THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

Flexibility from local resources

Congestion management in distribution grids, carbon emission reductions, and frequency containment reserves

Nima Mirzaei Alavijeh

Department of Electrical Engineering
Chalmers University of Technology
Gothenburg, Sweden, 2024

Flexibility from local resources
Congestion management in distribution grids, carbon emission reductions, and frequency containment reserves

NIMA MIRZAEI ALAVIJEH
ISBN 978-91-8103-119-5

Doktorsavhandlingar vid Chalmers tekniska högskola
Ny serie nr 5577
ISSN 0346-718X

Department of Electrical Engineering
Chalmers University of Technology
SE-412 96 Gothenburg, Sweden
Phone: +46 (0)31 772 1000

This Ph.D. thesis incorporates content from the author's licentiate thesis: N. Mirzaei Alavijeh, *Flexibility from Local Resources: Congestion Management in Distribution Grids and Carbon Emission Reductions.* Lic. thesis, Chalmers Tekniska Högskola, Sweden, 2023
Papers I, IV, and V are the accepted authors copies. Cite the original published version © 2021 IEEE, © 2023 IEEE
Papers II, III, and VI are open-access articles licensed under Creative Commons Attribution 4.0 International License.
Paper VII is a submitted paper © 2024 the authors.

Cover: The cover illustration is generated by the author using DALL-E 2, an AI that creates images from text descriptions.

Printed by Chalmers Reproservice
Gothenburg, Sweden, November 2024

Flexibility from local resources
Congestion management in distribution grids, carbon emission reductions, and frequency containment reserves
NIMA MIRZAEI ALAVIJEH
Department of Electrical Engineering
Chalmers University of Technology

Abstract

Flexibility from resources within local energy systems has been discussed as a facilitator for the transition towards a carbon-neutral energy system. This thesis aims to elucidate three local flexibility usecases that contribute to harnessing local flexibility through effective incentive mechanisms and operation planning.

The first usecase is on **congestion management in distribution grids**, studying the challenges, design, and evaluation of local flexibility markets (LFMs). Methods include literature review, field studies, scenario planning, and simulation experiments. Five design challenges are identified: low market liquidity, reliability concerns, baselines, forecast errors at low aggregation levels, and high submeter measurement costs. An LFM design with a triple-market structure (long-term availability, day-ahead, and adjustment markets) is proposed to support decision-making and improve market reliability and liquidity. Adapted capacity-limitation products based on net-load and subscribed connection capacity of end-users are suggested. These products can reduce conflicts of interest, administrative costs, and submeter measurement costs. Probabilistic approaches are suggested for calculating the cost and value of the products, reducing the potential cost of forecast errors for market participants. A comparison toolbox for congestion management solutions is developed, offering researchers and distribution system operators (DSO) a qualitative comparison framework and a reusable modeling platform for quantitative comparison.

The second usecase is on **reducing carbon emission footprint** from local energy systems. A multi-objective optimization model is provided for identifying CO_2 emission abatement strategies and their cost using Chalmers Campus local multi-energy system as a case study. The results show that the carbon emission footprint of the local system could be reduced by 20.8% with a 2.2% increase in the cost over a year. Operation strategies for this purpose include the increase in the use of biomass boilers in heat production, the substitution of district heating and absorption chillers with heat pumps, and increased storage utilization. The cost of the strategies ranged from 36.6–100.2 (€/tCO_2).

The third usecase focuses on the operation planning of a battery energy storage

(BES) participating in Sweden's day-ahead (DA) electricity and **frequency containment reserve** (FCR) markets. Maximum potential profit, battery aging, and operation strategies are presented using a mixed-integer linear formulation that considers a detailed calendar and cycle aging for the battery while taking into account market technical requirements. Considering degradation in the optimization problem, a 1MW/1MWh BES in 2022 could gain a maximum potential profit of k€ 708 by stacking revenue in the DA and FCR markets while undergoing an expected aging of 1.7% in battery capacity. Analyzing the impact of considering degradation in the optimization problem has shown that the annual battery aging cost could decrease by 5%-29% without a significant impact on profit.

The results of this thesis benefit system operators, flexibility asset owners, policy makers, and researchers involved with local flexibility. It offers insights into the challenges and proposes solutions and algorithms for these usecases.

Keywords: Flexibility, local flexibility market, congestion management, baseline , distribution system operator, local energy system, emission abatement strategies, frequency containment reserves, battery degradation, revenue stacking

List of Publications

This thesis is based on the following appended papers, which are referred to in the text by their assigned Roman numerals:

I. N. Mirzaei Alavijeh, M. A. F. Ghazvini, D. Steen, L. A. Tuan, and O. Carlson, “Key drivers and future scenarios of local energy and flexibility markets,” in *2021 IEEE Madrid PowerTech*, 2021, pp. 1–6

II. I. Bouloumpasis, N. Mirzaei Alavijeh, D. Steen, and L. A. Tuan, “Local flexibility market framework for grid support services to distribution networks,” *Electrical Engineering*, pp. 1–19, 2021

III. N. Mirzaei Alavijeh, D. Steen, L. A. Tuan, and S. Nyström, “Capacity limitation based local flexibility market for congestion management in distribution networks: Design and challenges,” *International Journal of Electrical Power & Energy Systems*, vol. 156, p. 109 742, 2024

IV. N. Mirzaei Alavijeh, M. Song, W. Tobiasson, D. Steen, and L. A. Tuan, “A toolbox for comparing congestion management solutions for distribution networks,” in *2023 IEEE Belgrade PowerTech*, 2023, pp. 01–06

V. R. Sharma, N. Mirzaei Alavijeh, M. Mohiti, D. Steen, L. A. Tuan, and P. Loveryd, “Flexigrid tools for real-life demonstrations of local energy system concepts at Chalmers Campus testbed,” in *2023 IEEE Belgrade PowerTech*, 2023, pp. 01–06

VI. N. Mirzaei Alavijeh, D. Steen, Z. Norwood, L. Anh Tuan, and C. Agathokleous, “Cost-effectiveness of carbon emission abatement strategies for a local multi-energy system—a case study of Chalmers University of Technology Campus,” *Energies*, vol. 13, no. 7, 2020

VII. N. Mirzaei Alavijeh, R. Khezri, M. Mazidi, D. Steen, and L. A. Tuan, “Profit benchmarking and degradation analysis for revenue stacking of batteries in Sweden’s day-ahead electricity and frequency containment reserve markets,” *Applied Energy*, 2024 (Under review)

Nima Mirzaei Alavjeh (N.M.A.) has conducted most of the calculations, analysis, visualization, and writing in **Papers I, III, IV, VI, and VII**. N.M.A has developed most of the models in **Papers II-IV, and VII** and contributed to the modeling and validation of the results in **Papers V** and **VI**. N.M.A has also contributed to the writing and discussions in **Papers II** and **V**.

The following paper is published during the PhD studies but not included in the thesis:

- I. Bouloumpasis *et al.*, “Flexibility provision from battery storage and PV inverters using IoT platform: Real-life demonstrations at Chalmers Campus,” in *2024 IEEE PES Innovative Smart Grid Technologies Europe (ISGT-Europe)*, 2024

Acknowledgments

I want to express my sincere gratitude to my supervisors. I have learned a lot from you not only in technical matters, but also as a person. Thank you Tuan for being so patient and open to any idea, no matter how strange or off they were. Thank you for your undoubting trust and support. It has been heartwarming to feel secure through the ups and downs. Thank you David for being always available, no matter how many meetings you have in a day. How you can do that is still a mystery to me! Thank you for your positivity in any situation, and for your great enthusiasm and passion for solving problems. They have been not only a source of motivation but also inspiring. Thank you both for giving me this opportunity. Being at this point would not have been possible without your insightful comments and guidance.

My sincere gratitude also extends to my examiner, Ola Carlson. Thank you for your considerate support and calmness during the ups and downs. Reaching the finish line would not be possible without your guidance and advice at different stages.

I would also like to acknowledge the FlexiGrid Project "Enabling flexibility for future distribution grid" that is funded by the European Union's Horizon 2020 research and innovation programme under grant agreement No 864048. The financial support is gratefully acknowledged. I also thank all the colleagues within the project for their input and for many hours of fruitful discussions.

A special thanks goes to all my colleagues and friends at Chalmers. The memories, the laughter, and the warmth of all the afterwork gatherings, board game nights, fikas, and lunches will remain in my heart. I would like to extend this special thanks to my colleagues in our research group for being so helpful and supportive. I feel fortunate to have worked with such caring people as you.

Finally, my deepest gratitude to my parents, Hooman, Agnes, and Ashkan for being always there for me. I cannot find words to thank you for your unwavering encouragement, love, care, and support. Your presence keeps the flow in the river of my life.

Nima Mirzaei Alavijeh
Gothenburg, November, 2024

Acronyms

BES:	Battery energy Storage
CHP:	Combined Heat and Power
CL:	Capacity limitation
DA:	Day-ahead
DER:	Distributed Energy Resources
DN:	Distribution network
DSO:	Distribution System Operator
EMS:	Energy Management System
ET:	Energy Cost
FSP:	Flexibility Service Provider
FCR-N:	Frequency Containment Reserve for Normal Operation
FCR-D:	Frequency Containment Reserve for Disturbance
ICT:	Information and Communication Technology
LEM:	Local Energy Market
LER:	Limited Energy Reservoir
LESOOP:	Local Energy System Object-oriented Programming Platform
LFM:	Local Flexibility Market
MES:	Multi Energy Sytem
MILP:	Mixed-integer Linear Programming
PT:	Power Tariff
PV:	Photovoltaic Panel
RES:	Renewable Energy Sources
SoC:	State of Charge
SoE:	Stage of Energy
TSO:	Transmission System Operator
VCG:	Vickrey-Clarke-Groves

Contents

CHAPTER 1

Introduction

This chapter presents the problem overview, the scope, the aim and research questions, and the limitations.

1.1 Background

The transition towards a more carbon neutral energy system has initiated various trends, including increased penetration of renewable energy sources (RES), electrification [1], and the emergence of more intelligent and active end-users [2]. These trends can pose challenges for electricity networks, including reduced system inertia, increased frequency variations, lack of transfer capacity, and voltage band violations. Flexibility from distributed energy resources (DERs), such as batteries, electrical vehicles, and heat pumps, in local energy systems has been extensively discussed over the past decade as part of the solution to the challenges mentioned above. Flexibility can be defined as the modification of generation or consumption that is activated at a specific time and location for a specified duration [3], [4]. However, a challenge in fostering flexibility is designing incentive mechanisms and coordinating the activation of flexibility. Therefore, studying both the incentive mechanisms and the potential response of the involved actors can contribute to a smoother transition.

The current structure of the energy system is complex due to its multidimensional essence comprising social, technical, economic, and environmental dimensions. Therefore, to put a research work on flexibility in perspective, it is crucial to pinpoint where and how it can be used in the current structure. This is tried to be clarified using three aspects:

(i) Values and basic assumptions of actors,

(ii) Architectural blocks in a socio-technical system, and

(iii) Usecases of flexibility.

Aspect (i): Providing right incentives and designing functional mechanisms require various considerations, including values, drivers, and basic assumptions of different actors. First, depending on values and differences in basic assumptions, global warming solutions can be categorized into different pairs of opposites, including individual-driven vs. incentive-mechanism-driven solutions [5]. This pair of opposites categorizes the solutions based on who is responsible for solving a problem. For example, at one extreme, individuals are held responsible for having an environmentally friendly lifestyle, while at the other end, political systems bare the responsibility [5]. Second, in addition to who bears the responsibility, actors' different value logic lead to different drivers and business models that are an essential piece for driving a change. For example, public actors can value system benefits (e.g. sustainability) and being a front-runner; community actors may value self-enhancement by creating an identity as e.g, a sustainable, innovative, and future-oriented community; households may value their benefit and independence the most; and commercial actors value profitability, predictability, being inspirational for others [6]. Therefore, the target group of a technical research can be better defined if the actors' value logic and view on sustainable development is better understood.

Aspect (ii): The socio-technical architecture of policy-driven solutions includes three blocks: incentive mechanism, agents and their response to the incentive mechanism, and the physical infrastructure [7]. Incentive mechanisms are designed to induce desirable agent behavior and thus a desirable impact on physical infrastructure. Research on flexibility can be about designing incentive mechanisms, modeling actors' responses, or modeling the physical infrastructure and components.

Aspect (iii): It is also important to clarify for what purpose flexibility is utilized. Hillberg et al. [8] categorize the need for flexibility into flexibility for energy, power, transfer capacity, and voltage and illustrate them using space and time dimensions (Figure 1.1). The space dimension varies from local and regional distribution networks to transmission and system-wide levels. Flexibility for energy is for medium to long-term demand-supply balance. Flexibility for power is about short-term demand-supply balance for frequency stability. Flexibility for transfer capacity is for short to medium term ability to transfer power from supply to demand to solve local or regional congestions. Flexibility for voltage concerns short-term ability to keep the bus voltages within desirable limits. Another usecase of flexibility can be for emission reductions as an individual-driven solution in which some actors may change their behavior to reduce the emissions.

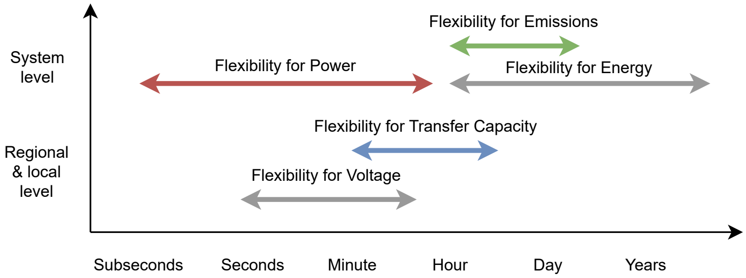


Figure 1.1: Flexibility usecases and their timescale (Adapted from [8])

1.2 Scope and motivations

Considering the above-mentioned aspects, the scope of this thesis is divided into three parts (Figure 1.2). The first part deals with incentives-mechanism-driven solutions to relieve transfer capacity at local and regional levels. It covers mechanism design and operation planning of actors under such mechanisms. The second part is about individual-driven solutions to reduce carbon emissions by changing operation strategies. The third part also deals with incentive mechanism-driven solutions, but for regulating grid frequency. However, this part only focuses on identifying the optimal operation strategy of agents and not on the incentive mechanism design.

Part one is focused on a market-based mechanism to incentivize and coordinate local flexibility resources for congestion management in distribution grids. Different solutions have been proposed for congestion management, including grid reinforcements, market-based solutions, innovative tariff designs, rule-based approaches, or comprehensive methods including a mixture of the above-mentioned solutions [4], [9]. The motivation for focusing on market-based solutions lies in its recognition and promotion by regulators and other actors in Europe. For example, the European Parliament has promoted market-based solutions in Article 32 of the Electricity Market Directive (2019/944) of the EU clean energy package [10]. The Association of European Energy Exchanges has mentioned market-based solutions as the most

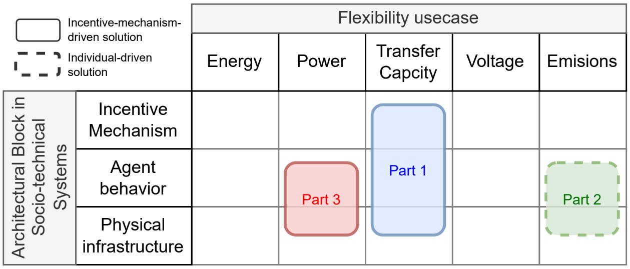


Figure 1.2: The focus of the thesis

efficient approach to match the supply and demand for flexibility [11]. Moreover, market-based solutions are identified as being part of the solution by Council of European Energy Regulators [9]. Local flexibility markets (LFMs) are an example of market-based mechanisms.

The design of LFMs are accompanied by challenges, and various designs such as [12]–[16] are proposed in the literature. However, there is no consensus on the design, including LFM structure, product definition, and its characteristics [17]. In addition, concerns such as metering, coordination, and baseline methodologies need to be further studied [17]. Therefore, in this thesis, 1) a step is taken backward to identify the LFM design challenges and uncertainties in its implementation, 2) a market design is proposed to address the identified challenges and uncertainties, 3) algorithms are suggested for bidding and operation planning of the market actors, and 4) a toolbox is developed to evaluate and compare congestion management solutions.

Part two is concerning an individual-based action to reduce carbon emissions utilizing local flexibility resources. Based on values and drivers, public and community actors may be willing to take individual actions to reduce carbon emissions to bring system benefits (e.g. sustainability), be a front-runner, or establish a future-oriented and innovative identity [6]. However, the operational means and their cost for such actors on a local level have to be identified. In this thesis, operation strategies and their cost-effectiveness are analyzed for a local multi-energy system, including three energy carriers of electricity, district heating, and district cooling.

Part three focuses on operation strategies and battery degradation of a battery owner when responding to market-based incentives for providing frequency containment reserves (FCR). Recent trends comprise the introduction of a down regulation market for FCR during disturbances (FCR-D down-regulation) in year 2022 [18], a drastic increase in the supply of FCR services by distributed flexibility resources [19], and the introduction of the Nordic technical requirements for limited-energy reserves (LERs), such as batteries [20]. These trends underscore the importance of studying operation strategies of distributed flexibility resources such as batteries considering the increasing complexity of decision-making for multimarket participation while considering the technical requirements for LERs. In addition, it is important to analyze the impact of multi-market participation on battery degradation for a more sustainable utilization of these resources. In this thesis, the operation strategy and a detailed battery degradation model is formulated as a mixed-integer linear program for simultaneous participation of a battery in Sweden's day-ahead spot and FCR markets, i.e. FCR in normal operation (FCR-N), and disturbances (FCR-D up-regulation and FCR-D down-regulation). The study includes evaluating both calendar and cycle aging of the battery in addition to incorporating the technical requirements of the Nordic FCR markets.

1.3 Aim and research questions

This thesis aims to elucidate three areas in the local flexibility research. The first area is the design of a market-based incentive mechanism for congestion management in distribution grids. The second area is the operation planning of local flexible asset owners, with the aim of reducing their carbon emission footprints. The third area is about operation planning of battery owners for multi-FCR market participation. The corresponding research questions and papers are visualized in Figure 1.3 and elaborated below:

1. An incentive-mechanism-driven utilization of local flexibility for congestion management in distribution networks:
    - **RQ1.1**: What are the challenges of designing an LFM and the uncertainties in its implementation?
        - What are the key drivers and future scenarios for LFMs? - **Paper I**
        - What are the common design challenges for LFMs? - **Paper III**
    - **RQ1.2**: What LFM design addresses the identified challenges in RQ1.1? - **Papers II** and **III**
    - **RQ1.3**: How can the performance of the designed LFM be compared to other congestion management solutions? - **Paper IV** and **V**
2. An individual-driven utilization of local flexibility to reduce carbon emission footprints

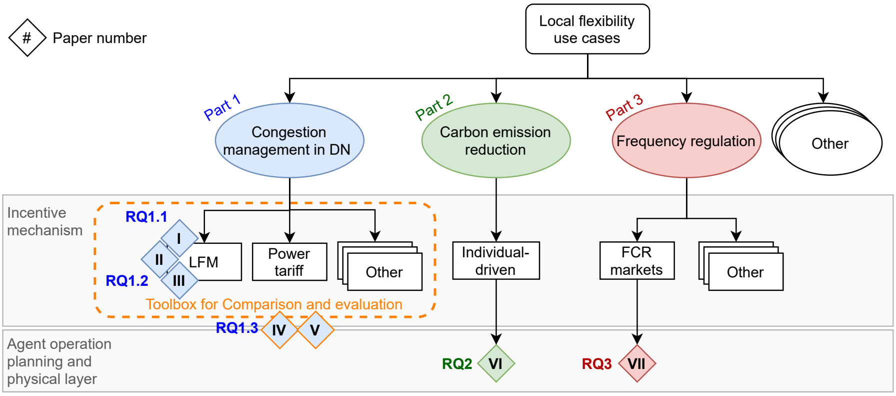


Figure 1.3: The map of papers

- **RQ2**: What are the operation strategies and their costs for reducing carbon emissions utilizing flexible resources in a local multi-energy system? - **Paper VI**

3. An incentive-mechanism-driven utilization of local flexibility for frequency containment reserves
    - **RQ3**: What are the maximum potential profit and expected battery degradation for a battery energy storage when participating in Sweden's day-ahead spot and FCR markets while considering battery degradation, and the technical requirements of Nordic FCR markets? - **Paper VII**

1.4 Contributions

The main contributions of the thesis are:

- Regarding **RQ1.1**, key factors influencing the future of the local markets for energy and flexibility in Europe are explored and ranked. Qualitative plausible future scenarios for these markets are developed. The impacts of the scenarios are analyzed to provide suggestions for addressing these impacts. In addition, five challenges are identified for LFM design, including low market liquidity, reliability, baselines, forecast errors at low aggregation levels, and the high cost of measurements.
- Regarding **RQ1.2**, an LFM design is proposed that facilitates the decision-making of market participants by designing aspects that improve market liq-

uidity, reliability and handling of forecast errors. Moreover, a new capacity-limitation product is proposed that is not defined with respect to a baseline and does not require submeter measurements, leading to lower costs and conflict of interest in delivery validation. Generic algorithms are also proposed for calculating utility and cost of the flexibility product.

- Regarding **RQ1.3**, a toolbox is proposed to support a systematic comparison of different congestion management solutions for distribution networks. The toolbox consists of two parts: i) a qualitative analytical framework to identify the barriers of implementing different solutions; ii) a scalable and extendable modeling platform to quantitatively assess their effects under the same system condition. Moreover, the Chalmers demonstration test-bed has been improved to host tools such as forecasting tools for load, PV, and congestion, energy management systems, and local flexibility markets to enable validating the efficacy of the tools under more realistic conditions.

- Regarding **RQ2**, emission abatement strategies and their cost are identified for a local multi-energy system (MES) operation by developing and utilizing a multi-objective optimization for cost and emissions. The MES operation is optimized for over a year with a rolling, short-foresight time horizon, and three energy carriers of district heating, district cooling, and electricity.

- Regarding **RQ3**, a novel mixed-integer linear programming model is developed for optimal participation of battery energy storage in the Nordic day-ahead spot and FCR markets. The developed model aims to maximize the potential profit of a battery owner by stacking revenue from these markets while considering a detailed battery degradation model and the technical requirements of the Nordic FCR markets.

1.5 Limitations

Proving the functionality of a market is limited to the designed agents. In real life, the strategy space of agents is infinite, while in protected simulation and demonstration environments, the strategy space is limited. The behavioral and social aspects that impact the strategy of agents are not considered in this thesis. Moreover, monetary values presented in this thesis are dependent on the definition of agents and test systems. Therefore, such values should be interpreted carefully considering the assumptions on agents' business models, processes, assets, time of year, etc.

1.6 Thesis outline

This thesis is written as a collection of papers in which Chapters 2-5 describe an overview and summary of the papers and their connections. Detailed results and discussions are provided in the appended papers. The content is as follows. **Chapter 2** provides a background and an overview of the related literature including flexibility usecases, the state-of-the-art for LFM design, the sources of flexibility in a local energy system, and optimal operation of these resources from agents' perspective. **Chapter 3** elaborates the research approach including overarching methodologies that are used in this thesis, and an overview of the utilized methods. **Chapter 4** presents and discusses the main results concerning each research question. **Chapter 5** concludes the work and presents the potential future work.

CHAPTER 2

Background and related work

This chapter provides the background and the works related to the research questions presented in Chapter 1. It elaborates different flexibility usecases, the state-of-the-art for local flexibility markets for congestion management in distribution grids, and the state-of-the-art for operation of local flexibility resources for providing frequency containment reserves and operation strategies aiming to reduce carbon emission footprints

2.1 Flexibility usecases

In this section, the extended flexibility usecases from [8] (Figure 1.1) are explained by answering three questions: what challenge each usecase aims to solve, what the potential solutions are for solving each challenge, and how local flexibility resources can be utilized for the challenge.

Energy

This usecase aims to match the supply and demand of electricity for time periods longer than an hour. Variation and lack of control over RES generation can cause demand-supply imbalances depending on, for example, whether the wind blows or the sun shines.

Energy system studies focus on strategies for managing these variations and their costs using dispatch and capacity models. Reference [21] categorizes these so called variation management strategies into:

1. Shifting strategies: to store excess of low-cost electricity from RES for later use and to shift the electricity demand to match better the supply
2. Absorbing strategies: to use other energy carriers/sectors for absorbing the excess of supply from RES
3. Complementing strategies: to complement RES generation by dispatchable resources

In the context of local flexibility resources, the results of such studies can be used for designing incentive mechanisms such as subsidies and taxes that promote a specific mix of local technologies that leads to a lower system cost. Moreover, price signals from mechanisms such as wholesale electricity markets can be used to induce a certain behavior in local flexibility resources, aiming to keep the supply-demand balance at these relatively longer time periods.

Power

This usecase also aims to balance the supply and demand of electricity, but in shorter time periods (i.e., subseconds, seconds, and minutes). The balance in such time resolutions is essential for the stability of the system and especially for the frequency stability.

There already exist various incentive mechanisms for keeping the frequency stable. Examples are various products in ancillary service markets, e.g., Fast Frequency Reserves (FFR), Frequency Containment Reserves (FCR), and Frequency Restoration Reserves (FRR). Local flexibility resources can be used to deliver these products to transmission system operators (TSOs).

Grid transfer capacity

This usecase aims to solve congestion at regional and local distribution networks. Electrification in the transport, heating, and industry sectors, and more active control of DERs by end-users, are expected to increase the peak load and therefore the need for a larger transfer capacity [1], [2]. This is conventionally handled by DSOs through grid reinforcements. However, grid reinforcement as a solution to these trends can be costly and accompanied by long investment lead times.

In addition to grid reinforcement, other solutions are suggested to address local and regional congestion, including market-based solutions (e.g., LFMs and local energy markets (LEMS)), innovative tariff designs, active network management, or comprehensive methods including a mixture of the above-mentioned solutions [4],

[9]. Local flexibility resources can be utilized through direct/indirect incentives from market-based and tariff-based solutions, or control signals from active network management solutions.

Voltage regulation

This usecase aims to keep the voltage within a span at local and regional grids. Voltage lower band violations can occur when new loads are connected along the feeders on medium to low voltage levels because of a gradual voltage drop along the feeders. Voltage upper band violations can be seen when distributed RES (e.g., PV systems) inject power along the feeder, especially during hours with low consumption.

Examples of conventional methods for voltage regulation in radial distribution grids are on-load tap changer transformers and shunt capacitors for voltage regulation [22]. There also exist other methods such as market-based and active network management methods which can be utilized to incentivize local flexibility resources for voltage regulation in distribution networks [23].

Carbon Emissions

This usecase aims to reduce carbon emission footprint that can be seen as an individual action for reducing the emissions. Local flexibility resources can be utilized for a more sustainable operation of local energy systems considering both costs and emissions.

2.2 LFMs for grid transfer capacity in distribution grids

Local flexibility markets are an example of market-based solutions for managing congestion in distribution networks. LFMs are complex multi-dimensional systems, including social, technical, and economic dimensions. These markets are under development and are accompanied by various challenges. Therefore, for a successful design, key factors and trends that impact the future of these markets in addition to design challenges must be identified. LFMs should also be evaluated in comparison to other solutions to find the most suitable solution from a holistic perspective. The following subsections present key factors and trends impacting the future of LFMs', followed by a review of design challenges and evaluation studies.

2.2.1 Key factors, trends, and future scenarios

The development and evaluation of LFMs is an ongoing research topic in Europe. Understanding the key factors and trends that impact the future of these markets can contribute to a better design and successful implementation.

Based on related literature and experiences from previous projects [9], [12], [24]–[26], and in addition to input from four DSOs in Sweden, Switzerland, Turkey, and Bulgaria, 20 key factors and impacting trends are identified for LFMs that are presented in **Paper I**. The identified factors are categorized into four groups: technical, social, political, and financial, to provide a more holistic perspective. The identified factors and trends cover, for example, the availability of different DERs, digital grid monitoring and control, smart and digital end-users, and relevant new competencies. In addition, the factors cover the tendency of end-users for active participation in LFMs, and changes in the regulatory framework, for example, the unbundling regulations and introduction of regulatory incentives for DSOs to adopt market-based flexibility solutions. Moreover, carbon taxes, wholesale electricity prices, and grid tariffs are examined as potential influencing factors.

Scenario planning methods can be used to explore these key factors and trends and provide insight to different stakeholders, such as, policymakers, system operators, flexibility service providers, and researchers. Scenarios are possible forms of the future that provide narratives for a context and facilitate decision-making [27]. It is important to highlight that scenarios are not predictions of the future, but rather an exploration of the drivers of change and multiple plausible future situations [27], [28]. Scenario planning provides a structured conversation to familiarize decision-makers with different uncertainties and to build a shared understanding of such uncertainties [29].

Scenario planning methods are used in different research areas. In the energy systems area, there exist examples of using such methods in [30]–[34]. However, no study has been found in the context of LFMs.

2.2.2 Design challenges

The design space for markets is quasi-infinite including various parameters within auction design, product design, and technical requirements [35]. Therefore, instead of jumping into the review of LFM designs, a step is taken backward to identify the suitable properties of a market mechanism and the expected challenges in LFMs. Thereafter, the different LFM designs are analyzed to find the gaps in addressing these challenges. In this section, an overview of the suitable properties and the commonly mentioned challenges for LFM design is provided. The challenges are collected by reviewing proposed LFM designs, experiences from different projects, and workshops with DSOs in the FlexiGrid project [36]. The literature gap to address these challenges is provided in Section 2.5.1.

Suitable properties from mechanism design field

To identify the design challenges and their importance, an overview of desirable market properties in economics theory is essential. Mechanism design is a branch of economics with applications in different contexts such as agreements, voting, privatization, and markets. This branch focuses on starting from suitable outcomes of an economic institute and asks how it can be designed to achieve the outcomes. The general desirable properties of a mechanism in the context of local markets are presented in [37], [38], including:

- **Efficiency**: The mechanism should maximize the social welfare of its participants considering their revealed preferences.
- **Incentive compatibility**: The mechanism should be designed to incentivize participants to declare their true preferences (e.g., the true cost/utility).
- **Budget balance**: The mechanism should be designed in a way that its operator would have neither deficit nor excess in its financial balance.
- **Group rationality**: A desirable mechanism should be designed in a way that no individual or group of participants would be willing to separate from the market to obtain greater benefits. The result of such a property is the stability of the mechanism.

If LFM is viewed as an economic mechanism, these properties can elaborate the impact of its design challenges and reveal gaps in the way it is addressed.

The design challenges

The challenges below are commonly mentioned in the literature:

1. Low market liquidity
2. Reliability concerns
3. Challenges regarding defining baselines for a baseline-based flexibility product
4. Forecast errors due to low aggregation levels
5. The high costs concerning the need for extra measurements and information and communication technology (ICT) infrastructure.

Low market liquidity is commonly mentioned in various studies such as [3], [12], [26], [39]–[41]. The low liquidity can be due to the geographical limit of the local markets, and the lack of flexible resources available in the transition phase where end users become flexible and LFMs are adopted [3]. A less liquid market is less competitive and more prone to instability [42] and market manipulation [43]. Thus, for LFM as a mechanism, the incentive compatibility property can be affected as a result of low market liquidity. Low liquidity can also lead to uncertainties in supply or demand that can affect the willingness to engage and consequently the group rationality property. Although low liquidity can impact incentive compatibility and group rationality, efficiency would not be affected as it is defined based on declared costs/utilities. These points are summarized in Table 2.1.

Table 2.1: Negatively-impacted desirable market properties as a result of the common LFM design challenges. Abbreviations are IC: Incentive compatibility, and GR: Group rationality.

LFM design challenges	Impacted market property	Reason
Low market liquidity	IC	Potential gaming
	GR	Uncertainties in supply/demand
Reliability concerns	IC	Potential low liquidity due to reliability concerns leading to potential gaming
	GR	Uncertainties in supply/demand hindering market access for risk averse actors
Baselines	IC	Potential gaming through baselines
	GR	Conflict of interests, and transparency issues
Forecast errors	GR	Extra costs due to failures in delivery, or wrong estimations for the required/available service quantity
High measurement and ICT costs	GR	Extra costs for sub-meter measurement and communication besides higher system complexity

The reliability challenge is partially related to market liquidity and the security of supply for flexibility. This is crucial for DSOs to ensure a reliable, secure, and efficient distribution network as their core responsibility [10]. Local markets are especially presented as a substitute for grid reinforcements [24] that cannot be done overnight if there is a lack of flexibility. In addition, flexibility service providers (FSPs), including property managers and real estate owners, can have reliability concerns for the return of investments considering a potential lack of (flexibility) demand leading to uncertain revenue streams [26], [44]. Moreover, FSPs can be risk averse as flexibility provision can negatively affect the comfort of their tenants, especially if the control of the assets is directly handed to DSOs [24], [45]. Low liquidity and uncertainties in the supply/demand of flexibility can affect market reliability and hinder market access for more risk-averse actors. As summarized in Table 2.1, the group-rationality property can be impacted as uncertainty can lead to participants leaving the market or not willing to join. Moreover, market liquidity, and thus incentive compatibility of the market, can be impacted if there are not sufficient incentives and reliability for the participants in the local markets.

The challenges with baseline are mentioned in various sources such as [39], [46], [47]. The baseline refers to a reference power profile that represents the power profile of a flexibility provider if they do not offer any flexibility services. Reference [46] evaluates different methods for defining a baseline and argues why baselines are not suitable for LFMs based on four criteria of transparency and simplicity, inclusive use of flexibility, manipulation-proofness, and compatibility with continuous and smart control of flexibility resources. They conclude that the baseline-based flexibility products are not aligned with active participation of DER owners in different markets because finding admissible days to calculate the baseline would be more challenging. In addition, they highlight that these products can cause uncertainty, complexity, potential market manipulations, and conflict of interest between stakeholders. As summarized in Table 2.1, baseline challenges can affect incentive compatibility through potential market manipulations and affect group rationality by adding uncertainty, conflicts of interest, and transparency issues.

The forecast error challenge can be due to a smaller aggregation at local levels [48]. Inaccuracy of forecasts can cause problems in defining baselines in an LFM [46], [49], or in forecasting the behavior of end-users [47] for a cost-effective delivery of the promised service. Forecast errors can lead to higher costs for all stakeholders. For example, they can cause failures in delivery, or wrong estimations for the required/available service quantity. This can lead to penalties or over/under procurement. The extra costs may impact group rationality because participants may choose not to engage or leave the market.

The last challenge is the potential need for extensive measurements and investments in ICT platforms required to validate the delivery and communications between market participants. This challenge has been raised in discussions with DSOs in the FlexiGrid project's consortium. A market design that requires fewer measurements is preferred for monetary and complexity reasons. Similarly to the forecast error challenge, the extra cost and complexity can impact the group rationality property for the LFM mechanism.

2.2.3 Evaluation

The most suitable congestion management solution depends on the context comprising various parameters such as the grid size, its topology and characteristics, DSOs size and resources, regulations, load profile and its rate of increase, lead-time and cost of grid reinforcement, and available technical infrastructure. Therefore, in addition to suitable properties from the field of mechanism design (presented in Section 2.2.2), an LFM design should be compared with other available solutions for congestion management to find the most suitable option in each composition of parameters. In this section, a review of studies that have compared different solutions is provided.

Reference [50] has qualitatively compared LFM, dynamic tariff design, and nonfirm connections. They concluded that the non-firm connection agreements can only be applied to new users of the grid due to potential legal consequences if enforced upon existing users. Therefore, nonfirm connection agreements alone may be insufficient and could benefit from being complimented by LFMs. Moreover, the feasibility of fully dynamic tariffs was deemed naturally impractical due to inherent issues of equality and fairness, as well as the uncertainty associated with users' reactions. Consequently, the authors suggest the integration of LFMs with a semireflective dynamic tariff as a potential solution. However, they do not use a specific structured framework for comparison.

Reference [51] has presented various types of congestion management tools and categorized them using different aspects including: i) operational (short-term) vs. investment (long-term) options, and network vs. load and generation; ii) basic categories for regulatory options; and iii) target actors of congestion management instruments. The authors have also provided three real-life examples: Cross-zonal capacity allocation, re-dispatch instruments, and flexibility markets in The Netherlands. They have concluded that a holistic consideration of different incentives for congestion management as well as other ancillary services is required for effective congestion management. Moreover, the impact of the incentive on market parties' freedom of connection, trade, and dispatch should be considered to improve the overall efficiency of the electricity market design. However, the authors do not use a structured holistic comparison framework that includes social, regulatory, and technical aspects.

Reference [52] has presented a simulation platform as the first step towards an assessment framework for congestion management mechanisms. They have conducted case studies on tariff designs that consider DER penetration levels and load placement. The authors have concluded that a wide variety of factors affect the comparison results and, therefore, a systematic analysis framework is essential. However, the comparison is only quantitative, including voltages, cost for EVs and revenue for

DSOs, and loading level of grid components. Other aspects such as social, regulatory, and complexity are not considered.

Reference [53] has investigated the effectiveness of congestion management methods when flexible loads can cause congestion by being activated simultaneously in response to a low imbalance-price. They have quantitatively compared energy, peak, and tier tariffs with flexibility markets. However, the authors do not consider LEMs and capacity-limitation-based LFMs in their comparisons.

References [54] and [55] have summarized congestion management methods with market-based and non-market-based approaches. However, the methods focus more on the congestion problem at the transmission level. Reference [56] has reviewed congestion management tools for distribution networks with high penetration of distributed energy resources. It covers market-based methods and direct control methods. Market-based methods consist of dynamic tariff, distribution capacity market, shadow price, and flexible service market. The direct control methods are comprised of network reconfiguration, and active and reactive power controls. However, the comparison is focused on elaborating optimization algorithms for different methods rather than conducting a quantitative comparison study.

2.3 Operation of local flexibility resources for carbon emission reduction

Multi-energy systems (MESs) are suggested to enhance the potential for flexibility and synergies in the overall energy system by integrating and managing different energy carriers (such as electricity, district heating, district cooling, and natural gas) simultaneously [57]. A study of the combination of local energy systems and MESs for carbon emission reductions can be a usecase for the flexibility of MESs in local energy systems.

Within the two research areas of local energy systems and MESs, previous studies [57]–[59] have reviewed definitions, trends, challenges, and have categorized the literature. Grosspeithsch et al. [58] categorized the literature into four categories: general overview, model and optimization, energy management and system analysis, and case study.

One feature of the model and optimization category is that energy systems have traditionally been modeled solely on the basis of cost minimization objectives. However, multi-criterion optimization can help broaden decision making to consider cost, environmental aspects, reliability, social impact, utilization of renewable energy, etc [60]. As global concerns about greenhouse gas emissions increase, carbon emissions have become an increasingly important criterion to be considered in optimizing the operation of local MESs. For instance, Majidi et al. [61] proposed a cost and emission framework to assess demand response programs, and Bracco et al. [62] developed a multi-objective model to evaluate the operation of a multi-energy system considering four different building types and three energy carriers (heat, gas, and electricity). Wang et al. [63] demonstrated that a multi-objective optimization will not give one single solution but rather a set of Pareto optimal solutions. Often, the objectives are conflicting and different approaches to solve the minimization problem exist, e.g., mixed integer linear programming (MILP) with weighted sums [64], evolutionary algorithms [65], game theory [66], particle swarm optimization [67], genetic algorithms [68], etc.

Furthermore, an optimization model can have short foresight (close to real-time) or long foresight depending on the purpose and the characteristics of the energy technologies included in the system. Optimizations with long foresight result in a more optimal management of resources, especially in energy systems with seasonal storage, conventionally dispatchable units, and perfect foresight. However, such long-term optimizations require long-term forecasts and can be computationally expensive as the size and complexity of the model increases [69].

On the other hand, optimization with short foresight lowers computational time that is favorable for simulating complex systems [70] and has less challenges with the quality of forecasts. This is especially important for systems with a large share of RES because, as the share of intermittent RES increases in the system, their stochastic nature starts to affect forecasts, availability, and prices of energy carriers. Therefore, if the model represents a system that includes a large share of RES, or reacts in response to the energy prices of a system with a large share of RES, a close to real-time modeling approach with short foresight can represent agents' and their energy technologies' behavior closer to reality [71].

There exist a handful of studies on the modeling and optimization of MESs. For example, Wu et al. [64] investigated the simultaneous optimization of annual cost and CO_2 emissions in the design and operation of a distributed energy network where DERs can exchange heat with each other through pipelines. A MILP model with a weighted sum approach is used in this multi-objective optimization. Di Somma et al. [72] also used a weighted sum approach to develop a multi-objective linear programming model considering both cost and emissions. The impact of various energy technologies on the objective function was evaluated by sensitivity analyses. A limitation of this study is its focus on one customer and not on a community of customers. Falke et al. [73] developed a multi-objective model for the design and operation of distributed energy systems using a heuristic optimization approach. The model decomposes into three submodels: heating network planning, buildings renovation planning, and operation simulation. However, cooling loads and district cooling are not considered. Yan et al. [74] studied the operation optimization of multiple distributed energy systems where the emissions are considered in the form of monetary costs through a carbon tax. The DERs in this model can exchange electricity and thermal energy with each other, and electricity can be sold back to the grid. Although emissions cost is considered through carbon tax in this study, the trade-off between emissions and monetary costs is not discussed. In [65], an evolutionary algorithm is used to solve a multi-objective isolated MES model with a high share of renewables, including investments in RES as decision variables. The paper shows that different operational approaches may be beneficial for different seasons. In [75], an MES model is developed that includes possible constraints in energy flows within the MES. For the electricity network, this is accomplished using a DC load flow model, and a pipeline load flow model is used for the natural gas network.

2.4 Operation of local flexibility resources for participation in FCR markets

Optimizing and analyzing the participation of distributed flexibility resources in FCR markets is becoming more important due to recent trends and changes in these markets. Firstly, in 2022, FCR-D down-regulation market was introduced in the Nordics [18], leading to a total of three FCR markets and the potential complexity of decision-making in these markets. Secondly, the technical requirements for LERs have been updated, including the introduction of a maximum available power requirement and the reduction of endurance requirements in the FCR-D markets [20]. Thirdly, prequalified storage assets in Sweden's FCR markets have increased by 650% from January 2023 to January 2024 [19] showing the interest of flexibility asset owners in these markets. In the light of these trends and changes, revisiting optimal decision-making for the participation of distributed flexibility resources in FCR markets can contribute to a faster and smoother integration of these resources while utilizing their maximum potential.

The literature on the application of battery energy storage (BES) in frequency regulation services can be divided into two distinct approaches: control-based and market-based.

The first approach focuses on the optimal control of BESs to effectively regulate frequency. In [76], a distributed control strategy was proposed for multiple BESs to regulate frequency in the power system with high penetration of renewable generation. In [77], an online frequency regulation strategy based on the Lyapunov optimization technique was proposed. Reference [78] suggests that frequency regulation signals can be divided into a slow component, directed at synchronous generators, and a fast component, directed to BESs. The authors of [79] propose a robust control strategy to manage distributed BESs for frequency regulation. These articles focus on developing control strategies for BESs to regulate frequency, and they do not address the maximization of profit that can be obtained by participating in ancillary service markets.

The focus of the second approach is on investigating the participation of BESs in ancillary service markets. To ensure an acceptable and sustainable operation of these assets, it is especially important to include the updated technical requirements and analyze the potential degradation of such assets due to participating in FCR markets. The importance of considering battery degradation is highlighted in [80] due to the considerable energy throughput and cycling in FCR-N services. Reference [81] has analyzed the degradation impact of providing FCR services in Germany based on measurements from a large-scale battery. The results indicate that BESs have been subjected to many cycles with a low average cycle depth, leading to a dominance of calendar aging over cyclic aging. In [82], degradation has been identified as the most critical factor affecting the profitability of BESs. In addition to the importance of the degradation in decision-making, the combination of prices and different technical requirements in the three markets further complicates the optimal utilization of flexibility resources. As shown in [80], selecting the best FCR market in each hour of BES scheduling can increase profitability by 22% compared to delivering only FCR-N. As investigated in [83], neglecting market requirements may lead to situations where balancing the BES is insufficient to provide the FCRs, resulting in penalties.

In light of the above-mentioned important factors, the literature related to the second approach is reviewed with a focus on battery degradation, multi-market decision making, and the inclusion of technical requirements. Reference [84] proposes a bidding strategy and online control methodology for BESs to enable participation in both the day-ahead market for electricity and FCR-N market. Although battery degradation is modeled in [84], participation in the FCR-D up/down markets is not considered. Furthermore, the proposed model is non-linear, adding a computational burden and challenges in finding the global optimum solution. In [85], a two-stage stochastic optimization model is developed for the optimal bidding of BESs in both the energy and the ancillary service markets. Although the model effectively addresses participation in the multi-FCR market, it falls short in full accounting for market requirements. Furthermore, the accuracy of battery degradation modeling in the proposed framework was deemed simplistic. In [86], EVs are aggregated as a BES, and a two-level optimization model is proposed to determine their optimal participation in the energy and ancillary service markets. In the proposed model, only participation in the FCR-N market is considered, and factors such as battery degradation and market requirements are neglected. In [87], robust and stochastic methods were used to model the participation of aggregated EVs in the energy and ancillary service markets. In the developed model, a constant annual activation ratio was calculated for FCR using real historical data and incorporated into the supply-demand balance equation as a random variable. Although their developed model considered multi-FCR market participation, it was not developed with the technical requirements of Nordic FCR markets, and battery degradation is not a detailed model. The authors of [88] have introduced an optimization model for the sizing and scheduling of BESs to maximize income from participating in the energy and FCR-N markets. However, the proposed model has employed a simplified degradation model for the battery and has overlooked the FCR market requirements.

The literature has also been reviewed to understand the dis/advantages of different formulation approaches. Among the MILP formulations, two main categories could have been identified: energy-content-based (activation ratio) and droop-based power modeling. Energy-content-based approach considers an activation ratio of the power bid to be used in the energy balance constraint of flexibility resources. This activation ratio can be scenario-based [87], an average [89], or based on high-resolution historical frequency values [80]. The advantage of this approach is it's independence from the time resolution of the model. However, it does not link power to droop curves for service activation, leading to difficulties in modeling cycle aging due to its dependence on dis/charge power. In addition, a constant average activation ratio can lead to unrealistic representation of energy throughput from activation. The droop-based power modeling approach, as in [85], models power and energy throughput using a direct link to the droop curves for activation. The down side is the dependency on time resolution. The larger the time step, the lower the accuracy of power and energy. This can cause unrealistic energy throughput for flexibility resources. To model a detailed battery degradation while having an accurate energy-throughput representation, a novel modeling approach is required that combines these two approaches.

2.5 Research gap

2.5.1 LFMs for congestion management in distribution grids

Key factors, trends, and future scenarios

Although key factors/trends related to the future of LFMs are mentioned sporadically in the literature, scenario planning methods have not been widely used in the research area of energy management systems to familiarize different stakeholders with the uncertainties in the implementation of new concepts. Moreover, there are no studies on LFMs that use such methods to explore key factors that impact the future of these markets, develop plausible future scenarios, and analyze the implications.

In summary, the following contributions can be made: 1) introducing scenario planning methods to provide insight for future developments of emerging concepts in the energy system's area, 2) exploring and ranking the key factors that affect the future of LFMs, and 3) developing qualitative plausible future scenarios for LFMs, analyzing the implications of the scenarios while providing suggestions to handle the implications.

LFM design

Five main LFM design challenges have been identified in Section 2.2.2. In this section, the literature gap is identified and discussed with respect to addressing these challenges.

To address the liquidity and the reliability challenges, two groups of approaches are identified in the literature. The first group paves the way for a higher liquidity and reliability, while the second is focused on preventing the potential consequences of low liquidity such as market manipulations.

Belonging to the first group, reservation payments and long-term contracts have been well-known as ways of securing supply and incentivizing investments (in flexible assets). [44] have categorized the reservation payments as a controversy in LFMs and discuss their advantages and disadvantages. In our previous work [90], we had considered long-term reservations based on a mixed-price of reservation and activation prices; however, the mixed-price approach can increase market complexity while complicating interpretation of clearing prices. Moreover, linkages between the reservation and activation payments/markets are to be explored further. [15] have proposed a "Right-to-Use" option as a flexibility reservation due to uncertainties in their day-ahead (DA) flexibility market. Although helpful in handling DA uncertainties, this suggestion would not meet the long-term planning horizon of DSOs and potential investors in flexible assets. Therefore, an interconnected long-term reservation and short-term activation with a simpler pricing approach that establishes a more robust linkage between the two markets would be beneficial.

From the second group, incentive-compatible payment allocation methods such as Vickrey-Clarke-Groves (VCG) can be utilized to prevent market manipulation. However, VCG is not budget-balanced and can lead to practical challenges. One-sided VCG is suggested as a potential solution in [13]. However, a one-sided VCG is not individually rational for DSOs. In theory, it can lead to DSOs paying more than their declared willingness and thus leaving or not adopting the market.

In contrast to issues with individual rationality and budget balance, issues with incentive compatibility can be improved by measures that increase the liquidity and prevent market manipulations. Some examples filling this gap are long-term reservation payments and multi-bids ([91]) for the first group of approaches, and market monitoring, anti-trust law, and price caps ([44]) for preventing market manipulations as the second group.

The challenges related to baseline-based flexibility products are discussed and tried to be addressed in [13], [46] by proposing a new class of products called capacity limitation products. A capacity limitation (CL) product is a service that keeps the consumption/generation below or above a certain limit. However, [13] mention that the functionality of their CL product is dependent on the truthful declaration of assets by FSPs. For example, an FSP can provide the limitation of using its heat pump with respect to the nominal capacity of the heat pump. However, the FSP could instead turn on an undeclared electric heater. Since delivery validation is done based on submeter measurements on the declared devices, the FSP would get paid for providing flexibility, although it had not contributed to reducing the congestion. Moreover, the proposed CL product seems to require submeter measurements for all flexible assets, which can lead to higher costs and complexity for the validation of the service delivery. Therefore, a CL product design that is not dependent on the truthful declaration of DERs capacity can facilitate delivery validation. In addition, if the product requires less measurements and thus less ICT-related costs, the fifth challenge can be overcome.

From a mechanism design perspective, forecast errors at low aggregation levels have been addressed diversely in the literature. For example, Enera's market allows its continuous auction up to 5 minutes before the delivery time [17]. This approach can allow an improvement of forecasts as we approach delivery time, but it can come at the expense of market efficiency losses as continuous auctions have lower allocation efficiency compared to call-auctions [92]–[94]. Bouloumpasis et al. [90], IREMEL [95], InterFlex [96], INTERFACE [97] markets, and [98] take another approach and include an intraday/real-time flexibility market [17]. Considering these different approaches, it is beneficial to assess what suits better for reducing the impact of forecast errors.

In summary, an LFM design that facilitates market participants' decision-making by design aspects improving market liquidity, reliability and handling of forecast errors can contribute. Moreover, proposing a new flexibility product that is not calculated with respect to a baseline and does not require submeter measurements can lead to lower costs and conflict of interests in delivery validations. Lastly, proposing generic algorithms for calculating utility and cost of the flexibility product can support market participants for a smoother adoption of the market.

LFM evaluation

As presented in Section 2.2.3, there exist studies on the evaluation of LFMs with respect to other congestion management solutions for distribution grids. However, no holistic comparison framework has been found that includes regulatory, social, and technical aspects. Moreover, the studies do not simultaneously include a wide range of solutions such as LFMs, local energy markets (LEMs), grid tariffs, bilateral contracts, and grid reinforcements. Except reference [52], the quantitative studies does not present a scalable, reusable modeling platform that can be used to compare different solutions.

In summary, taking a holistic comparison perspective including a wide range of congestion management solutions can contribute to identify a suitable combination of solutions. The suitable combination of solutions is highly dependent on the test-system. Therefore, presenting a comprehensive toolbox to support implementing a systematic comparison of various solutions on different test-systems can be valuable. The toolbox can consist of two parts: 1) a qualitative analytical framework to identify the barriers of implementing different solutions; 2) a scalable and extendable modeling and demonstration platform to quantitatively assess various solutions on different test-systems.

2.5.2 Operation of local flexibility resources for carbon emission reduction

There exist studies on multi-objective optimization considering both cost and emissions with different energy carriers. However, a study that specifically identifies emission abatement strategies from multi-objective optimization models and evaluates the abatement cost for these strategies could not be found. In addition, no previous study has been found that multi-objectively optimizes the three energy carriers (i.e., electricity, district heating, and district cooling) using a short foresight rolling horizon over a year.

In summary, a study that identifies the emission abatement strategies and their cost could provide insights on carbon pricing and investigate the possibilities of operating local MESs in a more environmentally responsible manner. In addition, the benefit of considering the above-mentioned three energy carriers is that synergies can be captured for emission abatement through technologies such as heat pumps and absorption chillers.

2.5.3 Operation of local flexibility resources for participation in FCR markets

The literature has underscored a few important aspects for the participation of BESs in FCR markets. These include studying battery degradation, multi-market decision making, and the inclusion of the technical requirements for FCR markets. However, the authors have not come upon a study that simultaneously includes all of these aspects.

In summary, contributions can be provided by a study and a novel MILP model for revenue stacking in Sweden's DA and the three FCR markets, considering technical requirements and comprehensive battery degradation modeling including both calendar and cycle aging.

CHAPTER 3

Research approach

This chapter presents the overarching methodologies and the utilized methods besides their link to the research questions and the papers.

The research approach taken for answering the research questions include two methodologies: Design Research and Operation Research. As shown in Figure 3.1, Part 1 requires Design Research methodology to design the incentive mechanism (i.e., LFM) while Operation Research methodology is needed to model agents' behavior and operation in all three parts. In this chapter, these methodologies and their relevance are elaborated in Sections 3.1 and 3.2. Thereafter, different utilized means/methods in the methodologies are explained in Section 3.3.

3.1 Design research for LFM design

Design is a complex, multidimensional phenomenon that involves: people, a multitude of activities and procedures, a variety of disciplines, tools and methods; as well as a micro-economic context [99]. This complex nature of design can lead to diverse research topics and methods, which if not organized under an overarching methodology, can lead to multiple unconnected streams [99] and therefore reduce

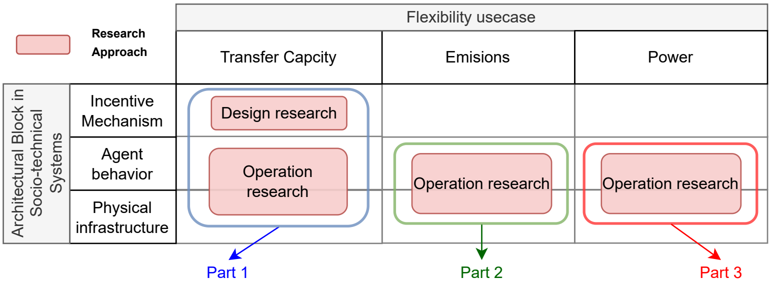


Figure 3.1: Utilized overarching research approaches for each focus

the potential for value delivery.

The complexity and multi-dimensional nature of design highlight the need for an overarching methodology. The Design Research methodology aims at understanding and improving design and requires: (1) a model/theory of the existing situation, (2) a vision (model/theory) of the desired situation, and (3) a vision of the support/solution that can transform the existing situation into the desired and maintain it [99].

LFM design falls under the design research area due to its multifaceted nature, and the broadness of the research questions and design space.

Blessing et al. [99] propose a generic set of steps for design research methodology. This is utilized as the overarching methodology in this thesis for structuring the design procedure of LFM. The overview of the methodology is presented in Figure 3.2 and includes four main stages:

1. **Research Clarification**: This is to find indication and evidence to formulate a realistic and promising research goal. It is mainly done by literature study. An initial description of the existing situation and a description of the desired situation will be developed.
2. **Descriptive Study I**: Having a clear goal, more influencing factors are identified to elaborate the existing situation. It aims to to determine the factors that should be addressed to improve the situation. As an outcome, a better understanding of the situation will be developed.
3. **Prescriptive Study**: Having a clear understanding, a vision is developed for improving the situation using one or more factors identified in the previous stage. The outcome would be a support/solution to improve the existing situation towards the identified desired situation.
4. **Descriptive Study II**: To investigate the impact of the prescribed sup-

port/solution and evaluate its success.

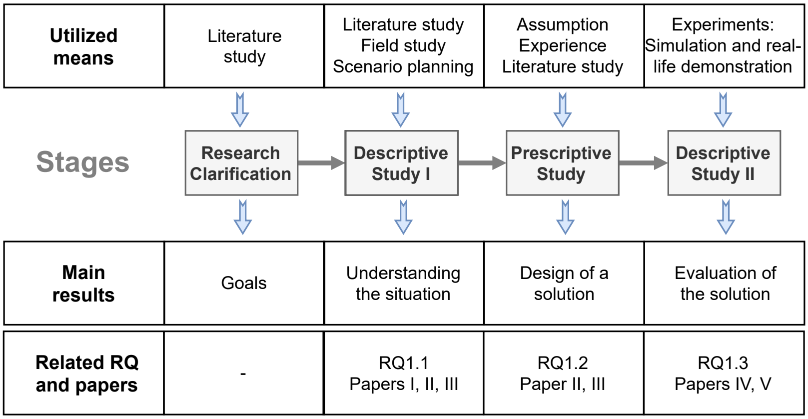


Figure 3.2: Overview of the applied design research methodology (Adapted from [99]). The bold arrows between stages show the main process flow.

To put the methodology in perspective, related RQs and papers for each stage are presented in Figure 3.2. The literature has been reviewed in Stage one to better understand the state-of-the-art, clarify the purpose of the work, and define the research questions. **RQ1.1** focuses on identifying the challenges and key factors in LFM design and is thus covered in Stage two which aims to identify the factors that should be addressed to improve the existing situation. **Paper I** and parts of **Papers II** and **III** discuss these factors and challenges. **RQ1.2** is about proposing a market design that addresses the identified challenges and is therefore covered in stage three, which aims to prescribe a solution to improve the existing situation. **Papers II** and **III** are two published iterations on the solution. **RQ1.3** is about design evaluation and is covered in stage four which aims to investigate the impact of the proposed solution. This research question is an ongoing work, and **Papers IV** and **V** are the tools that enable such an evaluation.

The presented methodology covers the design of the incentive mechanism, i.e. LFM. However, the agents' behavior and their decision making need to be modeled as well. This falls into operation research, which is explained in the following section.

3.2 Operation research for optimal operation and decision-making

Operation research is "a collection of conceptual, mathematical, statistical, and computational modeling techniques used for the structuring, analysis, and solving of problems related to the design and operation of complex human systems" [100]. Quantitative modeling has been mentioned as the basis for most research in the field where "the relationship between control variables and performance variables are developed, analyzed, or tested" [101]. In this thesis, modeling agents' response to an incentive mechanism or extracting their optimal operation strategy falls into the operation research field. In this application, the control variables can be DERs setpoints or agents' bids, while performance variables can be operation costs, revenues, and carbon emissions.

Will et al. [101] categorize this model-based research into two classes: empirical quantitative modeling research and axiomatic quantitative modeling. The Empirical class aims to find and explain the relationship between the performance and control variables while the axiomatic class aims to obtain solutions within the defined model and make sure that these solutions provide insights into the structure of the problem as defined within the model. The operation research in this thesis is under the second class because the aim is to find the optimal operation and extract potential behaviors instead of finding the relation between performance and control variables based on real-life empirical data.

Conducting an axiomatic quantitative modeling includes:

1. conceptualizing and specifying the scientific model of the problem,
2. solving the problem and proving its optimality, and
3. reflecting on the solution and its link with the model concept.

In this thesis, optimization is used in **RQ1.2** and **RQ1.3** for LFM clearing, and for the bidding and scheduling of FSPs, in **RQ2** for multi-objective operation planning of multi-energy system, and in **RQ3** for cost optimal decision making of battery owner considering the market prices and rules, battery degradation, and technical requirements. **Papers III**, **VI**, and **VII** include the conceptualization and relevant model formulations. The problem formulations are mixed-integer linear programming and are solvable using commercial solvers such as Gurobi. Reflections on the solutions are presented in each paper.

3.3 Utilized methods

The methodologies presented can be seen as overarching frameworks that connect various methods required at different stages in the methodologies. The utilized methods are:

- Literature review
- Field studies
- Scenario planning
- Mathematical optimization
- Experiments including simulations and real-life demonstrations

Literature review is an essential part of all the stages. Field studies have been used as a complementary method to literature review. It includes meetings and workshops with different actors for identifying key factors concerning each research question and keeping the work relevant to real-life applications. Scenario planning methods have been used to rank the impact and uncertainty of the key factors to develop potential scenarios for the future of local markets. Mathematical optimization is an essential piece of the puzzle for formulating market clearing algorithms, and modeling agents' behavior and extracting their optimal operation. Computer simulations and real-life demonstrations have been used as experiments that cover implementation and evaluation of market designs and operation strategies.

Literature review, field studies, and mathematical optimization are rather well known. However, the utilized scenario planning method may be less known to readers. Moreover, the experiment setup including simulations and real-life demonstrations is case-specific. These two methods are further elaborated in the rest of this section.

Scenario planning

Scenario planning has contributed to answering **RQ1.1** especially concerning the uncertainty and impact of the key factors/trends and future scenarios for LFMs development. Scenario planning methods can be used to explore key factors and trends and provide insight to different stakeholders. Scenarios are possible forms of future that provide narratives for a context and facilitate decision-making [27]. However, it is important to keep in mind that scenarios are not predictions of the future, but rather an exploration of the drivers of change and multiple plausible future situations [27], [28]. Scenario planning provides a structured conversation to familiarize decision-makers with uncertainties and to build a shared understanding of such uncertainties [29].

Three main schools of techniques for developing scenarios are intuitive logics, probabilistic modified trends methodology, and the French approach La prospective

[102], [103]. Each of these techniques has been evolved in different institutes to achieve specific purposes. The intuitive logics school is one of the most dominating methods for scenario development, and has received a lot of attention in the literature for scenario planning [102]. This approach was originally used by Pierre Wack at Shell in the 1960s [102]. The purpose of this method is to make sense of situations and developing strategies, while it can also be an ongoing learning activity [102]. It has been chosen for the work in this thesis as it is a process-oriented methodology and it aims to provide insights into an on-going learning activity. This approach does not require complex computer-based analysis [102] and can be used as initial input for designing a concept. The output is a set of plausible qualitative scenarios in a narrative form. This set of equally plausible scenarios include strategic options, implications and early warning signals [102] which can be used as input to different stakeholders involved in designing the local markets.

The utilized approach for defining the scenarios based on the intuitive logics school is a process proposed by Conway [104]. This approach is a more generic form of approaches proposed by Schwartz [105] and the Stanford Research Institute International (SRI) [106], [107]. The approach is explained in details **Paper I**. Here, the overview of the approach is explained to facilitate understanding of the presented scenario matrix in Section 4.1.

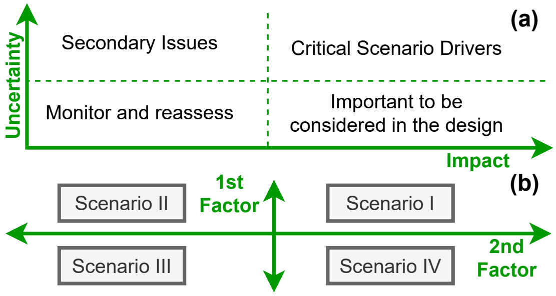


Figure 3.3: Factors ranking and scenario matrix: (a) uncertainty-impact ranking (modified figure from [31], [104]), (b) scenario matrix based on the two most uncertain and impactful factors

In summary, the approach starts by providing a list of key factors or trends impacting the future of LFMs. These factors and trends are then ranked based on their impact and uncertainty utilizing a survey and workshops with experts in the field. The results can be organized in the form of Figure 3.3a and further narrowed down by scores from a cross-impact analysis [108] that explores the impact of factors on each other. The most impactful but less uncertain factors are highly suggested to be considered while designing the project outputs. Factors with high uncertainty but low impact are secondary issues. Less impactful and less uncertain factors are to monitor and reassess if needed. The two most impactful and uncertain factors are used for forming the two axes of a four-quadrant scenario matrix (Figure 3.3b). The extreme ends of each axis describe a world based on the uncertainty of the factor/trend. This leads to four different worlds (scenarios) that are further assessed and described to build a narrative, identify the implications of the narratives. The relevance and plausibility of the narratives and their implications are then checked with a group of experts in the field.

Experiments

The experiments have been conducted through two means, computer simulations and real-life demonstrations. The details of experiment setups have been explained in **Papers III-VI**. However, to provide an overview to the reader, the utilized test-systems, data, and the developed modeling platform are presented in this section.

Two test systems have been used in this thesis: CIGRE's European Low Voltage Distribution Network [109] (**Paper III**), and Chalmers Campus Testbed [110], [111] (**Papers IV-VI**). The case-study in **Paper VII** comprises a 1MW-1MWh battery located in the SE3 bidding area of the Nordic electricity market.

The residential subnetwork of CIGRE's European Low Voltage Distribution Network is chosen because of potential for conducting comparable studies and benchmarking. However, in this network, neither the load is flexible nor the components of the residential subnetwork are congested. Therefore, the loads were replaced by six agents, of which 4 are flexible. In addition, the transformer rating had to be reduced. For this test system, load data are taken from [112] and a local DSO in Sweden, and solar radiation data is obtained from [113].

The Chalmers testbed is chosen because of the availability of data and the possibility of conducting real-life demonstrations. A subarea of the testbed that is used to evaluate the LFM design is presented in **Papers IV** and **V**. In the case study of **Paper VI**, the entire campus is considered, including district heating and district cooling systems, as explained in detail in **Paper VI**. The subarea utilized to evaluate the LFM design is smaller due to the higher complexity of the required ecosystem for evaluating the LFM. The smaller area facilitates troubleshooting and elaboration of the results.

To switch between simulation and demonstration studies for LFM evaluation, and to compare different congestion management solutions, a reusable modeling platform is required. Moreover, various tools (e.g., energy management system, congestion forecasting, bidding and market clearing algorithms, and communication functions with the physical layer) need to be integrated in the same platform. Therefore, the Local Energy System Object-Oriented Programming (LESOOP) platform has been developed as a part of the answer to **RQ1.3**. LESOOP has a reusable structure and can host various tools. The overview of LESOOP's architecture and functionalities is provided in Section 4.3 and the details are provided in **Paper IV**.

An example of LESOOP's application in evaluating the LFM design is presented in Section 4.3.1. The example is not published, and the details of the setup utilized are provided here. The one-line diagram of the utilized network is presented in Figure 3.4 which is a 10.5kV network. To impose congestion, the capacity of the line between buses 07:8.1 and 07:8.1.2 is reduced by 85%, to 927 kVA. A lagging power factor of 0.95% is assumed for the loads. Three agents are defined as presented in Table 3.1. The specifications of the PV and the battery energy storage (BES) of the agents are presented in Table 3.2. At this stage, the results are obtained assuming perfect forecasts for loads and PV generation.

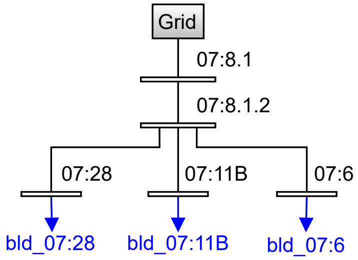


Figure 3.4: One-line network diagram and agents' locations in the Chalmers testbed sub-area that is used for the most recent results presented in Section 4.3.1

The algorithms used for the bidding of the agents are as presented in **Paper III**. The economic parameters used in the algorithms of the agents are presented in Table 3.3 that includes power tariffs ($\rho^{\mathrm{P}_{\mathrm{tariff}}}$) for the largest peak in the month, grid energy tariffs ($\rho^{\mathrm{gridtariff}}$), energy tax ($\rho^{\mathrm{tax}}$), tax returns ($\rho^{\mathrm{taxreturn}}$) in the case of export of energy to the grid, and connection capacity fee (ρ^{CC}). ρ^{CC} is based on the average of the fees from a DSO in Sweden [114]. $\rho^{\mathrm{gridtariff}}$ is based on the average of the grid tariffs for apartments and houses from [115].

Table 3.1: Agents' definition in the most recent results presented in Section 4.3.1

Agent id	Bus	Connection Capacity	Flexible	DERs
$\text{bld}_{07:28}$	07:28	1000	Yes	3 InflexLoads, 1 BES
$\text{bld}_{07:6}$	07:6	1000	No	2 InflexLoads, 1 PV
$\text{bld}_{07:11B}$	07:11B	1000	Yes	2 InflexLoads, 1 PV, 1 BES

Table 3.2: DERs specifications in the most recent results presented in Section 4.3.1. $\overline{e}^{bes}$: BES energy capacity, $\overline{p}^{bes,dch}$: BES maximum discharging power, $\overline{p}^{bes,ch}$: BES maximum charging power, $\overline{p}^{pv}$: PV nominal power

DER ID	Agent	$\overline{e}^{bes}$	$\overline{p}^{bes,dch}$	$\overline{p}^{bes,ch}$	$\overline{p}^{pv}$
$\text{bes}_{07:28}$	$\text{bld}_{07:28}$	250 kWh	95 kW	60 kW	-
$\text{bes}_{07:44}$	$\text{bld}_{07:11B}$	65 kWh	25 kW	25 kW	-
$\text{pv}_{07:11}$	$\text{bld}_{07:11B}$	-	-	-	73 kW
$\text{pv}_{07:6}$	$\text{bld}_{07:6}$	-	-	-	38 kW

Table 3.3: Economic parameters used for the most recent results presented in Section 4.3.1

$\rho^{\text{P}_{\text{tariff}}}$ (SEK/kW, month)	$\rho^{\text{gridtariff}}$ (SEK/kWh)	ρ^{tax} (SEK/kWh)	$\rho^{\text{taxreturn}}$ (SEK/kWh)	ρ^{CC} (SEK/kW)
36.25 [115]	0.31 [115]	0.36 [116]	0.6 [117]	0.17[114]

CHAPTER 4

Summary of the main results and discussions

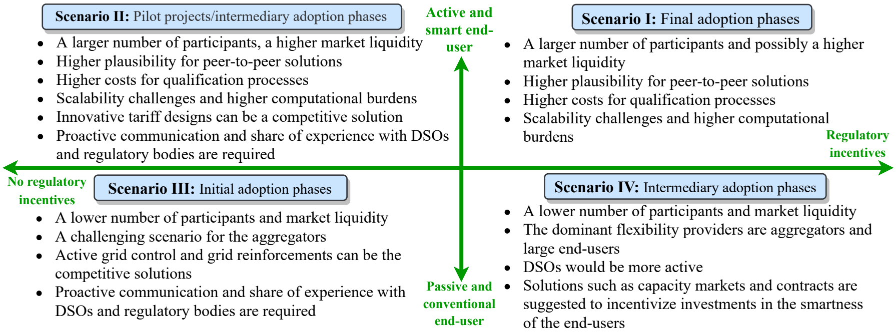
This chapter summarizes and discusses the main results corresponding to the research questions.

4.1 RQ1.1: Key factors, design challenges, and future scenarios for LFMs

RQ1.1 aimed to identify the influencing factors, trends, and design challenges for LFMs besides developing scenarios for the future of LFMs based on the most impactful and uncertain factors/trends. The results for RQ1.1 can facilitate a better understanding of the situation and the aspects to be considered in the design.

Twenty key factors/trends have been identified and presented in **Paper I**. Utilizing scenario planning and surveys, these factors/trends are ranked in the paper based on their impact and uncertainty. The three most uncertain and impactful factors/trends are found to be i) availability of smart and digital end-users, ii) tendency of end-users for active participation, and iii) positive changes in regulatory incentives for DSOs.

A scenario matrix, which forms four scenarios, is made based on the three factors mentioned above. In Figure 4.1, the Y-axis of the matrix represents two characteristics of end-users. The first characteristic is whether end-users are willing to participate in local markets (being active or passive), and the second is whether end-users are automated, digital, and can have a fast and precise control over their flexible assets or not (being smart or conventional). The X-axis represents the existence of regulatory incentives for DSOs to promote local markets. Due to the monopolistic nature of DSOs, there are regulations that financially regulate DSOs. These regulations can favor capital expenditures over operation costs. Therefore, investing in infrastructure can be financially more attractive for DSOs than using operational measures such as local markets. Changes in the regulatory framework have a profound impact on the deployment of LFMs. The scenarios developed are explained in Figure 4.1 and in details in **Paper I**.



Scenario II: Pilot projects/intermediary adoption phases
- A larger number of participants, a higher market liquidity
- Higher plausibility for peer-to-peer solutions
- Higher costs for qualification processes
- Scalability challenges and higher computational burdens
- Innovative tariff designs can be a competitive solution
- Proactive communication and share of experience with DSOs and regulatory bodies are required

Scenario I: Final adoption phases
- A larger number of participants and possibly a higher market liquidity
- Higher plausibility for peer-to-peer solutions
- Higher costs for qualification processes
- Scalability challenges and higher computational burdens

Scenario III: Initial adoption phases
- A lower number of participants and market liquidity
- A challenging scenario for the aggregators
- Active grid control and grid reinforcements can be the competitive solutions
- Proactive communication and share of experience with DSOs and regulatory bodies are required

Scenario IV: Intermediary adoption phases
- A lower number of participants and market liquidity
- The dominant flexibility providers are aggregators and large end-users
- DSOs would be more active
- Solutions such as capacity markets and contracts are suggested to incentivize investments in the smartness of the end-users

Figure 4.1: Scenario matrix for the future of local flexibility markets

In **Paper III**, five main challenges are identified to better understand the state-of-the-art and a better proposal for market design. The challenges are identified based on literature review, field studies, and experiences from similar projects. These challenges are:

1. Low market liquidity
2. Reliability concerns
3. Challenges regarding defining baselines for a baseline-based flexibility product
4. Forecast errors due to low aggregation levels
5. The high costs concerning the need for extra measurements and ICT infrastructure.

The challenges have been explained in detail in **Paper III** and Section 2.2.2.

The identified challenges are closely related to the uncertainty shown in the Y-axis of the scenario matrix. The uncertainty is whether flexible assets are accessible to be involved in local markets. LFM designs that do not consider measures to improve LFM reliability, handle forecast errors, and solve potential conflicts due to baselines are prone to lower liquidity and potential failures. The design challenges are not directly linked to the uncertainty in the X-axis because the lack of regulatory incentives for DSOs can profoundly undermine the existence of LFMs. Therefore, the question of LFM design and its challenges would be less relevant in a future where regulatory incentives are not in place for DSOs.

The identified key factors and challenges in RQ1.1 can be utilized for a more functional LFM design and thus a more successful implementation. In the next section, an LFM design that considers these challenges is proposed 4.2.

4.2 RQ1.2: A comprehensive LFM design

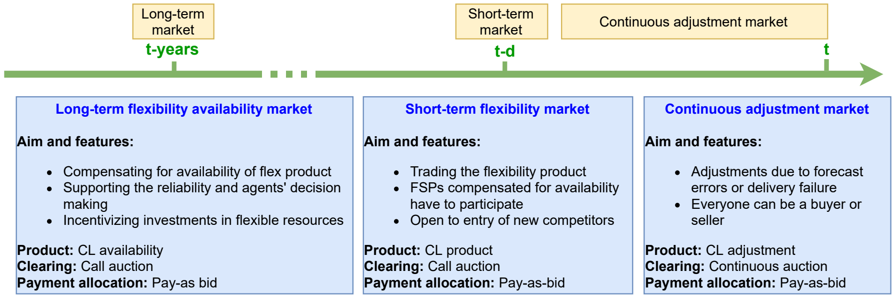
The aim of RQ1.2 has been to propose an LFM design that considers the identified challenges in RQ1.1. For this purpose, multiple design iterations have been done of which two are published in **Papers II** and **III**. The latest iteration is **Paper III**. This iteration has used and further improved part of the ideas from the design in **Paper II**. Therefore, the rest of this section focuses on the latest design, **Paper III**.

The overview of the proposed design in **Paper III** is presented in Figure 4.2. The traded products are adapted CL-products from [13] that result in end-users keeping their net-loads under a cap, or above a floor depending on if a congestion event is driven by the excess of demand or generation. The net-load (P^{net}) is defined in Equation (4.1) for each FSP where P^{con} is the consumed power and P^{gen} is the generated power. The design is organized in three markets. The long-term market aims to compensate for the availability of flexibility, similar to capacity mechanisms in electricity system [118]. In the short-term market, the flexibility product is traded. The continuous adjustment market is an intraday market for adjusting the quantities traded in the short-term market. The markets are double-sided auctions with social welfare maximization as their objective functions. The first two markets are call-auctions and the third is a continuous auction. Pay-as-bid (PAB) is chosen as the payment allocation method. The arguments for the choices above and the trade-offs are discussed in detail in **Paper III**.

$$P_t^{\text{net}} = P_t^{\text{con}} - P_t^{\text{gen}}, \quad \text{where} \quad P_t^{\text{con}}, P_t^{\text{gen}} \geq 0 \tag{4.1}$$

The proposed product design consists of two types depending on whether congestion is demand- or generation-driven. Demand-driven congestion occurs when the total power extraction of end-users causes overloading of a grid component. For generation-driven congestion, total power injection causes overloading in addition to potential voltage-limit violations. Consequently, the proposed CL products are:

- CL-cap (for demand-driven congestions): Enforces flexibility service providers



Long-term flexibility availability market

Aim and features:

- Compensating for availability of flex product
- Supporting the reliability and agents' decision making
- Incentivizing investments in flexible resources

Product: CL availability
Clearing: Call auction
Payment allocation: Pay-as bid

Short-term flexibility market

Aim and features:

- Trading the flexibility product
- FSPs compensated for availability have to participate
- Open to entry of new competitors

Product: CL product
Clearing: Call auction
Payment allocation: Pay-as-bid

Continuous adjustment market

Aim and features:

- Adjustments due to forecast errors or delivery failure
- Everyone can be a buyer or seller

Product: CL adjustment
Clearing: Continuous auction
Payment allocation: Pay-as-bid

Figure 4.2: Overview of the market horizons

(FSPs) to keep their net-load under a certain cap.

- CL-floor (for generation-driven congestions): Enforces FSPs to keep their net-load above a certain floor.

The CL-products are defined using net-load (p^{net}) and subscribed connection capacity ($\overline{P}^{\text{net}}$) of FSPs. As shown in (4.2a), by selling q kW of CL-cap, an FSP should restrict its p^{net} by q kW with respect to $\overline{P}^{\text{net}}$. A similar logic is presented in (4.2b) where the FSP keeps its p^{net} above a certain floor. Figure 4.3 illustrates the products for three FSP types: consumer, prosumer, and generator. p^{net} is always negative for generators. So, if a flexible generator has sold a CL-cap, it might need to increase its generation that contributes to relieving a demand-driven congestion. p^{net} is always positive for consumers. Therefore, if a flexible consumer has sold a CL-floor, it might have to increase its consumption that contributes to alleviating a generation-driven congestion.

$$p_t^{\text{net}} \leq \overline{P}^{\text{net}} - q_t^{\text{CLcap}} \tag{4.2a}$$

$$p_t^{\text{net}} \geq -\overline{P}^{\text{net}} + q_t^{\text{CLfloor}} \tag{4.2b}$$

The proposed product design has several advantages: i) calculation of its quantity is not with respect to a baseline and instead, is calculated with respect to the static and transparent values of connection capacities that can provide a certainty for DSOs regarding the cap for cumulative loading after flexibility procurement; ii) the product is technology neutral because it does not impose the method for changing the net-load. FSPs, therefore, can find the most cost-efficient method; iii) it hinders the potential manipulation by not declaring flexible assets (mentioned in [13]) because it is defined and verified by the net-load and is not dependent on the declaration of flexible assets; and iv) it does not require ICT systems for gathering and managing submeter measurements and thus leads to lower ICT-related costs.

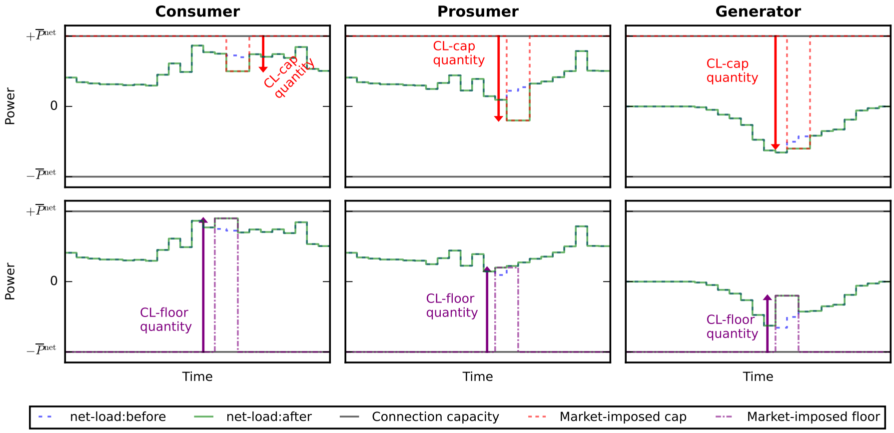


Figure 4.3: Conceptual illustration of capacity limitation products for different type of grid users. CL-cap is for demand-driven congestion and CL-floor for generation-driven congestion.

On the other hand, the CL product is accompanied by challenges including its potential heterogeneity, and consequently complexities in bidding and clearing algorithms. CL product is most likely not homogeneous. Oxford dictionary of economics [119] defines heterogeneous goods as "Goods which differ in specifications or quality, or bear different brand names which convey information to customers". Although the specification and the unit of the CL product is consistent, i.e. limiting connection capacity by 1 kW, its "quality" varies. The quality of a CL product can be defined based on its purpose to change the net-load of FSPs and thus reducing congestion. Procured CL quantity can have two qualities. One part does not have an impact on the net-load of FSPs because it only covers their unused connection capacity. This segment offers low utility to the DSO. The remaining quantity exhibits higher quality as it alleviates congestion and provides greater utility to the DSO. Homogeneity is a fundamental assumption in microeconomics, and most supply and demand models "simply assume that all goods in the market are identical" [120]. Therefore, the law of demand does not necessarily need to hold in the case of a heterogeneous good such as the CL product. Figure 4.4 illustrates the expected marginal utility and cost curves for when utilized and unutilized capacities were traded separately versus when they are traded together. When traded separately, marginal utility and cost for unutilized capacity are expected to form a flat curve since they do not affect FSPs' behavior. The marginal utility and cost of utilized capacity are expected to have a downward and upward slope, respectively. This is because as more is purchased by the DSO, the overloading would be lower, and as more is sold by an FSP, the deviation from its cost-optimal behavior grows. When these two "quality" classes are traded together, the demand curve of the product becomes heterogeneous, resulting in a non-downward sloping demand curve for the DSO. This potential heterogeneity leads to complexities in the bidding and clearing algorithms, which are discussed in **Paper III**.

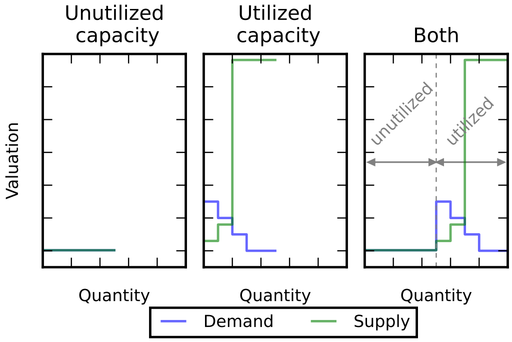


Figure 4.4: Heterogeneity of the CL product

The summary of measures to address the design challenges is as follows:

- **Challenges 1 and 2 (the low liquidity and reliability concerns):** The design contributes to increasing the liquidity in LFMs and reducing the reliability concerns by allowing multi-bids (i.e., bidding as curves), and incentivizing participation by an interconnected long-term market for availability;
- **Challenges 3 and 5 (the baseline issue and ICT costs):** A new capacity limitation product is introduced with suggestions on algorithms for quantifying its cost/value. The new product addresses the baseline challenge, and mitigate deficiencies of previous capacity limitation products regarding market manipulations through misreporting of the flexible assets, and high ICT costs related to measurements for delivery validation;
- **Challenge 4 (the forecast errors):** An interconnected adjustment market is included and different aspects are discussed to find a suitable auction type for addressing the forecast errors on low aggregation levels. Moreover, a probabilistic bidding algorithm is proposed for calculating the expected marginal utility of DSOs.

Despite the solutions presented, low market liquidity might persist due to geographical constraints and reasons not related to mechanism design. In this work, the provided solutions are focused within the mechanism design area. Causes outside of the mechanism design can be geographical constraints, barriers to digitalization and automation, bureaucratic prequalification procedures, lack of relevant competences, and contradictory or unclear regulations. Solution to these causes are beyond the scope of this work and can be a future work. For example, the liquidity can be improved if the market is utilized for larger geographical areas while leaving issues at lower levels to be solved by other methods such as grid reinforcement and tariff design. Evolutionary game theory can be used to analyze agents' strategic behavior as a function of the number of participants to find an approximation on the suitable geographical size for LFMs. A similar study to [121] can be done for this purpose.

Furthermore, There are other alternatives to the proposed design. An alternative is a reversed one-sided auction in which the DSO purchase by the merit order until the congestion is solved. However, in one-sided auctions, the willingness of DSOs for payment is not included and thus high costs might be imposed on DSOs. Another alternative design to LFMs are local capacity markets (also known as tradable access rights). In such mechanisms, a fixed amount of available connection capacity can be auctioned or grandfathered and then the connection capacity can be directly traded between the consumers and the DSO. Similar ideas have been discussed in [122]–[124]. A potential challenge for this alternative is consumer discrimination concerning capacity prices at different geographical locations. An alternative to market-based solutions is tariff-based solutions. There exist different types of tariffs such as time-of-use (ToU) tariffs and power tariffs. ToU tariffs, if used for reflecting the local grid constraints, can lead to consumer discrimination since they can differ depending on the consumers' location. Moreover, tariffs such as static ToU and power tariffs cannot cover unexpected events or adjustments and can also lead to rebound effects by shifting congestion to other hours. The discrimination also exists for LFMs since the opportunity for revenues from LFMs is only available to FSPs located in specific geographical areas with congestion issues. This can be especially discriminating towards end-users located at non-congested areas because DSOs pay FSPs through the collected grid tariffs from consumers located at both congested and non-congested areas. A potential measure addressing the discrimination issue can be varying the fixed part of the grid tariffs depending on the status of the grid where end-users are located. Consequently, studying a combination of solutions such as different tariff designs and market-based solutions would be valuable for finding the most social optimal solution [4].

The most suitable congestion management solution depends on the context, including various parameters such as the size of the grid and DSOs, regulations, social aspects, the load patterns and its expected rate of increase, lead-time and cost of grid reinforcements, and availability of technical infrastructure. Consequently, it is essential to contextualize LFMs and compare them with alternative solutions within each specific context to identify the most appropriate option or combination of options.

4.3 RQ1.3: Evaluation of the LFM design

In RQ1.3, the goal has been to develop the means for evaluating the proposed LFM design, including a comparison with other congestion management solutions. This thesis proposes a comparison toolbox in **Paper IV** for qualitative and quantitative comparison with other solutions. The Chalmers Campus testbed is enhanced (**Paper V**) for real-life demonstrations. This section explains the proposed modeling and demonstration platform for evaluating the design and the required testbed improvements that are implemented. An example using the comparison toolbox is presented in Section 4.3.1.

Furthermore, the notion of a capacity-limitation product has gained industry attention and has been under evaluation through real pilots in Sweden. Gothenburg's DSO, Göteborg Energi Nät, together with NODES, a commercial LFM operator, have launched a flexibility product called Max Usage in 2024, which has shown potential for upscaling [125]. The product is noted for its simplicity and minimal administration [126]. The Uppflex project has surveyed Swedish actors on their preferences on LFM design, showing that most of the study participants were positively disposed to the capacity-limitation product [127]. The product has been particularly interesting for charging infrastructure providers, offering a predictable and adaptable method for future flexibility provision business models [127].

The proposed comparison toolbox in **Paper IV** enables a systematic comparison of different congestion management solutions for local system challenges. It consists of two parts: i) a qualitative analytical framework to identify barriers in regulatory, technical, cultural, and complexity aspects; and ii) a scalable and extendable modeling platform called LESOOP to quantitatively assess solutions under the same system conditions.

LESOOP is developed for the application area of local energy system studies. To conduct such studies, the platform needs to be flexible with respect to test systems configuration, agents' definition and behavior, and solutions for the local challenges. Therefore, the ecosystem of local energy systems is defined by four main domains in the platform:

- **Network domain**: To represent different energy networks such as electricity, district heating, district cooling
- **Agent domain**: To represent the different type of agents such as households, industries, aggregators, and DSOs.

- **DER domain**: To represent the different energy assets such as storage, heat pumps, PVs, and inflexible loads
- **Solutions domain**: To represent the different solutions to local network challenges, e.g. LFMs, LEMs, etc.

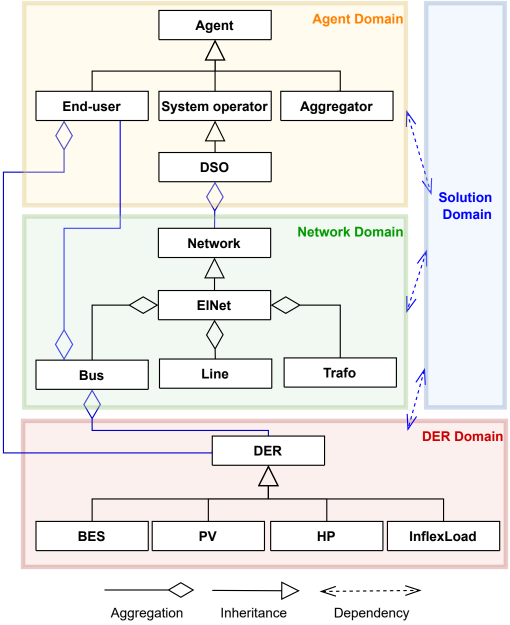


Figure 4.5: Overview of the domains and examples of their content in the form of a UML class diagram

Figure 4.5 presents an overview of the domains and their content as a Unified Modeling Language (UML) diagram. The solution domain is shown as an empty block it varies with the concept under study. The abstract classes can be seen on the higher levels of hierarchies in each domain. For example, the Agent superclass can have subclasses such as End-user, System operator, and Aggregator. The End-user class represents the individual end-users that are connected to the grid. It can be inherited by subclasses such as residential, industrial, and commercial end-users that can have their specific methods and DERs. The domains are connected to each other with the aggregation relationship, showing the association between objects. For example, a DSO may own one or multiple networks, each end-user could own one or multiple DERs, while each DER and end-user are connected to a bus.

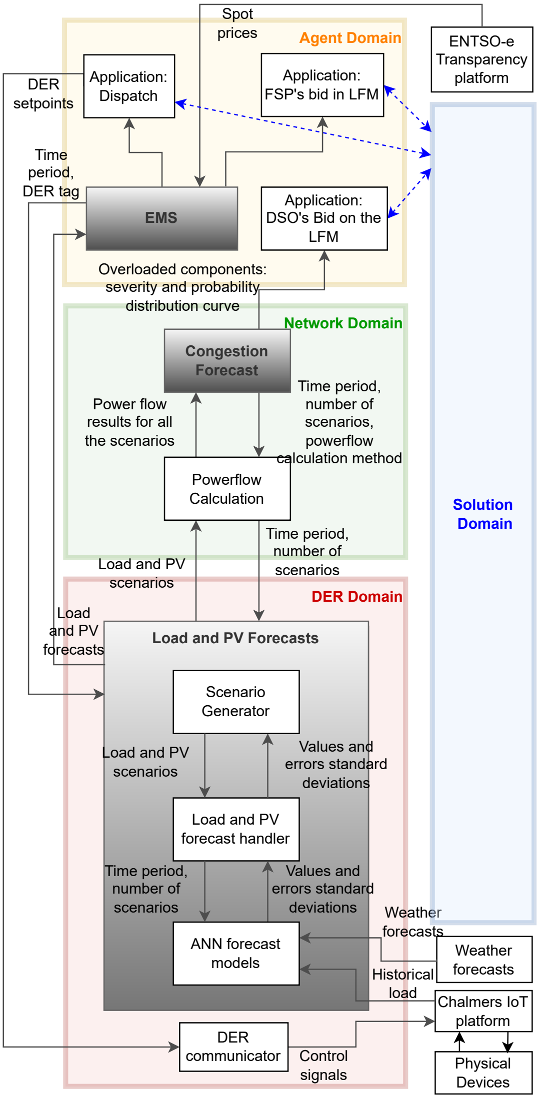


Figure 4.6: Overview of the required tools for demonstrating LFMs in Chalmers Campus testbed

This design makes the platform flexible and reusable for investigating different test systems and case studies. This can be done by initializing instances of different classes separately depending on the specific need of a study. For example, to compare agent-based mechanisms such as LFM and LEM, instances of classes from all domains are needed. The decomposed domain structure of LESOOP allows different solution blocks to be written separately and replaced while keeping the rest of the domains constant. This provides the possibility of comparing the different solutions. The platform can also be used for other purposes. For Building Energy Management System (BEMS) studies, only instances of the End-user class and the DER subclasses need to be initialized. In the case of a Model Predictive Control or a congestion forecast study, subclasses in the Network and DER domains would be sufficient.

Furthermore, multiple tools are needed to assess a solution. A quantitative assessment needs, for example, forecasting the production/consumption of DERs, estimating the power flow and congestion risk in grids, and simulating agents' behavior and control logic. These tools are implemented in the platform as class methods. To increase reusability, some tools are composed of a group of methods and are written as generic as possible to be independent of a specific application.

The improvements of the Chalmers Campus testbed are presented in **Paper V**. They include developing and integrating the tools required for the demonstration in LESOOP. The tools are, for example, forecasting tools for load, PV, and congestion, energy management systems (EMS) and bidding algorithms to enable evaluation of the proposed LFM under more realistic conditions. The overview of integrating these tools into LESOOP, including their communication and related applications, is presented in Figure 4.6.

4.3.1 Using LESOOP to evaluate LFM design: a case study

This section presents an example of using LESOOP to compare the LFM design with other congestion management solutions. The setting of the example has been explained in Section 3.3. The short-term activation market of the design is evaluated for the period of 2023-02-02 to 2023-03-01 using perfect forecasts. The evaluation includes running the explained setup for four cases: LFM+PT+ET, LFM+ET, PT+ET, and ET. LFM+PT+ET is when LFM, power tariffs (PT), and energy costs (ET) are considered simultaneously. The rest of the cases follow the same logic showing which economic incentives are considered.

The load-duration curves for the active power loading of the line between buses 07:8.1 and 07:8.1.2 are presented in Figure 4.7. Since the traded flexibility product is based on the active power, the loading is presented as the percentage of the active power limit of the line to have a more accurate analysis on the impact of the LFM. The active power limit of the line is 882 kW, which is approximated by multiplying the capacity of the line (927 kVA) by the assumed power factor of 95%. The comparison of the cases can be done by two indicators: a) the number of congested hours, and b) the severity of the congestion.

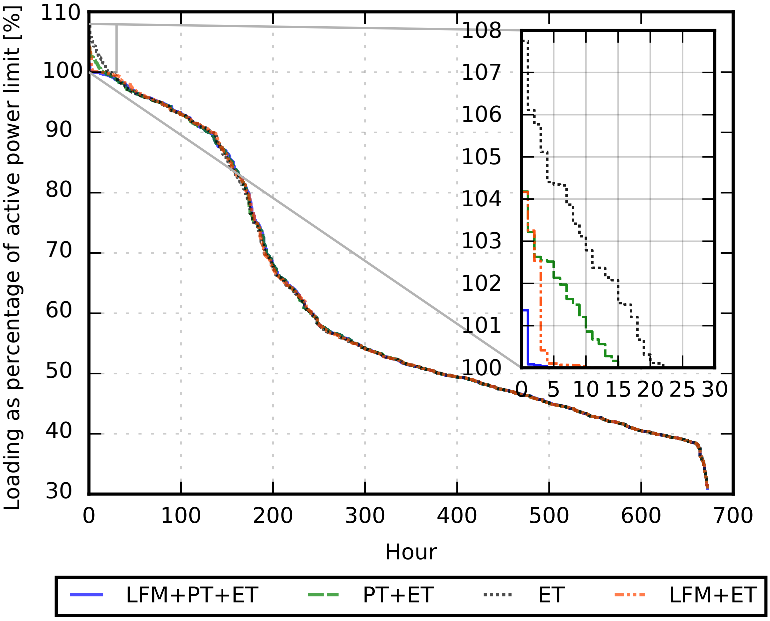


Figure 4.7: The active power load duration curve of the line between buses 07:8.1 and 07:8.1.2 for four cases: LFM+PT+ET: LFM, power tariffs, and energy cost, LFM+ET: LFM and energy cost, PT+ET: power tariffs and energy cost, ET: only energy cost.

The number of congested hours is reduced from 22 in case ET to 15 in case PT+ET, 9 in case LFM+ET, and 3 in case LFM+PT+ET. Moreover, Figure 4.8 shows that the two cases related to LFM have a higher incidence of loading just below the line capacity compared to the other two cases. This is due to the activation of LFM that has shifted the overloading to values less than the line capacity.

The severity of congestion can be indicated by the area under each load duration curve in Figure 4.7. The calculated area is limited to the congested hours and the 100% limit for a clearer comparison. The values of this indicator are presented in

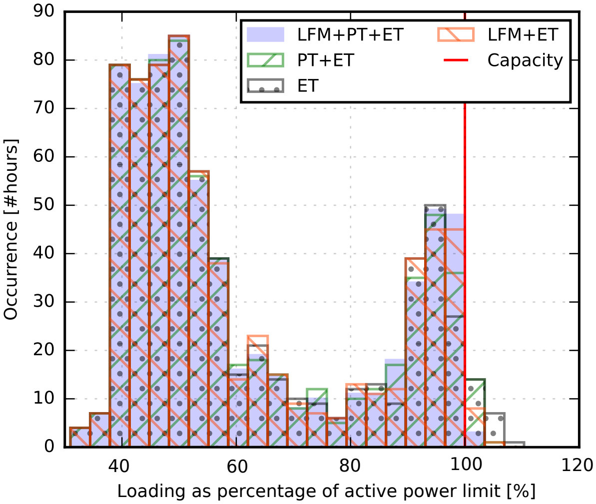


Figure 4.8: The histogram of active power loading in the line between buses 07:8.1 and 07:8.1.2 for four cases: LFM+PT+ET: LFM, power tariffs, and energy cost, LFM+ET: LFM and energy cost, PT+ET: power tariffs and energy cost, ET: only energy cost.

Table 4.1: Congestion severity for the four cases: LFM+PT+ET: LFM, power tariffs, and energy cost, LFM+ET: LFM and energy cost, PT+ET: power tariffs and energy cost, ET: only energy cost.

Case	LFM+PT+ET	LFM+ET	PT+ET	ET
Severity [$\% \cdot \mathrm{h}$]	1.3	10.0	24.6	63.2

Table 4.1. The severity of the cases follows the same order as the number of congested hours. The LFM+PT+ET has the lowest severity and ET has the highest severity.

Since the focus of the evaluation is on LFM design, overloading events for LFM-related cases are further analyzed. Based on the analyses, the overloading hours for these cases can be divided into two groups: 1) overloading due to neglecting grid losses in the procurement procedure of the CL product, and 2) overloading due to rebound effects from activating the LFM.

The first group of overloading in LFM-related cases includes loading slightly higher than 100% (Figure 4.7). This group consists of 2 hours in the case LFM+PT+ET, and 5 hours in the case LFM+ET. The reason is that grid losses are not considered in the current setting for procuring CL products. In the current test system, the losses are low because the grid is strong in addition to the fact that congestion is imposed by limiting the maximum current of the respective line and not changing the physical characteristics of the line. However, in real-life, the losses need to be incorporated by, for example, seeing losses as an "end-user" that consumes electricity and considering it as an inflexible end-user. This "end-user" can be represented through the methods explained in Section 3.7 of **Paper III**.

The second group of overloading in LFM-related cases consists of 1 hour in case LFM+PT+ET, and 4 hours in case LFM+ET. In these hours, the market was not activated. This indicates that the DSO had not expected any congestion in these hours based on the latest schedule from the agents. However, after the market is cleared for the respective days, the agents reschedule their assets to deliver the product for the cleared hours. Compared to the original schedule, the rescheduling includes a total increase of 51-63 kW in the battery load for the case LFM+ET. The increase is 18 kW for the hour in LFM+PT+ET. Since the only varying factor between LFM+PT+ET and LFM+ET is the inclusion of power tariffs, the results suggest that deploying power tariffs besides the presented LFM design could have reduced rebound effects in this study.

As an example of the supply-demand curve, hour 11 on 14 February in case LFM+PT+ET is presented in Figure 4.9. For this hour, the cleared quantity for CL-cap stands at 2118 kW. This is equal to the difference between the line's active power limit (882 kW) and the total connection capacities downstream (3000 kW).

Figures 4.10 and 4.11 present the flexible agents' dispatch on the same date and case, showing the net import (p_{imp}), the gross load (p_{load}), the imposed cap by the LFM, the spot price (ρ_{spot}), the BES charge/discharge power (p_{bes}) with positive and negative values representing charge and discharge respectively, the state-of-charge of BES (SoC_{bes}), and the generated power from PV (p_{pv}). The figures show how the agents keep their net-load below the imposed cap by LFM to deliver the service. The rebound effect of case LFM+PT+ET occurs at hour 10 on the 14th of Feb. because of rescheduling of agent $\mathrm{bld}_{07:28}$.

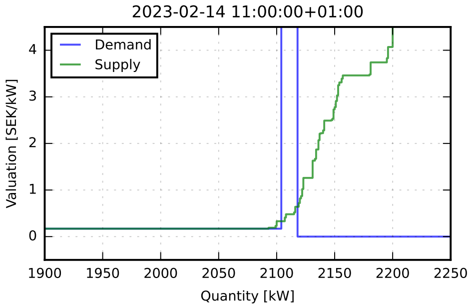


Figure 4.9: Supply and demand curves at hour 11 on Feb. 14th for Case LFM+PT+ET

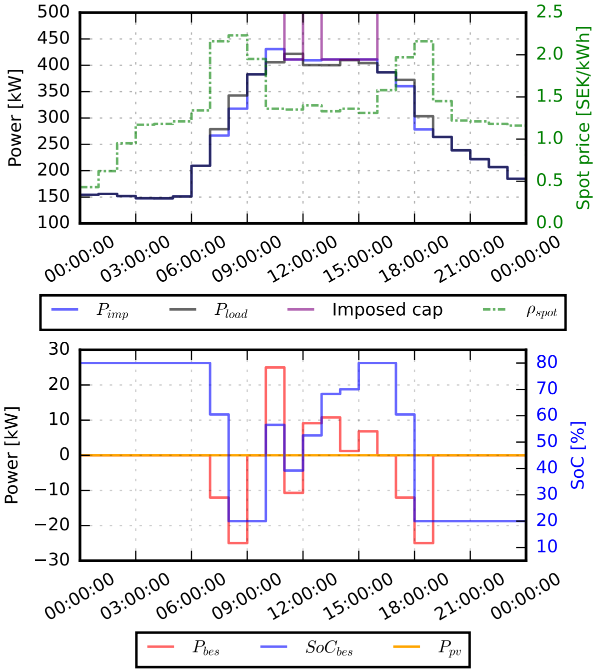


Figure 4.10: Operation of agent $\text{bld}_{07:28}$ on Feb. 14th for Case LFM+PT+ET

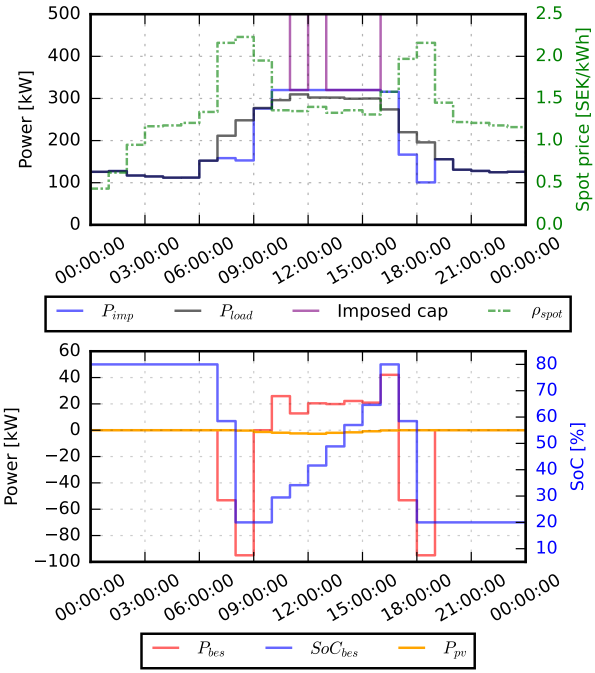


Figure 4.11: Operation of agent $\text{bld}_{07:11\text{B}}$ on Feb. 14th for Case LFM+PT+ET

4.4 RQ2: Operation of local flexibility resources for carbon emission reduction

RQ2 is the second focus of this thesis that aims to identify operation strategies and their cost to reduce carbon emissions by utilizing local flexibility resources. The strategies are identified for a case study on Chalmers Campus local multi-energy system (MES). For this purpose, a multi-objective optimization model for cost and emissions is utilized, which was developed in previous projects. The MES operation is optimized for over a year with a rolling, short-foresight time horizon, and for three energy carriers: district heating, district cooling, and electricity. The details of the work is presented in **Paper VI**.

The trade-off between the annual cost and carbon emissions is presented in Figure 4.12. This trade-off is obtained by varying the weighting factor (β) for the emissions. This is shown in (4.3) where C_h is the hourly operation cost, E_h is the hourly carbon emissions, and $\mathcal{H}$ is the set of hours in a year. β is varied from zero to one and can be seen as an additional carbon tax on the emissions. This approach is chosen to make the carbon emission reductions comparable with carbon prices.

$$\min \sum_{h \in \mathcal{H}} C_h + \beta \cdot E_h \tag{4.3}$$

The change in annual cost C and emissions E, with respect to pure economic optimization, is shown in Table 4.2. The range used for β is divided into different phases based on observed changes in the operation strategy that are referred to as emission abatement strategies. The results show that, using all identified abatement strategies, a 20.8% emission reduction could be achieved with a 2.2% increase in the cost.

The identified abatement strategies include: increased use of biomass boilers in heat production, substitution of district heating and absorption chillers with heat pumps, and higher utilization of storage units. It should be noted that the system was shown to be limited in the low-grade heat that was available from the district cooling system, which artificially constrained the dispatch of the available heat pumps. This system would therefore benefit from bore holes or other low-grade heat sources which would lead to greater dispatch of the higher efficiency heat pumps. Furthermore, the utilization of the combined heat and power (CHP) unit was shown to be sensitive to the relative weighting of emissions vs. cost in the objective function. The relative share of electricity production from the CHP unit is also shown to decrease at higher emissions weighting factors due to the relatively higher emissions in the district heating system compared to the electricity system.

As shown in Table 4.2, the total carbon dioxide abatement cost is 36.6–100.2

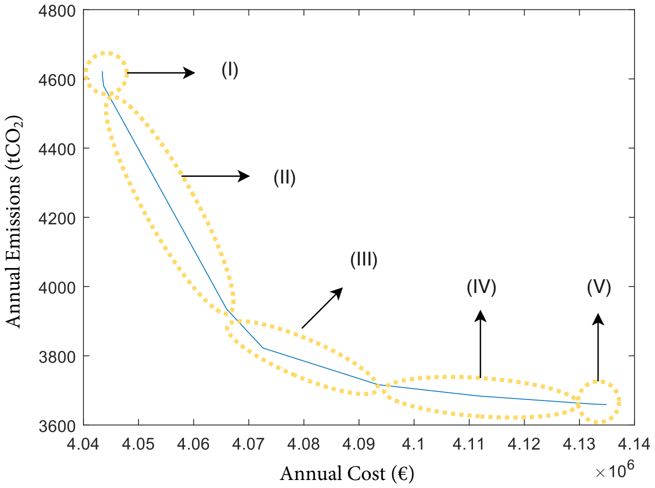


Figure 4.12: The trade-off between the total annual cost and emissions

Table 4.2: The average changes in cost and emissions compared to pure economic optimization (i.e., $\beta = 0$), and the cost of emission reduction.

Phase	**(I)**	**(II)**	**(III)**	**(IV)**	**(V)**
β	$[0, 10^{-4})$	$[10^{-4}, 10^{-3})$	$[10^{-3}, 10^{-2})$	$[10^{-2}, 10^{-1})$	$[10^{-1}, 1)$
$\Delta C/C^{\beta=0}$ (%)	$4e^{-4}$	0.3	1.0	1.9	2.2
$\Delta E/E^{\beta=0}$ (%)	-0.2	-7.9	-18.5	-20.5	-20.8
$\Delta C/\Delta E$ (€/tCO_2)	-3.3	-36.6	-67.6	-97.2	-100.2

(€/tCO_2), which is higher than the average carbon price in the EU Emission Trading Scheme and carbon tax prices in Sweden in 2019, but at the same level as similar pilot projects in Sweden [128].

The results can provide insight to local MES operators that aim to reduce their carbon emission footprints in terms of potential strategies and consequent costs. Moreover, similar studies can provide insight into carbon pricing if incentive mechanisms are to be designed for emission reductions from local energy communities. It is also worth mentioning that the presented costs and strategies are based on this specific case study and general conclusions cannot be made from only one case study.

4.5 RQ3: Operation of local flexibility resources for participation in FCR markets

RQ3 focuses on proposing a MILP formulation to optimize battery energy storage scheduling for revenue stacking in Sweden's DA and FCR markets, considering a detailed battery degradation model and technical requirements. **Paper VII** proposes a MILP formulation that maximizes the battery owner's daily profit in the day-ahead electricity market, and FCR-N, FCR-D up-, and down-regulation markets. A detailed linearized BES aging model including calendar and cycle aging is included together with the technical requirements for market participation.

Successive daily optimizations are run for a complete year using a time step of one minute. The simulation is run for a 1MW-1MWh battery located in the SE3 market zone using real data from 2022. The impact of degradation is assessed for five market participation modes:

- Case w/o FCR: do not participate in FCR,
- Case FCR-N: participate only in FCR-N,
- Case FCR-DU: participate only in FCR-D up,
- Case FCR-DD: participate only in FCR-D down,
- Case multi: multi-market participation is allowed at each hour.

The five modes are run twice, once when the degradation cost is included in the objective function and once without the degradation cost. This is to find out the size of battery degradation and its impact on profit from FCR markets.

The results are evaluated from two perspectives: monetary and operation strategy. The monetary perspective compares the cases based on profit and degradation costs. The operation strategy compares the distribution of state-of-energy (SoE), baseline reference power, and bid size. In addition, it compares the number of hours for participating in different combinations of markets.

The monetary results are presented in Table 4.3. Profit for cases without considering degradation in the objective function is obtained by post-calculating the aging cost and subtracting it from the objective function values. The results show that the multi-market case has a significantly larger profit compared to other market participation cases while having the second smallest degradation cost. Another observation is that considering degradation in optimization does not have a considerable impact ($\leq 1\%$) on the profit except in case w/o FCR. However, the total annual aging cost has been reduced by 5%-29% when battery degradation is considered in optimization. This highlights that considering degradation in the objective function can provide operation strategies that not only result in a similar profit but also a longer lifetime for the battery. Battery utilization is visualized in Figure 4.13 to clarify the reduction in battery degradation. The SoE and power data points show a shift towards smaller absolute values when degradation is considered. This explains the reduction of the aging costs when degradation is considered in optimization.

Table 4.3: Annual monetary results in k€

Case	**W/o deg. in objective**				**With deg. in objective**				**Δ Cost tot. age.**
	Profit	**Cost cal. age.**	**Cost cyc. age.**	**Cost tot. age.**	**Profit**	**Cost cal. age.**	**Cost cyc. age.**	**Cost tot. age.**	
w/o FCR	30	5.7	3.9	9.6	32	4.2	3.4	7.6	-21%
FCR-N	213	3.9	6.2	10.2	214	3.8	5.9	9.6	-5%
FCR-DU	560	6.3	3.1	9.5	561	4.4	2.6	6.9	-27%
FCR-DD	303	3.5	2.7	6.2	303	2.6	2.3	4.9	-21%
Multi	706	4.5	3.0	7.5	708	3.1	2.2	5.4	-29%

The loss in battery capacity for the year is presented in Figure 4.14. The largest degradation is expected in the FCR-N cases, while the lowest degradation is expected for the FCR-D down cases. This is due to the high energy throughput and cycling for FCR-N cases, while the FCR-D down cases require both lower cycling and lower SoE levels. In addition, FCR-N cases have the highest cycle aging, while FCR-D up cases show the highest calendar aging. It is also worth noting that the multimarket participation cases have shown a lower degradation compared to the w/o FCR case because the battery is utilized at lower SoE and lower power setpoints.

To better understand the difference in the operation strategies, the distribution of SoE in the beginning of each hour ($\mathcal{S}_h$), baseline power (p_h^{bl}), and bid size (p^{Θ}) are presented in Figure 4.15. Baseline power (p_h^{bl}) is the reference power used for

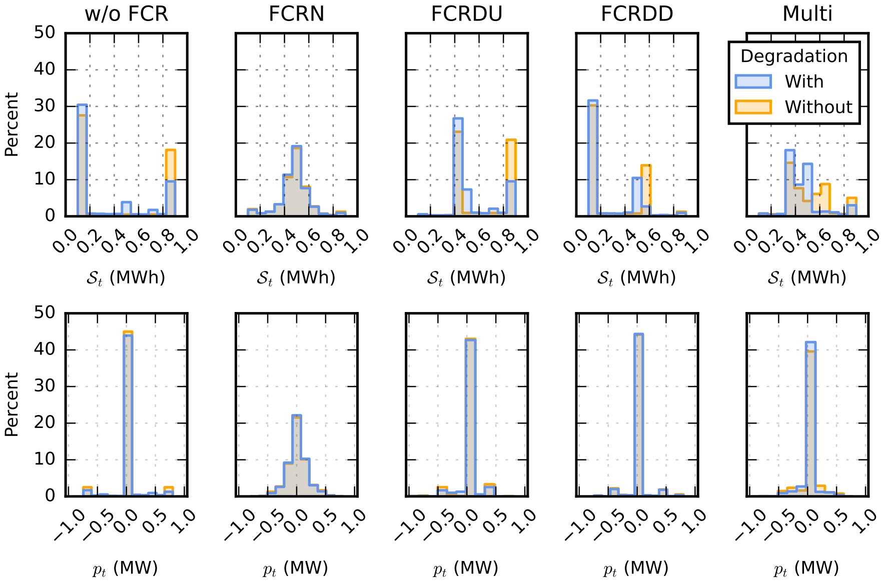


Figure 4.13: The battery utilization in different cases visualized by the histogram of battery SoE ($\mathcal{S}_t$) and power (p_t) as a percentage of all time step in a year

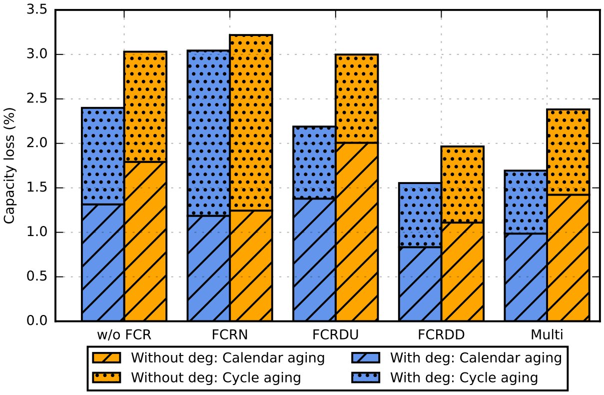


Figure 4.14: The annual battery capacity loss due to calendar and cycle aging for the different market participation cases

calculating the response to frequency deviation. The baseline is equivalent to the position in the DA electricity spot market and its sign follows the load convention. The dashed lines show the first, second, and third quartiles. SoE at the beginning of each hour is considered a part of the strategy because it is one of the main variables to satisfy endurance requirements. For multi-market cases, the sum of bids in all the FCR markets is presented in Figure 4.15.

Several general observations can be made regarding the most dominant values for the strategy variables presented in Figure 4.15. SoE at the beginning of each hour ($\mathcal{S}_h$) seems less discrete in the FCR-N case compared to the other cases. The dominant baseline power for all the cases is zero MW while the FCR-N case also shows a less discrete distribution. These two observations can highlight the potential complexities of real-life planning of an optimal FCR-N strategy compared to the other market participation cases which most likely boil down to the large energy throughput and a more regular activation of FCR-N services.

The dominant bid size for the FCR-DU and FCR-DD cases is 1 MW (Figure 4.15). The larger bids were possible at hours with a non-zero reference power (p_h^{bl}). The bids in the FCR-N case are limited to 0.4 MW due to considering technical requirements and the battery capacity. FCR-N is a symmetrical service with a required 1h endurance. Therefore, for example, if the SoE is at 0.5MWh, only 0.4MW can be provided for 1h in each direction considering the allowed SoC range of 10%-90%. For case Multi, the sum of the bids in all FCR markets is presented showing a dominant sum at 1.6 MW. This is the dominant optimal bidding strategy,

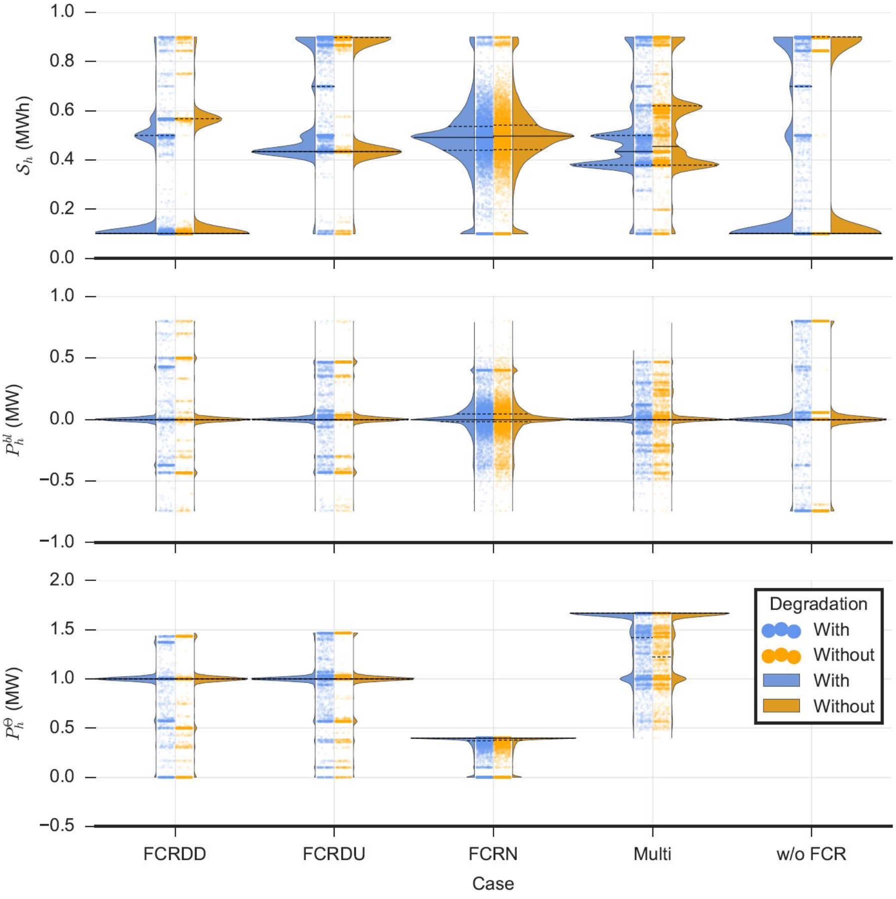


Figure 4.15: Operation strategy including the distribution of SoE at the beginning of each hour ($\mathcal{S}_h$), baseline power(p_h^{bl}), and bid size (p_h^{Θ}) for the simulated cases

which is a simultaneous bid in FCR-D up and down markets (Table 4.4). The sum is limited to 1.6 MW due to the technical requirement on the power, which indicates a 20% power availability in the opposite direction. The bid size results are yet another observation regarding the impact of considering technical requirements and their importance in obtaining realistic bidding and operation strategies.

Table 4.4: Choice of market presented in the number of hours in a year

Case	**None**	**N**	**DU**	**DD**	**N+DU**	**N+DD**	**DU+DD**	**All**
	Without deg. in objective function							
w/o FCR	8760	-	-	-	-	-	-	-
FCR-N	892	7868	-	-	-	-	-	-
FCR-DU	73	-	8687	-	-	-	-	-
FCR-DD	279	-	-	8481	-	-	-	-
Multi	0	3	1741	145	164	76	6110	521
	With deg. in objective function							
w/o FCR	8760	-	-	-	-	-	-	-
FCR-N	715	8045	-	-	-	-	-	-
FCR-DU	70	-	8690	-	-	-	-	-
FCR-DD	202	-	-	8558	-	-	-	-
Multi	0	2	1540	147	93	75	6382	521

The mix of markets chosen in each case is presented in Table 4.4. The inclusion of degradation in the objective function has led to a higher number of hours of market participation. This is because the BESS can reduce calendar aging by regulating SoE. The change in strategy comprises a larger number of participation hours, but with a reduction in the number of hours that have the larger bid sizes. This effect can be seen more clearly for the largest bids in the FCR-DD and FCR-DU cases presented in Figure 4.15. The dominant bid combination for case Multi is simultaneous FCR-DU and FCR-DD participation. This dominant bid combination in addition to the SoE levels in Figure 4.13 can clarify why the total battery degradation in Multi case is between the FCR-DU and FCR-DD cases (Figure 4.14).

It is worth noting that the model should not be seen as a ready-for-market bidding algorithm. The presented profit values are the theoretical maximum profit given the perspective of an oracle. In real life, these profits might not be achieved to their full extent due to the lack of information and uncertainties in the input parameters. However, the model and its results can be interpreted as a benchmark indicating the maximum potential profit and the potential impact of considering battery degradation in the optimization. Hence, the model can be used as an oracle model to evaluate and compare real-life bidding models that take into account the uncertainty of the input parameters.

CHAPTER 5

Conclusions and Future Work

This chapter concludes the thesis by providing the key takeaways from the results and recommendations for future word.

5.1 Key takeaways

This thesis has aimed at adding insights on three usecases of flexibility from local resources: 1) incentive mechanism-driven congestion management in distribution networks by local flexibility markets, 2) individual-driven carbon emission reduction in local multi-energy systems by multi-objective operation planning, and 3) incentive mechanism-driven frequency regulation by frequency containment reserve markets. In Section 1.3, five research questions were defined for this purpose that have formed the foundation for this thesis. The key takeaways concerning each research question are provided below.

Regarding **RQ1.1** the following takeaways can be provided on the design challenges and key factors/trends for the future of LFMs. Incorporating design aspects that support the development of automated and flexible end-users and facilitate their participation in LFMs are important for a higher market liquidity at local levels. Moreover, the reliability of LFM mechanisms should be improved because DSOs should be able to rely on LFMs as a substitute to grid reinforcement, and

FSPs would require a more reliable revenue stream from these markets. Flexibility products or incentive mechanisms that do not require baselines can reduce conflict of interest and high administrative costs of delivery validation related to baseline-based products. In addition, products that require submeter measurements and a more complex communication infrastructure for delivery validation can hinder the adoption and upscaling of LFMs.

RQ1.2 was about proposing an LFM design that considers the challenges in RQ1.1. A design with a triple-market structure including long-term availability, day-ahead, and adjustment markets can support decision making of market participants and improve reliability and liquidity of the market. In addition, the liquidity can be further improved by implementing LFMs for larger geographical areas while studying hinders such as barriers for digitalization and automation, bureaucratic pre-qualification procedures, lack of relevant competences, and contradicting/unclear regulations. The adapted capacity-limitation products, that are calculated based on net-load and subscribed connection capacity of end-users, can reduce conflict of interests, and administrative and ICT costs related to the delivery validation. Moreover, probabilistic approaches for calculating the cost and value of the product, such as the proposed algorithms in this thesis, can reduce the potential cost of forecast errors for market participants while providing insights on how the utility and cost can be calculated for the proposed product.

Regarding **RQ1.3** on the evaluation of the design, it is important to consider that the most suitable congestion management solution depends on the context, including parameters such as the size of the grid and DSO, regulations, social aspects, load patterns and its expected rate of increase, the lead time and cost of grid reinforcements, and the level of grid monitoring, and availability of smart meters. Therefore, LFMs should be evaluated qualitatively and quantitatively in comparison to other congestion management solutions such as LEMs, innovative tariffs, bilateral contracts, and grid reinforcement. For this comparison a comparison toolbox is needed that includes a qualitative comparison framework and a modeling platform for quantitative comparison. This toolbox is developed and presented as part of the answer to this RQ. In an example for using the toolbox, four cases of LFM+PT+ET, LFM+ET, PT+ET, and ET were quantitatively compared in a subarea of the Chalmers campus testbed. The results showed that the case LFM+PT+ET (that is, simultaneous consideration of LFM, power tariff, and energy cost) has the lowest number of congested hours. Moreover, rebound effects from activating the LFM were observed that are due to the rescheduling of agents' assets after the LFM market clearing results are published. The comparison of cases LFM+PT+ET and LFM+ET suggested that enforcing power tariffs besides LFM could reduce the number of congested hours due to rebound effects in this case study.

In **RQ2**, the aim was to identify emission abatement strategies and their cost for a flexible local multi-energy system. Chalmers Campus testbed was used for the case study, including electricity, district heating, and district cooling systems. The results of the case study showed that the carbon emission footprint of the local system could have been reduced by 20.8% with a 2.2% increase in the cost. The operation strategies for this purpose included the increase in the use of biomass boilers in heat production, the substitution of district heating and absorption chillers with heat pumps, and the greater utilization of storage units. The analysis showed that the cost of the strategies ranged from 36.6 to 100.2 (€/tCO_2).

RQ3 aimed to revisit the multi-market operation strategies of a battery for participating in Sweden's day-ahead electricity and the three FCR markets to include a detailed battery degradation model and market technical requirements. The results showed that, for a 1MW/1MWh battery in 2022, the highest profit could have been achieved in the multi-market participation that was dominated by simultaneous bidding in FCR-D up and down markets. The results showed a maximum potential profit of 708k€ with an expected 1.7% battery capacity loss. The largest degradation was for the dedicated FCR-N participation case with 3.0% battery capacity loss, while the lowest degradation was shown to be for the dedicated FCR-D down participation case with 1.6% capacity loss. In addition, the results have shown that although considering degradation in the optimization does not have a significant impact on the profit, it can decrease the aging by 5%-29% leading to a more sustainable utilization of the battery. The results have also clearly demonstrated the impact and importance of fulfilling the technical requirements of the Nordic FCR markets.

This thesis may be useful to system operators, flexibility asset owners, policy makers, and researchers engaged in the usecases discussed for local flexibility resources. The thesis can provide insights for a better understanding of the challenges, and propose potential solutions and toolboxes for implementing and evaluating these usecases.

5.2 Recommendations for future work

The following is a short list of recommendations for future work:

- *A comprehensive comparison study of the LFM design:* The evaluation of the LFM design may be continued by first identifying the most important factors affecting the comparison, and then studying various combinations of these factors. The factors can be the size and distribution of flexibility resources, the size and topology of the grid, load patterns of the agents, bidding algorithms, time of year, tariff designs, etc
- *Strategic behavior analysis:* The potential strategic behavior of flexibility

providers in LFMs can be studied using evolutionary algorithms from game theory. This is specially important due to the heterogeneous essence of the CL-product and low market liquidity in LFMs.

- *Interplay of LFMs, power tariffs, and energy communities:* Energy communities are another concept that may co-exist in future distribution networks. Studying the interplay between the LFMs, power tariffs and energy communities are both interesting and essential.
- *LFMs vs. FCR market participation:* The decision-making problem of flexibility assets owners can be extended to include LFMs. Such an study can be formulated to find what prices should be offered by DSOs in LFMs so that LFMs could be competitive with profits from FCR markets.
- *Uncertainty handling:* Both the LFM evaluation and multi-FCR market participation works can be extended to include and evaluate uncertainty and uncertainty handling methods.
- *Battery sizing for multi-FCR participation:* The technical requirements such as power and endurance constraints largely impact the bids on FCR markets. It is interesting to look into what power to energy ratio is the most profitable choice for battery owners aiming to participate in FCR markets.
- *Including other frequency support markets:* The multi-FCR market participation can be extended by including other markets such as FFR and FRR.
- *Aggregation and flexibility resource portfolios:* Multi-FCR market participation can be extended to study aggregation of various flexibility resources to find the most profitable flexibility portfolios. Each flexibility resource has its own characteristics about uncertainty, capacity, endurance, cost, etc. Potential synergies can exist by aggregating different types of flexibility resources.
- *Comparing different battery chemistries*: It would be interesting to compare the degradation of different battery chemistries in the case of multi-FCR market participation.

References

[1] Y. Zou, J. Zhao, X. Gao, Y. Chen, and A. Tohidi, "Experimental results of electric vehicles effects on low voltage grids," *Journal of Cleaner Production*, vol. 255, p. 120 270, 2020, ISSN: 0959-6526.

[2] C. Heinrich, C. Ziras, A. L. Syrri, and H. W. Bindner, "Ecogrid 2.0: A large-scale field trial of a local flexibility market," *Applied Energy*, vol. 261, p. 114 399, 2020, ISSN: 0306-2619.

[3] N. Mirzaei Alavijeh, M. A. F. Ghazvini, D. Steen, O. Carlson, *et al.*, "Key drivers and future scenarios of local energy and flexibility markets," in *2021 IEEE Madrid PowerTech*, IEEE, 2021, pp. 1–6.

[4] X. Jin, Q. Wu, and H. Jia, "Local flexibility markets: Literature review on concepts, models and clearing methods," *Applied Energy*, vol. 261, p. 114 387, 2020, ISSN: 0306-2619.

[5] F. Hedenus, M. Persson, and F. Sprei, *Sustainable Development-Nuances and Perspectives.* Studentlitteratur AB, 2022.

[6] Y. Yang, W. Tobiasson, M. Warneryd, *et al.*, "D2.4. policy framework and business models enabling flexibility markets," Flexigrid project, Tech. Rep., 2022.

[7] D. Paccagnan, R. Chandan, and J. R. Marden, "Utility and mechanism design in multi-agent systems: An overview," *Annual Reviews in Control*, vol. 53, pp. 315–328, 2022, ISSN: 1367-5788.

[8] E. Hillberg, A. Zegers, B. Herndler, *et al.*, "Flexibility needs in the future power system," Tech. Rep., Mar. 2019, p. 48.

[9] EDSO, CEDEC, Eurelectric, and GEODE, *Guidelines of good practice for flexibility use at distribution level*, 2017.

[10] The European Parliament and the Council, *DIRECTIVE (EU) 2019/944 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 5 june 2019 on common rules for the internal market for electricity and amending Directive 2012/27/EU*, The European Parliament and the Council, 2019.

[11] Association of European Energy Exchanges (Europex), "A market-based approach to local flexibility – design principles," Europex, Brussels, Belgium, Tech. Rep., 2020.

[12] P. Olivella-Rosell, P. Lloret-Gallego, Í. Munné-Collado, *et al.*, "Local flexibility market design for aggregators providing multiple flexibility services at distribution network level," *Energies*, vol. 11, no. 4, p. 822, 2018.

[13] C. Heinrich, C. Ziras, T. V. Jensen, H. W. Bindner, and J. Kazempour, "A local flexibility market mechanism with capacity limitation services," *Energy Policy*, vol. 156, p. 112 335, 2021, ISSN: 0301-4215.

[14] NODES, *NODES Website*, `https://nodesmarket.com/`, (Accessed 2023-04-24).

[15] A. Esmat, J. Usaola, and M. Á. Moreno, "A decentralized local flexibility market considering the uncertainty of demand," *Energies*, vol. 11, no. 8, 2018, ISSN: 1996-1073.

[16] Piclo, *Piclo Market Website*, `https://www.piclo.energy/`, (Accessed 2023-04-24).

[17] O. Valarezo, T. Gómez, J. P. Chaves-Avila, *et al.*, "Analysis of new flexibility market models in europe," *Energies*, vol. 14, no. 12, p. 3521, 2021.

[18] Svenska kraftnät, *Information on different ancillary services*, `https://www.svk.se/en/stakeholders-portal/electricity-market/provision-of-ancillary-services/information-on-different-ancillary-services/`, (Accessed: 2024-06-12), May 3, 2024.

[19] Svenska kraftnät, *Utbud på marknaderna för reserver*, `https://www.svk.se/aktorsportalen/bidra-med-reserver/behov-av-reserver-nu-och-i-framtiden/utbud-pa-marknaderna-for-reserver/`, (Accessed: 2024-06-12), Apr. 11, 2024.

[20] ENTSO-E, "Technical requirements for frequency containment reserve provision in the nordic synchronous area," ENTSO-E, Tech. Rep., 2023.

[21] L. Göransson and F. Johnsson, "A comparison of variation management strategies for wind power integration in different electricity system contexts," *Wind Energy*, vol. 21, no. 10, pp. 837–854, 2018.

[22] P. Chaudhary and M. Rizwan, "Voltage regulation mitigation techniques in distribution system with high pv penetration: A review," *Renewable and Sustainable Energy Reviews*, vol. 82, pp. 3279–3287, 2018, ISSN: 1364-0321.

[23] M. Lundberg, O. Samuelsson, and E. Hillberg, "Local voltage control in distribution networks using pi control of active and reactive power," *Electric Power Systems Research*, vol. 212, p. 108 475, 2022, ISSN: 0378-7796.

[24] H. Pihl, J. Rossi, and M. Edvall, "D2.1, Report on barriers for adoption of innovative market design," FLEXIGRID project, Tech. Rep., 2020.

[25] A. Wolf, C. Sandels, and M. Shepero, "Lokal energilagring eller traditionella nätförstärkningar," Power Circle, Tech. Rep., 2018.

[26] N. Etherden, Y. Ruwaida, and S. Johansson, "Coordinet D4.5 – report on lessons learned, bug fixes and adjustments in products and routines within the swedish demo," CoodiNet project, Tech. Rep., 2020.

[27] G. Ringland, *Scenarios in business.* Wiley, 2002.

[28] S. P. Schnaars, "How to develop and use scenarios," *Long range planning*, vol. 20, no. 1, pp. 105–114, 1987.

[29] T. J. Stewart, "Dealing with uncertainties in mcda," in *Multiple criteria decision analysis: state of the art surveys*, Springer, 2005, pp. 445–466.

[30] K. Chen, Z. Ren, S. Mu, T. Q. Sun, and R. Mu, "Integrating the delphi survey into scenario planning for china's renewable energy development strategy towards 2030," *Technological Forecasting and Social Change*, vol. 158, p. 120 157, 2020.

[31] S. Kuiper, “The future of the dso enexis: A research on the strategic position of the dso in 2030 using scenario and trend analysis,” M.S. thesis, University of Twente, 2015.

[32] R. Alizadeh, P. D. Lund, A. Beynaghi, M. Abolghasemi, and R. Maknoon, “An integrated scenario-based robust planning approach for foresight and strategic management with application to energy industry,” *Technological Forecasting and Social Change*, vol. 104, pp. 162–171, 2016.

[33] S. W. Schuckmann, T. Gnatzy, I.-L. Darkow, and A. Heiko, “Analysis of factors influencing the development of transport infrastructure until the year 2030—a delphi based scenario study,” *Technological Forecasting and Social Change*, vol. 79, no. 8, pp. 1373–1387, 2012.

[34] Y. Shiftan, S. Kaplan, and S. Hakkert, “Scenario building as a tool for planning a sustainable transportation system,” *Transportation Research Part D: Transport and Environment*, vol. 8, no. 5, pp. 323–342, 2003.

[35] E. Heilmann, N. Klempp, and H. Wetzel, “Market design of regional flexibility markets: A classification metric for flexibility products and its application to german prototypical flexibility markets,” MAGKS Joint Discussion Paper Series in Economics, Tech. Rep., 2020.

[36] FlexiGrid Project, *FlexiGrid Project Website*, `https://flexigrid.org/`, (Accessed 2022-02-14), 2019.

[37] L. Mitridati, J. Kazempour, and P. Pinson, “Design and game-theoretic analysis of community-based market mechanisms in heat and electricity systems,” *Omega*, vol. 99, p. 102 177, 2021, ISSN: 0305-0483.

[38] C. Silva, B. F. Wollenberg, and C. Z. Zheng, “Application of mechanism design to electric power markets (republished),” *IEEE Transactions on Power Systems*, vol. 16, no. 4, pp. 862–869, 2001.

[39] J. Villar, R. Bessa, and M. Matos, “Flexibility products and markets: Literature review,” *Electric Power Systems Research*, vol. 154, pp. 329–340, 2018, ISSN: 0378-7796.

[40] C. Heinrich, “Local flexibility markets for distribution network operation,” Ph.D. dissertation, Technical University of Denmark, 2020.

[41] M. Brolin and H. Pihl, "Design of a local energy market with multiple energy carriers," *International Journal of Electrical Power & Energy Systems*, vol. 118, p. 105 739, 2020, ISSN: 0142-0615.

[42] S. Minniti, N. Haque, P. Nguyen, and G. Pemen, "Local markets for flexibility trading: Key stages and enablers," *Energies*, vol. 11, no. 11, p. 3074, 2018, ISSN: 1996-1073.

[43] M. Woerman, "Market size and market power: Evidence from the texas electricity market," in *Energy Institute at Haas working papers*, Energy Institute at Haas, University of California, Berkeley, CA, 2019.

[44] T. Schittekatte and L. Meeus, "Flexibility markets: Q&A with project pioneers," *Utilities Policy*, vol. 63, p. 101 017, 2020, ISSN: 0957-1787.

[45] M. Håkansson, "Energy actors' views on demand response from heat pumps," in *5th European Conference on Behaviour and Energy Efficiency*, ZHAW Zurich University of Applied Sciences, Zurich, 2018, pp. 153–154.

[46] C. Ziras, C. Heinrich, and H. W. Bindner, "Why baselines are not suited for local flexibility markets," *Renewable and Sustainable Energy Reviews*, vol. 135, p. 110 357, 2021, ISSN: 1364-0321.

[47] S. Nolan and M. O'Malley, "Challenges and barriers to demand response deployment and evaluation," *Applied Energy*, vol. 152, pp. 1–10, 2015, ISSN: 0306-2619.

[48] S. Pagliuca, I. Lampropoulos, M. Bonicolini, B. Rawn, M. Gibescu, and W. L. Kling, "Capacity assessment of residential demand response mechanisms," in *2011 46th International Universities' Power Engineering Conference (UPEC)*, 2011, pp. 1–6.

[49] N. Stevens, K. Merckx, P. Crucifix, *et al.*, "Deliverable D2.1 Markets for DSO and TSO procurement of innovative grid services: Specification of the architecture, operation and clearing algorithms," CoordiNet project, Tech. Rep., Feb. 20, 2021.

[50] T. Gómez, R. Cossent, and J. Chaves, "Flexible network access, local flexibility market mechanisms, and cost-reflective tariffs: Three regulatory tools to foster decarbonized electricity networks," in *Oxford Energy Forum*, 2020.

[51] L. Hirth and S. Glismann, “Congestion Management: From Physics to Regulatory Instruments,”

[52] Z. Chen, C. Ziras, and H. W. Bindner, “Towards an assessment framework for congestion management mechanisms in distribution networks,” in *2021 IEEE PES Innovative Smart Grid Technologies Europe (ISGT Europe)*, IEEE, 2021, pp. 01–05.

[53] A. Stawska, N. Romero, M. de Weerdt, and R. Verzijlbergh, “Demand response: For congestion management or for grid balancing?” *Energy Policy*, vol. 148, p. 111 920, 2021, ISSN: 0301-4215.

[54] N. I. Yusoff, A. A. M. Zin, and A. Bin Khairuddin, “Congestion management in power system: A review,” in *2017 3rd International Conference on Power Generation Systems and Renewable Energy Technologies (PGSRET)*, 2017, pp. 22–27.

[55] M. Attar, S. Repo, and P. Mann, “Congestion management market design- approach for the nordics and central europe,” *Applied Energy*, vol. 313, p. 118 905, 2022, ISSN: 0306-2619.

[56] S. Huang, Q. Wu, Z. Liu, and A. H. Nielsen, “Review of congestion management methods for distribution networks with high penetration of distributed energy resources,” in *IEEE PES Innovative Smart Grid Technologies, Europe*, 2014, pp. 1–6.

[57] P. Mancarella, “Mes (multi-energy systems): An overview of concepts and evaluation models,” *Energy*, vol. 65, pp. 1–17, 2014.

[58] D. Grosspietsch, M. Saenger, and B. Girod, “Matching decentralized energy production and local consumption: A review of renewable energy systems with conversion and storage technologies,” en, *Wiley Interdisciplinary Reviews: Energy and Environment*, vol. 8, no. 4, e336, 2019, ISSN: 2041-840X.

[59] B. P. Koirala, E. Koliou, J. Friege, R. A. Hakvoort, and P. M. Herder, “Energetic communities for community energy: A review of key issues and trends shaping integrated community energy systems,” *Renewable and Sustainable Energy Reviews*, vol. 56, pp. 722–744, Apr. 2016, ISSN: 1364-0321.

[60] A. T. D. Perera, V. M. Nik, D. Mauree, and J.-L. Scartezzini, "An integrated approach to design site specific distributed electrical hubs combining optimization, multi-criterion assessment and decision making," *Energy*, vol. 134, pp. 103–120, Sep. 2017, ISSN: 0360-5442.

[61] M. Majidi, S. Nojavan, and K. Zare, "A cost-emission framework for hub energy system under demand response program," *Energy*, vol. 134, pp. 157–166, 2017, ISSN: 0360-5442.

[62] S. Bracco, G. Dentici, and S. Siri, "Economic and environmental optimization model for the design and the operation of a combined heat and power distributed generation system in an urban area," *Energy*, vol. 55, pp. 1014–1024, 2013, ISSN: 0360-5442.

[63] R. Wang, Z. Zhou, H. Ishibuchi, T. Liao, and T. Zhang, "Localized weighted sum method for many-objective optimization," *IEEE Transactions on Evolutionary Computation*, vol. 22, no. 1, pp. 3–18, Feb. 2018, ISSN: 1941-0026.

[64] Q. Wu, H. Ren, W. Gao, and J. Ren, "Multi-objective optimization of a distributed energy network integrated with heating interchange," *Energy*, vol. 109, pp. 353–364, Aug. 2016, ISSN: 0360-5442.

[65] G. Li, R. Wang, T. Zhang, and M. Ming, "Multi-objective optimal design of renewable energy integrated cchp system using picea-g," *Energies*, vol. 11, no. 4, 2018, ISSN: 1996-1073.

[66] Y. Huang, W. Zhang, K. Yang, W. Hou, and Y. Huang, "An optimal scheduling method for multi-energy hub systems using game theory," *Energies*, vol. 12, no. 12, 2019, ISSN: 1996-1073.

[67] X. Fu, S. Huang, R. Li, and H. Sun, "Electric power output optimization for cchp using pso theory," *Energy Procedia*, vol. 103, pp. 9–14, 2016, Renewable Energy Integration with Mini/Microgrid – Proceedings of REM2016, ISSN: 1876-6102.

[68] J. Reynolds, M. W. Ahmad, Y. Rezgui, and J.-L. Hippolyte, "Operational supply and demand optimisation of a multi-vector district energy system using artificial neural networks and a genetic algorithm," *Applied Energy*, vol. 235, pp. 699–713, 2019, ISSN: 0306-2619.

[69] F. Domínguez-Muñoz, J. M. Cejudo-López, A. Carrillo-Andrés, and M. Gallardo-Salazar, “Selection of typical demand days for CHP optimization,” *Energy and Buildings*, vol. 43, no. 11, pp. 3036–3043, Nov. 2011, ISSN: 0378-7788.

[70] J. F. Marquant, R. Evins, and J. Carmeliet, “Reducing Computation Time with a Rolling Horizon Approach Applied to a MILP Formulation of Multiple Urban Energy Hub System,” *Procedia Computer Science*, International Conference On Computational Science, ICCS 2015, vol. 51, Jan. 2015, ISSN: 1877-0509.

[71] G. Erichsen, T. Zimmermann, and A. Kather, “Effect of Different Interval Lengths in a Rolling Horizon MILP Unit Commitment with Non-Linear Control Model for a Small Energy System,” en, *Energies*, vol. 12, no. 6, p. 1003, Jan. 2019.

[72] M. Di Somma, B. Yan, N. Bianco, *et al.*, “Multi-objective operation optimization of a Distributed Energy System for a large-scale utility customer,” *Applied Thermal Engineering*, vol. 101, pp. 752–761, May 2016, ISSN: 1359-4311.

[73] T. Falke, S. Krengel, A.-K. Meinerzhagen, and A. Schnettler, “Multi-objective optimization and simulation model for the design of distributed energy systems,” *Applied Energy*, vol. 184, pp. 1508–1516, Dec. 2016, ISSN: 0306-2619.

[74] B. Yan, M. D. Somma, P. B. Luh, and G. Graditi, “Operation Optimization of Multiple Distributed Energy Systems in an Energy Community,” in *2018 IEEE International Conference on Environment and Electrical Engineering and 2018 IEEE Industrial and Commercial Power Systems Europe (EEEIC / I CPS Europe)*, Jun. 2018, pp. 1–6.

[75] B. Böckl, M. Greiml, L. Leitner, P. Pichler, L. Kriechbaum, and T. Kienberger, “Hyflow—a hybrid load flow-modelling framework to evaluate the effects of energy storage and sector coupling on the electrical load flows,” *Energies*, vol. 12, no. 5, 2019, ISSN: 1996-1073.

[76] T. Zhao, A. Parisio, and J. V. Milanović, “Distributed control of battery energy storage systems for improved frequency regulation,” *IEEE Transactions on Power Systems*, vol. 35, no. 5, pp. 3729–3738, 2020.

[77] Q. Ma, W. Wei, L. Wu, and S. Mei, “Life-aware operation of battery energy storage in frequency regulation,” *IEEE Transactions on Sustainable Energy*, vol. 14, no. 3, pp. 1725–1736, 2023.

[78] E. N. Sofia Guzman, M. Arriaga, C. A. Cañizares, J. W. Simpson-Porco, D. Sohm, and K. Bhattacharya, “Regulation signal design and fast frequency control with energy storage systems,” *IEEE Transactions on Power Systems*, vol. 37, no. 1, pp. 224–236, 2022.

[79] A. Oshnoei, M. Kheradmandi, and S. M. Muyeen, “Robust control scheme for distributed battery energy storage systems in load frequency control,” *IEEE Transactions on Power Systems*, vol. 35, no. 6, pp. 4781–4791, 2020.

[80] A. Thingvad, C. Ziras, G. Le Ray, J. Engelhardt, R. R. Mosbæk, and M. Marinelli, “Economic value of multi-market bidding in nordic frequency markets,” in *2022 International Conference on Renewable Energies and Smart Technologies (REST)*, IEEE, vol. 1, 2022, pp. 1–5.

[81] K. Jacqué, L. Koltermann, J. Figgener, S. Zurmühlen, and D. U. Sauer, “The influence of frequency containment reserve on the cycles of a hybrid stationary large-scale storage system,” *Journal of Energy Storage*, vol. 52, p. 105 040, 2022.

[82] A. Krupp, R. Beckmann, P. Draheim, *et al.*, “Operating strategy optimization considering battery aging for a sector coupling system providing frequency containment reserve,” *Journal of Energy Storage*, vol. 68, p. 107 787, 2023.

[83] L. Koltermann, M. C. Cortés, J. Figgener, S. Zurmühlen, and D. U. Sauer, “Power curves of megawatt-scale battery storage technologies for frequency regulation and energy trading,” *Applied Energy*, vol. 347, p. 121 428, 2023.

[84] P. Astero and C. Evens, “Optimum operation of battery storage system in frequency containment reserves markets,” *IEEE Transactions on Smart Grid*, vol. 11, no. 6, pp. 4906–4915, 2020.

[85] I. M. Casla, A. Khodadadi, and L. Söder, “Optimal day ahead planning and bidding strategy of battery storage unit participating in nordic frequency markets,” *IEEE Access*, vol. 10, pp. 76 870–76 883, 2022.

[86] S. Gao, H. Li, J. Jurasz, and R. Dai, “Optimal charging of electric vehicle aggregations participating in energy and ancillary service markets,” *IEEE Journal of Emerging and Selected Topics in Industrial Electronics*, vol. 3, no. 2, pp. 270–278, 2022.

[87] I. Pavić, H. Pandžić, and T. Capuder, “Electric vehicle aggregator as an automatic reserves provider under uncertain balancing energy procurement,” *IEEE Transactions on Power Systems*, vol. 38, no. 1, pp. 396–410, 2023.

[88] R. K. Subroto, D. Gebbran, A. B. Moreno, and T. Dragičević, “Bess optimal sizing and scheduling for energy arbitrage and frequency containment reserve via dual-loop optimization,” in *2022 IEEE Transportation Electrification Conference & Expo (ITEC)*, IEEE, 2022, pp. 941–946.

[89] A. Mohamed, R. Rigo-Mariani, V. Debusschere, and L. Pin, “Stacked revenues for energy storage participating in energy and reserve markets with an optimal frequency regulation modeling,” *Applied Energy*, vol. 350, p. 121 721, 2023, ISSN: 0306-2619.

[90] I. Bouloumpasis, N. Mirzaei Alavijeh, D. Steen, and A. T. Le, “Local flexibility market framework for grid support services to distribution networks,” *Electrical Engineering*, vol. 104, no. 2, pp. 401–419, 2022.

[91] C. Rosen and R. Madlener, “An Experimental Analysis of Single vs. Multiple Bids in Auctions of Divisible Goods,” *SSRN Electronic Journal*, 2013, ISSN: 1556-5068.

[92] R. Scharff and M. Amelin, “Trading behaviour on the continuous intraday market elbas,” *Energy Policy*, vol. 88, pp. 544–557, 2016, ISSN: 0301-4215.

[93] F. Ocker and V. Jaenisch, “The way towards european electricity intraday auctions – status quo and future developments,” *Energy Policy*, vol. 145, p. 111 731, 2020, ISSN: 0301-4215.

[94] K. Neuhoff, N. Ritter, A. Salah-Abou-El-Enien, and P. Vassilopoulos, “Intraday markets for power: Discretizing the continuous trading,” Deutsches Institut für Wirtschaftsforschung (DIW), Berlin, Tech. Rep., 2016.

[95] IREMEL Project, *IREMEL Project Website*, `https://www.omie.es/es/proyecto-iremel`, (Accessed 2022-02-14), 2019.

[96] InterFlex Project, *InterFlex Project Website*, `https://interflex-h2020.com/`, (Accessed 2022-02-14), 2017.

[97] INTERFACE Project, *INTERFACE Project Website*, `http://www.interrface.eu/`, (Accessed 2022-02-14), 2019.

[98] A. Esmat, J. Usaola, and M. Á. Moreno, "Distribution-level flexibility market for congestion management," *Energies*, vol. 11, no. 5, 2018, ISSN: 1996-1073.

[99] L. T. Blessing and A. Chakrabarti, *DRM: A design reseach methodology.* Springer, 2009.

[100] M. Utley, S. Crowe, and C. Pagel, *Operational research approaches.* Cambridge University Press, 2022.

[101] J. Will M. Bertrand and J. C. Fransoo, "Operations management research methodologies using quantitative modeling," *International journal of operations & production management*, vol. 22, no. 2, pp. 241–264, 2002.

[102] R. Bradfield, G. Wright, G. Burt, G. Cairns, and K. Van Der Heijden, "The origins and evolution of scenario techniques in long range business planning," *Futures*, vol. 37, no. 8, pp. 795–812, 2005.

[103] M. Amer, T. U. Daim, and A. Jetter, "A review of scenario planning," *Futures*, vol. 46, pp. 23–40, 2013.

[104] M. Conway, "An introduction to scenario planning," in *Foresight Methodologies Workshop*, 2003, p. 99.

[105] P. Schwartz, *The art of the long view: paths to strategic insight for yourself and your company.* Currency, 1996.

[106] W. R. Huss and E. J. Honton, "Scenario planning—what style should you use?" *Long range planning*, vol. 20, no. 4, pp. 21–29, 1987.

[107] J. Ogilvy and T. Mandel, *How to construct and use scenarios*, 1986.

[108] S. A. van't Klooster and M. B. van Asselt, "Practising the scenario-axes technique," *Futures*, vol. 38, no. 1, pp. 15–30, 2006.

[109] K. Strunz, E. Abbasi, C. Abbey, C. Andrieu, U. Annakkage, *et al.*, "Benchmark systems for network integration of renewable and distributed energy resources. Task Force C6. 04.02," *CIGRE, Technical Brochure*, vol. 575, 2014.

[110] K. Antoniadou-Plytaria, A. Srivastava, M. A. F. Ghazvini, D. Steen, O. Carlson, *et al.*, "Chalmers campus as a testbed for intelligent grids and local energy systems," in *2019 International Conference on Smart Energy Systems and Technologies (SEST)*, IEEE, 2019, pp. 1–6.

[111] R. Sharma, N. Mirzaei Alavijeh, M. Mohiti, D. Steen, L. A. Tuan, and P. Loveryd, "Flexigrid tools for real-life demonstrations of local energy system concepts at Chalmers Campus testbed," in *2023 IEEE Belgrade PowerTech*, 2023, pp. 01–06.

[112] E. Nyholm, J. Goop, M. Odenberger, and F. Johnsson, "Solar photovoltaic-battery systems in swedish households – self-consumption and self-sufficiency," *Applied Energy*, vol. 183, pp. 148–159, 2016, ISSN: 0306-2619.

[113] Z. Norwood, E. Nyholm, T. Otanicar, and F. Johnsson, "A geospatial comparison of distributed solar heat and power in europe and the us," *PloS one*, vol. 9, no. 12, e112442, 2014.

[114] E.ON Energidistribution, *Our network fees for private customers*, `https://www.eon.se/content/dam/eon-se/swe-documents/swe-prislista-lag-sthlm-230101.pdf`, (Accessed: 2022-12-20), 2022.

[115] Göteborg Energi, *Network fees*, `https://www.goteborgenergi.se/privat/elnat/elnatsavgift`, (Accessed: 2022-11-26), 2022.

[116] Skatteverket, *Energy tax on electric power*, `https://skatteverket.se/download/18.339cd9fe17d1714c07739ac/1639754819253/skatte\satser%20el%20t.o.m.%202021-12-31.pdf`, (Accessed: 2017-07-01), 2022.

[117] Skatteverket, *Tax reduction for microprocuktion of renewable electricity - private residences*, `https://skatteverket.se/privat/fastigheter\ochbostad/mikroproduktionavfornybarelprivatbostad.4.12815e4\f14a62bc048f41a7.html`, (Accessed: 2022-11-26), 2022.

[118] "Capacity mechanisms," European Commission. (), [Online]. Available: `https://energy.ec.europa.eu/topics/markets-and-consumers/capacity-mechanisms_en` (visited on 10/10/2024).

[119] J. Black, N. Hashimzade, and G. Myles, *A dictionary of economics.* Oxford University Press, USA, 2012.

[120] P. Dorman, *Microeconomics a fresh start.* Springer, 2014.

[121] S. Phelps, S. Parsons, and P. McBurney, "An evolutionary game-theoretic comparison of two double-auction market designs," in *International Workshop on Agent-Mediated Electronic Commerce*, Springer, 2004, pp. 101–114.

[122] C. Brandstätt and R. Poudineh, "Rethinking the network access regime: The case for differentiated and tradeable access rights," in *Oxford Energy Forum*, The Oxford Institute for Energy Studies, vol. 124, 2020, pp. 24–28.

[123] S. Bjarghov, H. Farahmand, and G. Doorman, "Capacity subscription grid tariff efficiency and the impact of uncertainty on the subscribed level," *Energy Policy*, vol. 165, p. 112 972, 2022.

[124] G. L. Doorman, "Capacity subscription: Solving the peak demand challenge in electricity markets," *IEEE Transactions on Power Systems*, vol. 20, no. 1, pp. 239–245, 2005.

[125] F. Farrukh, *Effekthandel Väst: Maximum peak in electricity consumption reduced for the electricity grid during the winter*, `https://nodesmarket.com/effekthandel-vast-maximum-peak-in-electricity-consumption-reduced-for-the-electricity-grid-during-the-winter/`, (Accessed: 2024-04-23), NODES market, Mar. 7, 2024.

[126] Göteborg Energi, *Effekthandel Väst*, `https://www.goteborgenergi.se/foretag/elnat/effekthandel-vast`, (Accessed: 2024-07-26).

[127] UppFlex Project, *Hur kan lokal flexibilitet få rum att utvecklas*, `https://powercircle.org/lokalflex.pdf`, (Accessed: 2024-09-26), 2024.

[128] U. Isberg, L. Jonsson, S. Pädam, A. Hallberg, M. Nilsson, and C. Malmström, "Utvärdering av klimatklivet," WSP, Tech. Rep., 2017.