Chapter 9.2, which show that the LECs in the new test grid actively trade flexibility when demand is high to help the DSO meet the demand in the system. The grid was created with the help of the German DSO S.W.W Wundsiedel, who provided accurate information about their grid. The grid was thoroughly explained in Chapter 8.

The second objective of this thesis focused on implementing information exchange by mail to ensure the security of information transfer for the participating market players. This was done by integrating a script that trades the necessary OPF results of each participant as a mail, in addition to the information security properties of the ADMM algorithm. This mail was only sent to the master script, showing that the DSO did not need direct access to any given LEC information to perform its OPF, only the information the LFMO would provide them. This implementation is shown in Appendix D and explained in Chapter 7.4.1. The implementation also works as proof that this model could be used in a decentralized manner, meaning that each market participant could perform their own OPF simulations and only trade to each other what was necessary. This gives each participant more security with regard to utilizing this type of model.

The third objective of this thesis was to introduce distributed generation into the grid and see how flexibility could help solve any balancing problems arising from its intermittent nature. The results from the simulations with the distributed generators were shown in Chapter 9.2.4 and indicated significant upsides to this integration, especially if flexibility is around to aid in any balancing issues. The results show that the combination of distributed generation and flexibility could substantially reduce the need for importing power from the TSO, reducing the losses from importing.

The fourth objective of this thesis was to implement flexibility resources as a tool in DA market planning. This was done for some of the RES scenarios and resulted in a paper written about it for a conference. The introduction of DA flexibility trading worked as a proof of concept, and the results indicated a benefit from including flexibility trading in the DA market.

The work done in this thesis also includes an extensive review of the state of the art within the research field of the LFM. This review was compiled and presented in the earlier chapters and provided a solid theoretical background for the work and results presented in the latter. The literature review highlighted the functions of flexibility assets and how they could be utilized. In addition, the review introduced and thoroughly investigated the main participants of the LFM, further defining them within the field of the LFM. It also provided the necessary background for choosing the market clearing and structure of the LFM that the constructed model was subsequently based on.

Through the work on this thesis, the authors have contributed to the development of the field of LFM by consolidating different research ideas in the introduction chapters and providing a direct method for solving LFMs with DSO and LECs as the focus and providing their knowledge within LFM and operations planning. These contributions include:

- The creation of a realistic test grid through the use of raw data from a real-life DSO, allowing for a thorough discussion around the real-life applications of flexibility resources.
- A thorough review of the field of LFM, consolidating information about participants and the market mechanism.
- Submitting a paper to the 19th International Conference on the European Energy Market, titled "Framework and model for flexibility exchange between DSO and LEC", which was accepted and will be published in IEEE Proceedings.
- The further development of the LFM trading schemes, with additions ranging from minor improvements to the model to implementing flexibility trading in the DA market.

This thesis shows that the optimal coordination between the DSO and LECs with the inclusion of demand-side flexibility and battery resources will provide extensive economic benefits and stability to the grid.

10.2 Further work

In this thesis, the model focuses on simulating a DSO-LEC coordination. As discussed, other preliminary work has looked at TSO-DSO coordination and even the coordination of one TSO and several DSOs. A natural extension to the model would thus be to include all three parts in the simulation and optimize a TSO-DSO-LEC coordination. With such an extension, all three levels of participation would be included, and one would thus have a more complete market coordination.

Even though this thesis aimed at making more realistic test cases to examine the robustness of the model, the test cases can still be made closer to real-life grids. A more complete, realistic test case could be made with more data on other grid voltage levels. For this thesis, it would, for example, have been beneficial to have access to realistic data of the LV grid as well as the MV grid. This would have made the LECs more realistic, which would have improved the test cases greatly.

A more thorough and complex implementation of intermittent power generation would be an interesting research topic. This thesis simulated different scenarios separately due to limited time and resources. A better implementation of the intermittent generation would make the model more dynamic and realistic. This intermittency should also be extended to the flexible generation of the LECs, as most of the DGs of LECs rely on RES, like solar and wind power.

Another way to make the model more dynamic would be to investigate how different FRs are activated. This and the preliminary theses have paid little to no attention to the technical constraints of different FRs and how different characteristics make them suitable for some situations and maybe not others. For example, response time greatly impacts how the resources can be utilized. As such, investigating which resources fit best for different users and adding this to the model would be valuable.

To make the test cases even more realistic, a better and more thorough investigation into prices and costs would be beneficial. As more research and test pilots are being conducted, more dynamic prices can be added to the flexibility data, providing a better picture of economic challenges and benefits.

As discussed at the end of Chapter 5.3, the current model's coordination scheme heavily favors the DSO, which might make the TSO and power producers refrain from participating in the market. The preliminary theses working with a TSO-DSO coordination illustrated that the TSO also benefits from utilizing demand-side flexibility, and this thesis has discussed how the power producer can utilize this flexibility to introduce more intermittent DGs in the grid. As such, the flexibility must be divided fairly between participants to encourage active and effective market participation. More research into the market structure and coordination would be a rewarding addition.

As mentioned briefly in Chapter 2.4.2, industrial buildings also have a large potential for delivering flexibility through excess energy like heat. Many countries, for example, use CHP or gas resources for heating and cooking appliances. Electrical energy is, therefore, only a part of the energy market in most of the world. Transitioning to a multi-vector energy system is also important in moving toward a decentralized power market. As such, an interesting extension would be to include several energy systems in the model.

Adding flexibility to the DA market was an interesting addition to the model, but further improvements are needed. Extensive research into more accurate flexibility data for the DA market and better implementation of the model would make it possible to utilize demand-side flexibility not only to balance and maintain the power system when problems arise but also as an active part of planning power system operations.

To realize the use of demand-side flexibility, there are not only technical challenges that pose a threat. There are also challenges related to rules and regulations that must be addressed when designing a good LFM framework. A thorough study and identification of the laws and regulations that hinder the implementation of the LFM would provide valuable new information.

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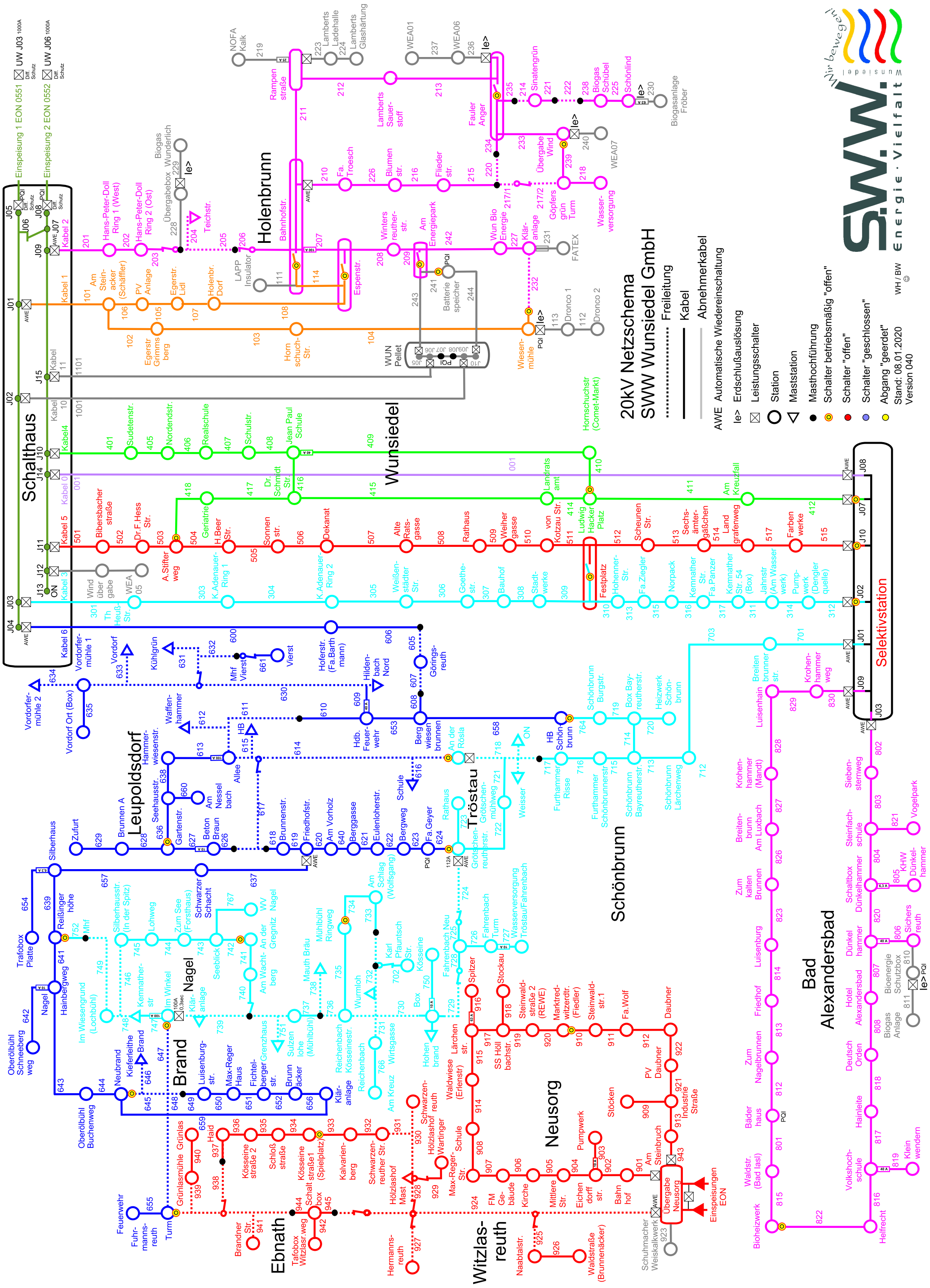
A German distribution grid



B General load data

	KW								
	Saturday	Sunday	Working day	Saturday	Sunday	Working day	Saturday	Sunday	Working day
0:15	0,453	0,560	0,433	0,575	0,641	0,552	0,513	0,598	0,498
0:30	0,436	0,519	0,389	0,543	0,592	0,492	0,481	0,556	0,445
0:45	0,422	0,480	0,351	0,516	0,550	0,440	0,452	0,520	0,399
1:00	0,405	0,442	0,319	0,490	0,511	0,399	0,426	0,484	0,362
1:15	0,381	0,406	0,296	0,459	0,474	0,371	0,399	0,449	0,336
1:30	0,352	0,372	0,279	0,426	0,440	0,354	0,371	0,413	0,318
1:45	0,323	0,343	0,268	0,394	0,409	0,343	0,346	0,380	0,307
2:00	0,298	0,319	0,261	0,367	0,383	0,335	0,325	0,351	0,298
2:15	0,281	0,303	0,257	0,349	0,365	0,328	0,310	0,331	0,291
2:30	0,271	0,291	0,253	0,337	0,352	0,322	0,300	0,316	0,285
2:45	0,265	0,283	0,252	0,329	0,342	0,315	0,292	0,306	0,280
3:00	0,261	0,277	0,250	0,325	0,335	0,309	0,287	0,298	0,277
3:15	0,258	0,271	0,248	0,322	0,330	0,304	0,284	0,291	0,275
3:30	0,255	0,266	0,247	0,320	0,325	0,300	0,281	0,285	0,275
3:45	0,253	0,260	0,245	0,319	0,321	0,298	0,278	0,280	0,276
4:00	0,250	0,256	0,245	0,319	0,319	0,298	0,277	0,277	0,277
4:15	0,248	0,252	0,246	0,321	0,319	0,301	0,276	0,276	0,278
4:30	0,246	0,248	0,248	0,323	0,320	0,307	0,276	0,276	0,280
4:45	0,245	0,246	0,252	0,324	0,321	0,316	0,276	0,276	0,283
5:00	0,245	0,245	0,256	0,325	0,319	0,325	0,277	0,277	0,287
5:15	0,246	0,245	0,262	0,325	0,317	0,337	0,279	0,277	0,296
5:30	0,250	0,246	0,276	0,326	0,313	0,356	0,283	0,277	0,313
5:45	0,258	0,248	0,305	0,330	0,310	0,387	0,291	0,276	0,344
6:00	0,271	0,250	0,357	0,341	0,309	0,436	0,303	0,277	0,394
6:15	0,292	0,254	0,435	0,360	0,312	0,507	0,323	0,278	0,467
6:30	0,319	0,259	0,530	0,387	0,319	0,589	0,351	0,284	0,552
6:45	0,354	0,264	0,627	0,421	0,332	0,670	0,388	0,294	0,641
7:00	0,394	0,271	0,714	0,463	0,351	0,740	0,436	0,314	0,719
7:15	0,441	0,282	0,778	0,512	0,379	0,790	0,496	0,345	0,780
7:30	0,493	0,298	0,822	0,566	0,415	0,823	0,563	0,387	0,822
7:45	0,551	0,327	0,849	0,623	0,463	0,845	0,631	0,440	0,851
8:00	0,612	0,373	0,863	0,682	0,522	0,863	0,698	0,506	0,868
8:15	0,677	0,439	0,867	0,740	0,595	0,882	0,758	0,583	0,878
8:30	0,741	0,520	0,863	0,796	0,676	0,900	0,811	0,668	0,881
8:45	0,799	0,609	0,852	0,850	0,762	0,916	0,856	0,755	0,881
9:00	0,847	0,698	0,836	0,900	0,847	0,927	0,895	0,842	0,879
9:15	0,881	0,780	0,817	0,946	0,927	0,930	0,926	0,923	0,876
9:30	0,903	0,856	0,797	0,986	1,000	0,927	0,952	0,995	0,873
9:45	0,917	0,924	0,778	1,017	1,062	0,920	0,975	1,058	0,868
10:00	0,927	0,986	0,762	1,039	1,114	0,911	0,996	1,108	0,863
10:15	0,934	1,041	0,751	1,050	1,152	0,901	1,017	1,144	0,856
10:30	0,942	1,091	0,744	1,054	1,181	0,893	1,037	1,172	0,847
10:45	0,950	1,139	0,740	1,056	1,208	0,886	1,055	1,197	0,841
11:00	0,959	1,188	0,740	1,060	1,236	0,884	1,071	1,225	0,836
11:15	0,970	1,237	0,743	1,069	1,269	0,887	1,083	1,261	0,836
11:30	0,982	1,284	0,749	1,084	1,304	0,897	1,093	1,299	0,842
11:45	0,998	1,322	0,760	1,103	1,336	0,913	1,104	1,334	0,855
12:00	1,018	1,348	0,778	1,124	1,358	0,938	1,119	1,358	0,879
12:15	1,039	1,356	0,803	1,146	1,368	0,970	1,137	1,366	0,913
12:30	1,061	1,345	0,829	1,164	1,362	1,003	1,157	1,356	0,948
12:45	1,078	1,318	0,851	1,176	1,338	1,028	1,172	1,325	0,978
13:00	1,087	1,273	0,863	1,177	1,295	1,039	1,177	1,273	0,991
13:15	1,084	1,213	0,859	1,165	1,231	1,027	1,169	1,201	0,980
13:30	1,073	1,144	0,843	1,144	1,158	0,999	1,151	1,117	0,953
13:45	1,055	1,071	0,819	1,114	1,083	0,961	1,125	1,035	0,916
14:00	1,034	1,002	0,794	1,082	1,018	0,922	1,098	0,964	0,879
14:15	1,012	0,941	0,769	1,048	0,969	0,886	1,070	0,914	0,847
14:30	0,991	0,889	0,748	1,017	0,934	0,855	1,044	0,881	0,822
14:45	0,972	0,845	0,728	0,989	0,906	0,828	1,019	0,857	0,799
15:00	0,954	0,810	0,708	0,970	0,879	0,804	0,996	0,836	0,778
15:15	0,938	0,781	0,691	0,957	0,847	0,783	0,975	0,813	0,756
15:30	0,924	0,756	0,675	0,951	0,813	0,765	0,957	0,788	0,735
15:45	0,913	0,735	0,662	0,947	0,778	0,751	0,942	0,762	0,715
16:00	0,906	0,714	0,655	0,943	0,746	0,740	0,932	0,735	0,698
16:15	0,902	0,693	0,654	0,936	0,718	0,733	0,928	0,710	0,684
16:30	0,907	0,678	0,660	0,928	0,697	0,731	0,931	0,689	0,676
16:45	0,927	0,673	0,676	0,922	0,683	0,733	0,939	0,676	0,675
17:00	0,970	0,687	0,703	0,922	0,676	0,740	0,954	0,671	0,682
17:15	1,036	0,723	0,742	0,927	0,679	0,753	0,975	0,678	0,698
17:30	1,117	0,774	0,792	0,940	0,689	0,770	1,001	0,696	0,724
17:45	1,199	0,832	0,849	0,960	0,707	0,793	1,034	0,724	0,757
18:00	1,268	0,890	0,911	0,986	0,730	0,820	1,071	0,762	0,799
18:15	1,313	0,940	0,975	1,016	0,757	0,852	1,112	0,806	0,847
18:30	1,338	0,982	1,038	1,050	0,790	0,889	1,155	0,856	0,900
18:45	1,351	1,022	1,096	1,083	0,827	0,929	1,195	0,906	0,954
19:00	1,358	1,060	1,145	1,114	0,868	0,970	1,231	0,954	1,007
19:15	1,364	1,098	1,182	1,138	0,914	1,011	1,258	0,995	1,055
19:30	1,363	1,129	1,204	1,155	0,959	1,048	1,274	1,028	1,095
19:45	1,347	1,146	1,209	1,164	0,996	1,077	1,276	1,047	1,121
20:00	1,305	1,140	1,193	1,161	1,023	1,092	1,263	1,050	1,130
20:15	1,235	1,107	1,156	1,148	1,033	1,091	1,231	1,034	1,117
20:30	1,146	1,054	1,105	1,124	1,029	1,077	1,185	1,005	1,091
20:45	1,052	0,996	1,049	1,094	1,018	1,058	1,130	0,974	1,060
21:00	0,970	0,943	0,996	1,060	1,002	1,039	1,071	0,948	1,034
21:15	0,908	0,905	0,953	1,025	0,985	1,025	1,011	0,934	1,017
21:30	0,866	0,878	0,918	0,993	0,970	1,014	0,957	0,926	1,006
21:45	0,838	0,856	0,886	0,967	0,956	1,004	0,915	0,919	0,995
22:00	0,820	0,831	0,852	0,954	0,943	0,991	0,890	0,906	0,975
22:15	0,807	0,799	0,814	0,953	0,931	0,972	0,885	0,880	0,942
22:30	0,794	0,759	0,771	0,957	0,915	0,947	0,891	0,844	0,898
22:45	0,778	0,714	0,725	0,956	0,891	0,912	0,893	0,798	0,845
23:00	0,756	0,666	0,676	0,938	0,852	0,868	0,879	0,746	0,788
23:15	0,726	0,616	0,627	0,895	0,796	0,814	0,839	0,689	0,730
23:30	0,687	0,566	0,577	0,834	0,728	0,752	0,780	0,630	0,671
23:45	0,645	0,516	0,528	0,765	0,656	0,685	0,714	0,571	0,612
0:00	0,602	0,468	0,479	0,698	0,586	0,618	0,650	0,516	0,554

C Operational costs

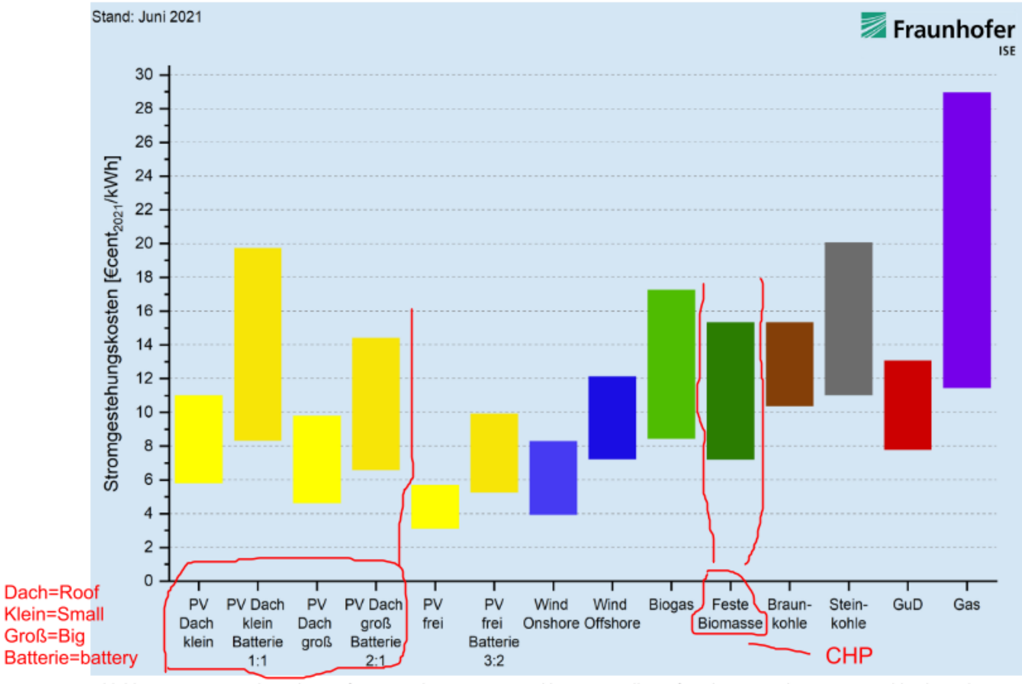


Abbildung 1: Stromgestehungskosten für erneuerbare Energien und konventionelle Kraftwerke an Standorten in Deutschland im Jahr 2021. Spezifische Anlagenkosten sind mit einem minimalen und einem maximalen Wert je Technologie berücksichtigt. Das Verhältnis bei PV-Batteriesystemen drückt PV-Leistung in kWp gegenüber Batterie-Nutzkapazität in kWh aus.

D Information exchange via mail code

D.1 Code for sending mail

```
from Input_declarations import *

def send_mail(sender, reciever, message, password, filepath, file_name):

    msg = MIMEMultipart()

    msg['Subject'] = file_name
    msg['From'] = sender
    msg['To'] = reciever

    with open(filepath + "/" + file_name, "rb") as file:
        sendable = MIMEBase("application", "octet-stream")
        sendable.set_payload(file.read())
        encoders.encode_base64(sendable)
        sendable.add_header("Content-Disposition",
                            "attachment; filename= %s" % file_name)
        msg.attach(sendable)
        file.close()


    with smtplib.SMTP('smtp.gmail.com', 587) as server:
        server.starttls()
        server.login(sender,password)
        server.send_message(msg)
```

D.2 Code for receiving mail

```
from Input_declarations import *

def recieve_mail(reciever, password,isDSO,checkWhatFile,
                            iteration,n,mail_recieve_path):


    server = imaplib.IMAP4_SSL('imap.gmail.com', 993)
    server.login(reciever, password)
    server.select("Inbox")

    check1,data = server.uid("search",None, "ALL")
    num = data[0].split()[-1]
    check2, data = server.uid("fetch",num,"(RFC822)")

    if check2 == "OK":
        mail_data = data[0][1]

        string_of_mail_data = mail_data.decode("utf-8")
        content_of_mail = email.message_from_string(string_of_mail_data)
        for segment in content_of_mail.walk():
            if segment.get_content_maintype() == "multipart":
                continue
            fileName = segment.get_filename()
            if bool(fileName):
                filePath = os.path.join(mail_recieve_path,fileName)
                if os.path.isfile(filePath) == False:
                    path = open(filePath, "wb")
                    path.write(segment.get_payload(decode=True))
                    path.close()


    temp = pd.read_csv(filePath)

    checkWhatFile.append(fileName)
```

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