THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

Flexibility from local resources

Congestion management in distribution grids and carbon emission reductions

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Gothenburg, Sweden, 2023

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Printed by Chalmers Reproservice
Gothenburg, Sweden, May 2023

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Abstract

Flexibility from local energy systems has been discussed as a facilitator for the transition towards a more carbon-neutral energy system. Two use cases of this flexibility are congestion management in electricity distribution networks, and an individual-driven reduction of carbon footprints. However, for taping into this flexibility, incentive mechanisms and an effective operation planning are essential. This licentiate thesis aims to provide new insights into two areas: 1) the design of market-based incentive mechanisms for congestion management in distribution grids, and 2) the operation planning of local flexible asset owners for reducing their carbon emission footprints.

The first area focuses on challenges, design, and evaluation of local flexibility markets (LFMs) for congestion management in distribution grids. The utilized methods include literature review, field studies including meetings and workshops with different actors, scenario planning methods, and demonstration and simulation experiments.

Results for identifying the challenges show that the most impactful and uncertain factors are the willingness and ability of end-users to participate in LFMs besides regulatory incentives for distribution system operators (DSOs). Moreover, five challenges are identified for LFM design including low market liquidity, reliability concerns, baselines, forecast errors at low aggregation levels, and the high cost of sub-meter measurements.

An LFM design is proposed to address the challenges. The design is a triple horizon market structure including reservation, activation, and adjustment horizons which can support decision making of market participants and improve reliability and liquidity of the market. Adapted capacity-limitation products are proposed that are calculated based on net-load and subscribed connection capacity of end-users. The products can reduce conflict of interests, and administrative and sub-meter measurement costs related to delivery validation and baselines. Moreover, probabilistic approaches for calculating the cost and value of the products are proposed that can reduce the potential cost of forecast errors for market participants while providing insights on how the utility and cost of the products can be calculated.

Evaluating the proposed design is an ongoing work utilizing simulations and real-life demonstrations. The most suitable congestion management solution can vary depending on the context and test-system. Therefore, the evaluation should include comparing the design with other congestion management solutions such as power tariffs. A comparison toolbox is proposed to be used by researchers and DSOs including a qualitative comparison framework and a reusable modeling platform for the quantitative comparison. Four cases are quantitatively compared using the toolbox on a sub-area of Chalmers campus testbed: i) LFM+PT+ET (i.e., considering the LFM, power tariff (PT), and energy cost (ET) simultaneously), ii) LFM+ET, iii) PT+ET, and iv) ET. The most recent results show that case (i), has the lowest number of congested hours. Moreover, congestions due to rebound effects from activating the LFM are observed. The comparison of cases (i) and (ii) suggests that enforcing power tariffs besides the LFM can reduce the rebound effects.

The second area utilizes a multi-objective optimization model for identifying CO_2 emission abatement strategies and their cost for Chalmers testbed local multi-energy system. The results of the case study shows that the carbon emission footprint of the local system can be reduced by 20.8% with a 2.2% increase in the cost. The operation strategies for this purpose include more usage of biomass boilers in heat production, substitution of district heating and absorption chillers with heat pumps, and higher utilization of storage. The cost of the strategies ranged from 36.6–100.2 (€/tCO_2).

The results from this thesis can be useful to system operators, flexibility asset owners, policy makers, and researchers who are dealing with the above-mentioned two use cases for local flexibility resources. The thesis can provide insights to these actors by contributing to a better understanding of the challenges, and proposing potential solutions and toolboxes for implementing and evaluating these use cases.

Keywords: Flexibility, local flexibility market, congestion management, distribution system operator, local energy system, emission abatement strategies

Acknowledgments

I want to express my sincere gratitude to my supervisors, Anh Tuan Le, and David Steen, for being always available, supportive, and positive during these three years. Being at this stage would not have been possible without your insightful comments, guidance, and being open to discussions. I also want to thank my examiner, Ola Carlson, for guiding me during my studies, and being available during the up and downs.

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 would also like to thank all the colleagues within the project for their input and many hours of fruitful discussions.

Additionally, a special thanks to all my colleagues and friends at Chalmers for all the afterwork gatherings, fikas, and lunches that we have shared together. I am grateful for all the laughter and warmth. I want to extend this special thanks to my colleagues in our research group for being so helpful and supportive. I am fortunate to work with such wonderful people.

Finally, my deepest gratitude to my parents, my brother, Agnes, and Ashkan for being always there for me. Thanks for your unwavering encouragement, love, care, and support. Your presence keeps the flow in the river of my life.

Nima Mirzaei Alavijeh
Gothenburg, Sweden
May, 2023

Acronyms

BES:	Battery energy Storage
CHP:	Combined Heat and Power
CL:	Capacity limitation
DA:	Day-ahead
DER:	Distributed Energy Resources
DSO:	Distribution System Operator
EMS:	Energy Management System
ET:	Energy Cost
FSP:	Flexibility Service Provider
ICT:	Information and Communication Technology
LEM:	Local Energy Market
LESOOP:	Local Energy System Object-oriented Programming
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
TSO:	Transmission System Operator
VCG:	Vickrey-Clarke-Groves

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CHAPTER 1

Introduction

This chapter presents the problem overview, the scope, the aim and research questions, and the list of publications.

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 emergence of smarter and more active end-users [2]. These trends can lead to 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, heat pumps, etc., in local energy systems has been discussed extensively during the past decade as a contributing solution to the above-mentioned challenges. Flexibility can be technically defined as a generation or consumption power modification activated at a defined time for a specified duration at a specific location [3], [4]. Incentives and coordination mechanisms for activating the flexibility are, however, one of the challenges. Therefore, studying further these mechanisms and actors' behavior can contribute to a smoother transition in the energy system.

The current structure of energy system is complex due to its multidimensional essence including social, technical, economic, and environmental dimensions. Therefore, to put a research on flexibility into perspective, it is essential 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) Use cases 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, solutions to the global warming can be categorized in different pairs of opposites including individual-driven vs. policy-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 life-style, while on the other end, political systems bare the responsibility [5]. Second, besides who bares the responsibility, actors' different value logics 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 own 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 actors' value logics 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 as a policy-driven solutions 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, and physical layer modeling.

Aspect (iii): It is also important to clarify for what purpose flexibility is utilized. Hillberg et al. [8] categorizes the need for flexibility into flexibility for energy, power, transfer capacity, and voltage and illustrates 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 use case of flexibility can be for emission reductions as an individual-driven solution in which some actors may change their behavior to reduce the emissions.

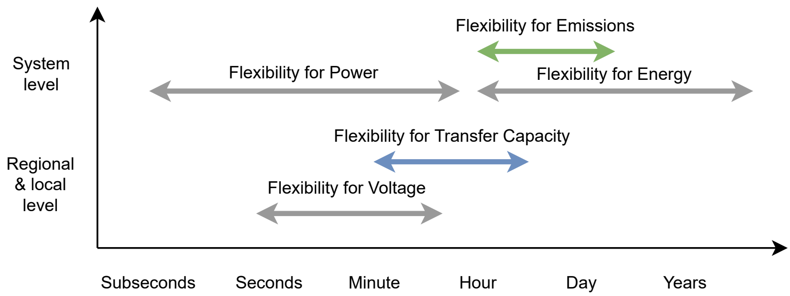

Figure 1.1: Flexibility use cases and their timescale (Adapted from [8])

1.2 Scope and motivations

Considering the above-mentioned aspects, the scope of this thesis is defined in two focuses (Figure 1.2). The first focus is on policy-driven solutions for solving transfer capacity at local and regional levels. It covers mechanism design and operation planning of actors in such a mechanism. The second focus is on individual-driven solutions for reducing carbon emissions by changing operation strategies.

The first focus is about a market-based behavior-influencing mechanism to

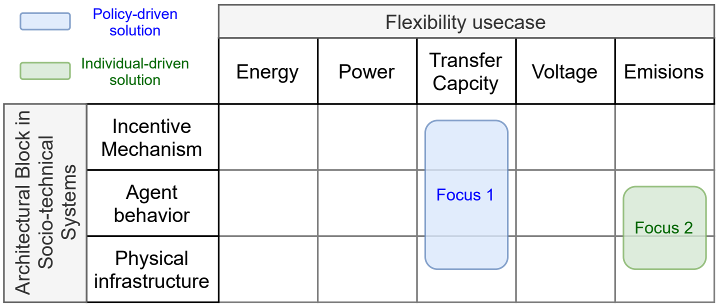

Figure 1.2: The focus of the thesis

incentivize and coordinate local flexibility resources for congestion management in distribution grids. There are different solutions 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 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 not a consensus on the design, and areas such as LFM structure, product definition and characteristics, and additional concerns, such as metering, coordination, and baseline methodologies need to be further studied [17]. Therefore, in this thesis, 1) a step is taken backwards 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 the market actors bidding and operation planning, and 4) the performance of the designed algorithm is evaluated and compared to other congestion management solutions.

The second focus 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 for reducing 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.

1.3 Aim and research questions

This licentiate thesis aims to provide new insights into two areas. The first area is the design of a market-based incentive mechanism to enable flexibility from local energy systems 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 corresponding research questions and papers are:

1. An policy-driven utilization of local flexibility for congestion management in distribution grids:
    - **RQ1.1**: What are LFM design challenges and 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? - Paper II and III
    - **RQ1.3**: How is the performance of the designed LFM compared to other congestion management solutions?
        - How to evaluate and compare congestion management tools? - Paper IV and V
        - What are the comparison results? - Ongoing work

2. An individual-driven utilization of local flexibility for emission reduction
   - **RQ2**: What are operation strategies and their cost for reducing carbon emissions utilizing flexible resources in a local multi-energy system? - Paper VI

1.4 Limitations

Proving the functionality of a market is limited to the designed agents. In real world, strategy space of the agents is infinite while in protected simulation and demonstration environments, the strategy space is limited. Moreover, monetary values presented in this thesis are dependent on the definition of agents and test-systems. Therefore, they should not be interpreted as universal cost or utility for flexibility. The agent definition includes aspects such as agents business model, processes, assets, time of year, etc.

1.5 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 of Chapters 2-5 are as follows. **Chapter 2** provides a background and an overview on the related literature including flexibility use cases, 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.

1.6 List of publications

The following are the list of publications related to this thesis:

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 A. T. Le, "Local flexibility market framework for grid support services to distribution networks," *Electrical Engineering*, pp. 1–19, 2021

III. N. Mirzaei Alavijeh, D. Steen, A. T. Le, and S. Nyström, "Capacity limitation based local flexibility market for congestion management in distribution networks: Design and challenges," *International Journal of Electrical Power and Energy System*, 2023 (Submitted)

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 (Accepted)

V. R. Sharma, N. Mirzaei Alavijeh, M. Mohiti, D. Steen, L. A. Tuan, and P. Löveryd, "Flexigrid tools for real-life demonstrations of local energy system concepts at chalmers campus testbed," in *2023 IEEE Belgrade PowerTech*, 2023 (Accepted)

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, ISSN: 1996-1073

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

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 use cases, 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 aiming to reduce carbon emission footprints.

2.1 Flexibility use cases

In this section, the extended flexibility use cases from [8] (Figure 1.1) are explained by answering three questions: what challenge each use case 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 use case aims for matching the supply and demand of electricity for over time periods longer than an hour. The variation and lack of control over RES generation can cause demand-supply imbalances depending on, for example, if 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. [24] 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 leading to a lower system cost. Moreover, price signals from mechanisms such as wholesale electricity markets can be used for inducing a certain behavior in the local flexibility resources aiming to keep the supply-demand balance at these relatively longer time periods.

Power

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

There already exist various incentive mechanisms for keeping the frequency stable. Examples are the 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 utilized for providing such products for transmission system operators (TSOs).

Grid transfer capacity

This use case aims to solve congestions at regional and local distribution networks. Electrification in 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.

Besides grid reinforcements, there are other solutions suggested to address local and regional congestions 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 use case aims to keep the voltage within a span at local and regional levels in the grid. Voltage lower band violations can happen with connecting new loads along the feeders on medium to low voltage levels due to 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 [25]. There also exist other methods such as market-based and active network management methods which can be utilized to incentivize the local flexibility resources for voltage regulation in distribution networks [26].

Carbon Emissions

This use case 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 congestion management in distribution grids. LFMs are complex multi-dimensional systems including social, technical, and economic dimensions. These markets are under development, and accompanied by various challenges. Therefore, for a successful design, key factors and trends impacting the future of these markets need to be identified besides the design challenges. Moreover, LFMs should be evaluated in comparison to other solutions for finding the most suitable solution from a holistic perspective. In the following subsections, first an overview of key factors and trends impacting the future of LFMs are presented. Thereafter, a review of the design challenges are provided besides a review of evaluation studies for these markets.

2.2.1 Key factors, trends, and future scenarios

As the research is ongoing on the development and evaluation of LFMs, understanding the key factors and trends that impact the future of these markets can contribute to a better design and a successful implementation.

Based on related literature and experiences from previous projects [9], [12], [27]–[29], and besides inputs from four DSOs in Sweden, Switzerland, Turkey, and Bulgaria, twenty key factors/trends are identified for LFMs that are presented in Paper I. The factors are identified for four categories, i.e. technical, social, political, and financial, to provide a more holistic perspective. The identified factors/trends cover, for example, the availability of different DERs, digital grid-monitoring and control, smart and digital end-users, and relevant new competences. In addition, the factors cover tendency of end users for active participation in LFMs, and changes in the regulatory framework regarding 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 included as potential impacting 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, service providers, and researchers. Scenarios are the possible forms of the future that provide narratives for a context and facilitate decision-making [30]. 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 [30], [31]. Scenario planning provides a structured conversation to familiarize decision-makers with different uncertainties and to build a shared understanding of such uncertainties [32].

Scenario planning methods are used in different research areas. In the energy systems area, there exist examples of using such methods in [33]–[37]. However, no study has been found in the context of LFMs.

2.2.2 Design challenges

The design space for markets is a quasi-infinite space including various parameters within auction design, product design, and technical requirements [38]. Therefore, instead of starting with reviewing LFM designs, the literature is first reviewed for finding expected challenges. Thereafter, the different LFM designs are reviewed to find the gap in addressing these challenges. In this section, an overview of commonly mentioned challenges for LFM design is provided by reviewing proposed LFM designs, experiences from different projects, and workshops with DSOs in the FlexiGrid project [39]. The literature gap in addressing these challenges is provided in Section 2.4.1.

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 [40], [41], 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 the participants for declaring 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 larger benefits. The result of such a property is the stability of the mechanism.

If LFM can be seen as an economic mechanism, these desirable properties can be used to elaborate the impact of its design challenges and to identify the gap in addressing these challenges.

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], [29], [42]–[44]. The low liquidity can be due to the geographical limit of the local markets, and a lack of available flexible resources in the transition phase of end-users becoming flexible and LFMs being adopted [3]. A less liquid market is less competitive and more prone to instability [45] and market manipulation [46]. Thus, if the LFM as a whole can be seen as a mechanism, the desirable market property of incentive compatibility can get 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 thus the group rationality property. While 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.

The reliability challenge is partially linked to low liquidity and security of supply for flexibility which is crucial for DSOs to ensure a reliable, secure,

Table 2.1: Negatively-affected desirable market properties as a result of the common LFM design challenges. Abbreviations are E: Efficiency, IC: Incentive compatibility, BB: Budget balance, GR: Group rationality.

LFM design challenges	E	IC	BB	GR	Reason
Low market liquidity		–		–	Potential gaming and uncertainties in flexibility supply/demand
Reliability concerns		–		–	Potential gaming and uncertainties in flexibility supply/demand
Baselines		–		–	Potential gaming, conflict of interests, and transparency issues
Forecast errors				–	Extra costs due to failures in delivery, or wrong estimations for the required/available service quantity
High measurement and ICT costs				–	Extra costs and system complexity

and efficient distribution network as their core responsibility [10]. The local markets are especially presented as a substitute to grid reinforcements [27] that cannot be implemented over-night if there is a lack of flexibility. On the other hand, the flexibility service providers (FSPs), including property managers and real estate owners, can have reliability concerns for return of investments considering a lack of (flexibility) demand and uncertain revenue streams [29], [47]. Moreover, FSPs can be risk averse as flexibility provision can negatively affect the comfort of their tenants, especially if the control of the assets are directly handed to the DSOs [27], [48]. Low liquidity and security of supply/demand can affect market reliability and hinder market access for more risk averse actors. Consequently, as summarized in Table 2.1, it impacts the group rationality property as it can lead to participants leaving the market or not being 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 [42], [49], [50]. [49] evaluates different methods for defining baseline and argue 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 for calculating the baseline would be more challenging. Moreover, they highlight that these products can cause uncertainty, complexity, potential market manipulations, and conflict of interests between the stakeholders. As presented in Table 2.1, the challenges with baselines can impact the incentive compatibility due to potential market manipulations, and the group rationality by introducing uncertainty, conflict of interests, and transparency issues.

The forecast error challenge can be due to a smaller aggregation at local levels [51]. The inaccuracy of forecasts can cause issues for defining baselines in an LFM [49], [52], or in forecasting the behavior of end-users [50] for a cost-efficient delivery of the promised service. The forecast errors can lead to higher costs for all the 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 the group rationality because the participants may choose to not engage or leave the market. This is summarized in Table 2.1.

The last challenge is the potential need for extensive measurements and investments in ICT platforms required for validating the delivery and communications between the 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. Similar to the forecast error challenge, the extra cost and the complexity can impact the group rationality property of the LFM mechanism (Table 2.1).

2.2.3 Evaluation

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

Reference [53] has compared qualitatively LFM, dynamic tariff design, and non-firm 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, non-firm 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 semi-reflective dynamic tariff as a potential solution. However, they do not use a specific structured framework for comparison.

Reference [54] 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, redispatch instruments, and flexibility markets in Netherlands. They have concluded that a holistic consideration of different congestion management incentives as well as other ancillary services is required for an effective congestion management. Moreover, the impact of the incentive on market parties' freedom of connection, trade, and dispatch should be considered for the overall efficiency of the electricity market design. However, the authors do not use a structured holistic comparison framework including social, regulatory, and technical aspects.

Reference [55] 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 considering DER penetration levels and placement of loads. 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 [56] 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 capacity-limitation based LFMs and LEMs in their comparisons.

References [57] and [58] have summarized the congestion management methods with both market based and non-market based approaches. However, the methods focus more on the congestion problem on transmission level. [59] reviewed the congestion management tools for distribution networks with high penetration of distributed energy resources. It covers the market-based methods and direct control methods. The market methods consist of dynamic tariff, distribution capacity market, shadow price and flexible service market. The direct control methods are comprised of network reconfiguration, reactive power control and active power control. However, the comparison is focused on elaborating the 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 [60]. A study of the combination of local energy systems and MESs for carbon emission reductions can be a use case for the flexibility of MESs in local energy systems.

Within the two research areas of local energy systems and MESs, previous studies [60]–[62] have reviewed definitions, trends, challenges, and the categories of literature that provide valuable insight into the topic. For example, Grosspeithsch et al. [61] 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 based solely on cost minimization objectives. However, multi-criterion optimization can help broaden decision making to consider cost, the environment, reliability, social impact, utilization of renewable energy, etc [63]. As global concerns about greenhouse gas emissions increase, carbon emissions become an increasingly important criterion to be considered in optimizing the operation of local MESs. For instance, Majidi et al. [64] proposed a cost and emission framework to assess demand response programs, and Bracco et al. [65] 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. [66] 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 [67], evolutionary algorithms [68], game theory [69], particle swarm optimization [70], genetic algorithms [71], etc.

Furthermore, an optimization model can have a short foresight (close to real-time) or a 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 [72].

On the other hand, optimization with a short foresight lowers the computational time (which would be of value when simulating complex systems) [73] and have lesser challenges with 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 including a large share of RES, or reacts in response to the energy prices from a system with a large share of RES, a close to real-time modeling approach with short foresight can represent agents' (energy technologies') behavior closer to reality [74].

There exist a handfull of studies in the area modeling and optimization of MESs. For example, Wu et al. [67] 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. [75] also used a weighted sum approach in developing 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 that it was carried out only on one customer and not a community of customers. Falke et al. [76] developed a multi-objective model for design and operation of distributed energy systems using a heuristic optimization approach. The model decomposes into three sub-model of heating network planning, buildings' renovation planning, and operation simulation. However, cooling loads and district cooling is not considered in this study. Yan et al. [77] 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 the emissions and the monetary costs are not discussed. In [68], an evolutionary algorithm is used to solve a multi-objective isolated MES model with high share of renewables, including investment in RES as decision variables. The paper shows that different operational approaches may be beneficial for different seasons. In [78], a MES model is developed which includes possible constraints in the energy flow 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 Research gap

2.4.1 LFMs for congestion management in distribution grids

Key factors, trends, and future scenarios

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

In summary, the following can be contributing: 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 has been identified in Section 2.2.2. In this section, the gap in the literature is identified and discussed with regards 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). [47] have categorized the reservation payments as a controversy in LFMs and discuss its advantages and disadvantages. In our previous work [79], we had considered long-term reservations based on a mixed-price of reservation and activation prices; however, the mixed-price approach can increase the market complexity while complicating interpretation of the clearing prices. Moreover, linkage 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. This suggestion, although being helpful for handling DA uncertainties, would not match 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, one-sided VCG is not individually rational for the 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 preventing market manipulations. Some examples filling this gap are long-term reservation payments and multi-bids ([80]) for the first group of approaches, and market monitoring, anti-trust law, and price caps ([47]) 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], [49] 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 functionality of their CL product is dependent on 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 switch on an undeclared electric heater. Since the validation of delivery is done based on sub-meter 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 sub-meter measurements for all flexible assets that can lead to higher costs and complexity for validation of the service delivery. Therefore, a CL product design that is not dependent on 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 relieved.

From a mechanism design perspective, the forecast errors at low aggregation levels have been addressed diversely in the literature. For example, Enera's market allows its continuous auction until 5 minutes before the delivery time [17]. This approach can allow improvement of forecasts as getting closer to the delivery time but it can come at the expense of market efficiency losses as continuous auctions have lower allocation efficiency compared to call-auctions [81]–[83]. Bouloumpasis et al. [79], IREMEL [84], InterFlex [85], INTERFACE [86] markets, and [87] 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 the 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 be contributing. Moreover, proposing a new flexibility product that does not require a baseline and sub-meter 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 evaluation of LFMs with respect to other congestion management solutions for distribution grids. However, a holistic comparison framework including regulatory, social, and technical aspects has not been found. 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 [55], the quantitative studies does not present an scalable, reusable modeling platform that can be used for comparing different solutions.

In summary, a holistic comparison between a wider range of congestion solutions is contributive. Moreover, presenting a comprehensive toolbox to support a systematic comparison of different solutions 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 different solutions under the same system condition.

2.4.2 Operation of local flexibility resources for carbon emission reduction

There exists 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.

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, Focus 1 requires Design Research methodology for designing the incentive mechanism (i.e., LFM) while Operation Research methodology is needed for modeling the agents behavior and operation in both Focus 1 and 2. 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, multi-dimensional phenomenon, involving: people, a multitude of activities and procedures, a variety of disciplines, tools and methods; as well as a micro-economic context [88]. This complex nature of design can

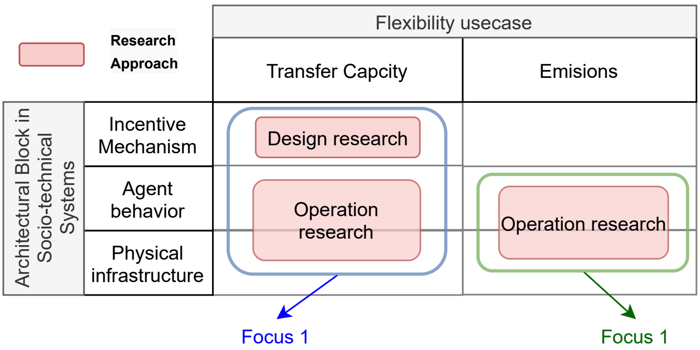

Figure 3.1: Utilized overarching research approaches for each focus

lead to diverse research topics and methods which if not organized under an overarching methodology, can lead to multiple unconnected streams [88] and therefore reducing the potential for delivering value.

The complexity and multi-dimensional nature of design highlight the need for an overarching methodology. 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 [88].

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. [88] 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 support/solution and evaluate its success.

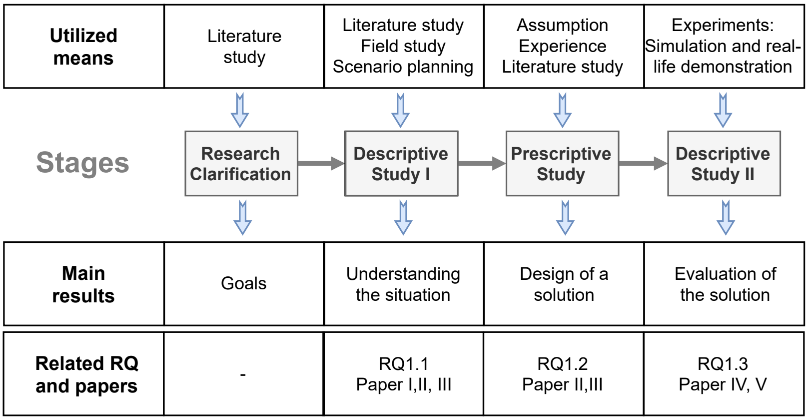

Figure 3.2: Overview of the applied design research methodology (Adapted from [88]). The bold arrows between stages show the main process flow.

To put the methodology into perspective, related RQs and papers for each stage are presented in Figure 3.2. Literature review has been conducted in Stage one to better understand the state of the art, clarify the aim of the work, and define the research questions. RQ1.1 is about identifying the challenges and key factors in LFM design and thus is covered in Stage two which aims to identify the factors that should be addressed to improve the existing situation. Paper I and parts of paper II and III discuss these factors and challenges. RQ1.2 is about proposing a market design that addresses the identified challenges and therefore is 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 evaluation of the design and is covered by stage four which aims to investigate the impact of the proposed solution. This research question is an ongoing work but 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 that 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 modelling techniques used for the structuring, analysis, and solving of problems related to the design and operation of complex human systems" [89]. Quantitative modeling has been mentioned as the basis of most research in the field where "the relationship between control variables and performance variables are developed, analyzed, or tested" [90]. 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 the operation cost or carbon emissions.

Will et al. [90] categorize this model-based research into two classes: empirical quantitative modeling research and axiomatic quantitative modeling. 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 the context of the conducted work in this thesis, papers III and VI include the conceptualization and the relevant model formulations. The problem formulations are mixed-integer linear programming and are solvable using using commercial solvers such as Gurobi. The reflections on the solutions have been presented in each paper.

3.3 Utilized methods

The presented methodologies 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 are case specific. These two methods are, therefore, 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 [30]. 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 [30], [31]. Scenario planning provides a structured conversation to familiarize decision-makers with uncertainties and to build a shared understanding of such uncertainties [32].

Three main schools of techniques for developing scenarios are intuitive logics, probabilistic modified trends methodology, and the French approach La prospective [91], [92]. 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 [91]. This approach was originally used by Pierre Wack at Shell in the 1960s [91]. The purpose of this method is to make sense of situations and developing strategies, while it can also be an ongoing learning activity [91]. 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 [91] 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 [91] 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 [93]. This approach is a more generic form of approaches proposed by Schwartz [94] and the Stanford Research Institute International (SRI) [95], [96]. 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.

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

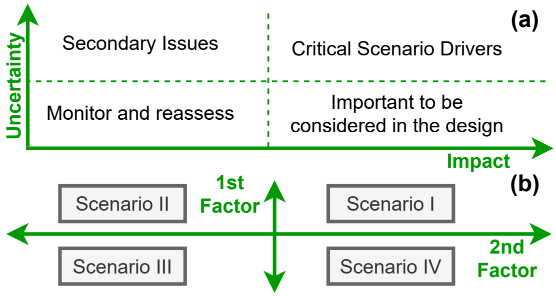

Figure 3.3: Factors ranking and scenario matrix: (a) uncertainty-impact ranking (modified figure from [34], [93]), (b) scenario matrix based on the two most uncertain and impactful factors

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 [97] 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 by two means of computer simulations and real-life demonstrations. The details of experiment setups have been explained in Paper 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 [98] (Paper III), and Chalmers Campus Testbed [22], [99] (Paper IV-VI).

The residential sub-network of CIGRE's European Low Voltage Distribution Network is chosen due to potentials for conducting comparable studies and benchmarking. However, in this network, neither loads are flexible, nor the grid components of the residential sub-network are congested. Therefore, the loads were replaced by six agents out of which 4 are flexible. In addition, the rating of the transformer had to be reduced. For this test-system, load data are taken from [100] and a local DSO in Sweden, and solar radiation data is obtained from [101].

The Chalmers testbed is chosen due to the availability of data and the possibility for conducting real-life demonstrations. The sub-area of the testbed that is going to be used for evaluation of the LFM design is presented in Paper IV, Section IV-B, and Paper V, Section II. Regarding the study conducted in Paper VI, whole campus is considered including district heating and district cooling system. The test system is explained in details in Paper VI. The area utilized for evaluating the LFM design is smaller due the higher complexity of the required ecosystem for evaluating the LFM. The smaller area facilitates troubleshooting and elaborating 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, 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 presented in Paper IV.

The most recent results from evaluation of the LFM design are presented in Section 4.3.1. These results are not published in any of the appended papers due to their recency. Therefore, the details of the utilized setup for the recent results are provided here. The one-line diagram of the utilized network is presented in Figure 3.4. To impose congestions, the active power capacity of the line between buses 07:8.1 and 07:8.1.2 is reduced to 882 kW which is equivalent to 85% reduction. Three agents are defined as in Table 3.1. The specifications of the PV and battery energy storage (BES) of the agents are presented in Table 3.2. At this stage, the results are obtained using prefect forecasts for loads and PV generations.

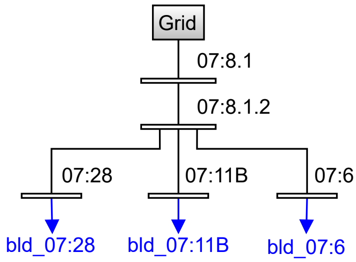

Figure 3.4: One-line network diagram and agents' locations in the Chalmers testbed sub-area that is used for the most recent results presented in Section 4.3.1

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 ($\rho^{\mathrm{P_{tariff}}}$) 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 [102]. $\rho^{\mathrm{gridtariff}}$ is based on the average of the grid tariffs for apartments and houses from [103].

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

Agent id	Bus	Connection Capacity	Flexible	DERs
$\mathrm{bld}_{07:28}$	07:28	1000	Yes	3 InflexLoads, 1 BES
$\mathrm{bld}_{07:6}$	07:6	1000	No	2 InflexLoads, 1 PV
$\mathrm{bld}_{07:11B}$	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	$\overline{e}^{bes}$	$\overline{p}^{bes,dch}$	$\overline{p}^{bes,ch}$	$\overline{p}^{pv}$
$\mathrm{bes}_{07:28}$	$\mathrm{bld}_{07:28}$	250 kWh	95 kW	60 kW	-
$\mathrm{bes}_{07:44}$	$\mathrm{bld}_{07:11B}$	65 kWh	25 kW	25 kW	-
$\mathrm{pv}_{07:11}$	$\mathrm{bld}_{07:11B}$	-	-	-	73 kW
$\mathrm{pv}_{07:6}$	$\mathrm{bld}_{07:6}$	-	-	-	38 kW

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

$\rho^{\mathrm{P_{tariff}}}$ (SEK/kW, month)	$\rho^{\mathrm{gridtariff}}$ (SEK/kWh)	ρ^{tax} (SEK/kWh)	$\rho^{\mathrm{taxreturn}}$ (SEK/kWh)	ρ^{CC} (SEK/kW)
36.25 [103]	0.31 [103]	0.36 [104]	0.6 [105]	0.17[102]

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

With regards to RQ1.1, the aim has been 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 what aspects shall be considered in the design.

Twenty key factors/trends have been identified and presented in **Paper I**. Utilizing scenario planning and by means of surveys in, 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, forming the four scenarios, is made based on the above-mentioned three factors. 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 if 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 the local markets. Due to the monopolistic nature of DSOs, there are regulations that financially regulate DSOs. These regulations can favor capital expenditures over operational costs. Therefore, investing in the infrastructure can be financially more attractive to DSOs rather than using operational measures such as local markets. Changes in the regulatory framework have a profound impact on deployment of LFMs. The developed scenarios are explained in Figure 4.1 and in details in **Paper I**.

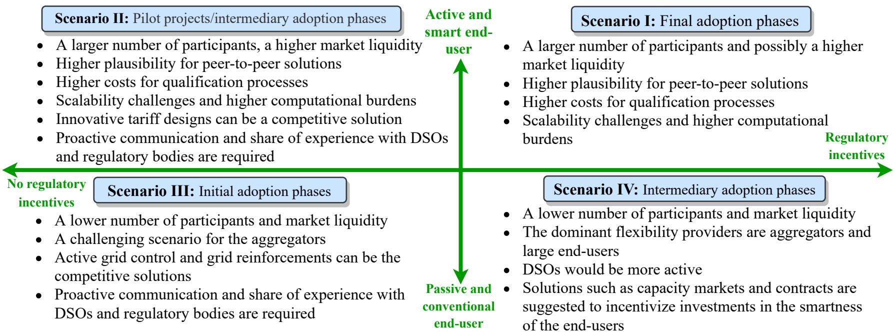

Figure 4.1: Scenario matrix for the future of local flexibility markets

In **Paper III**, five main challenges are identified for a better understanding of the state of art and a better proposal for the 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 linked to the uncertainty shown in the Y-axis of the scenario matrix. The uncertainty is whether the flexible assets are accessible to be involved in local markets. LFM designs that do not consider measures for improving the reliability of LFMs, handling forecast errors, and solving 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 for such 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. A potential LFM design that considers these challenges is proposed in the next section 4.2.

4.2 RQ1.2: A comprehensive LFM design

With regards to RQ1.2, the aim has been to propose an LFM design that considers the identified challenges in RQ1.1. For this purpose, multiple design iterations have been conducted of which two are published/under-review in **Papers II and III**. In this section, the latest iteration, i.e. **Paper III**, is presented.

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 market is organized in three market horizons. In the long-term horizon, the reservation of the product is traded, and in the short-term horizon, the activation of the product. In the intra-day adjustment horizon, adjustments are made to the traded quantities for activation. The markets in all the horizons are double-sided auctions with social-welfare maximization as their objective function. The first two horizons 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**.

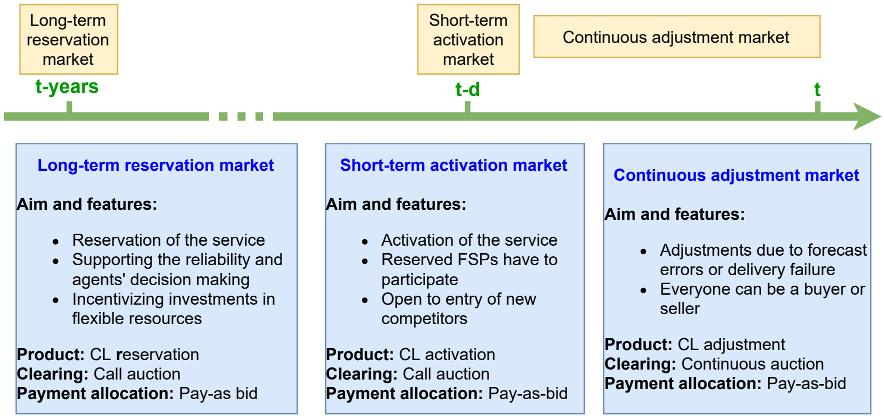

Figure 4.2: Overview of the market horizons

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

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

Figure 4.3 illustrates the products for three FSP types: consumer, prosumer, and generator. The CL-products are defined using net-load and subscribed connection capacity ($\overline{P}^{\text{imp}}$) of FSPs located downstream of the congested component. The net-load is defined as $netload = consumption - generation$ for each FSP. Therefore, negative values represent injections, and positive values the extractions. The quantity of the products are calculated with respect to the subscribed connection capacities of FSPs. As shown in Figure 4.3, there are two options to calculate the quantity of CL-cap for pure generators. An option is to calculate with respect to zero, and the other is with respect to the positive value of the connection capacity. The former is more intuitive as the positive side of the curve is never used for pure generators, while the latter leads to consistency in the definition of the CL-cap. Similar options hold for pure consumers when calculating CL-floor.

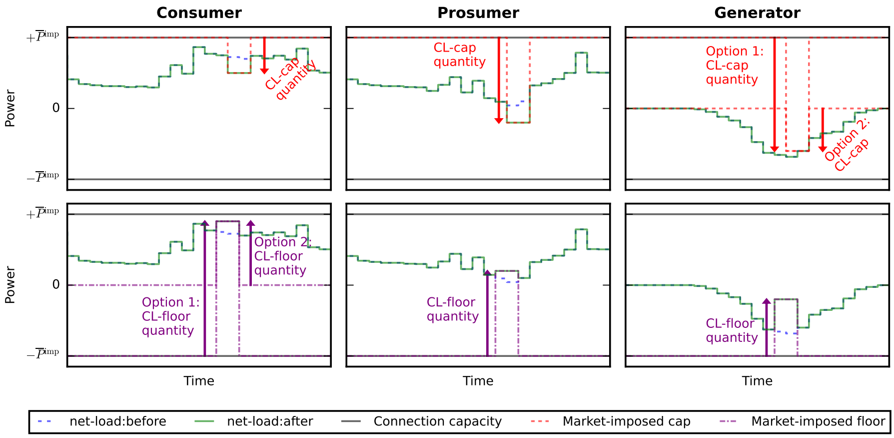

Figure 4.3: Conceptual illustration of capacity limitation products for different type of grid users. CL-cap is for demand-driven congestions and CL-floor for generation-driven congestion.

The summary of measures for addressing 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 reservation market;
- **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 presented solutions, the challenge of 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. The causes outside mechanism design can be geographical constraints, barriers for digitalization and automation, bureaucratic pre-qualification procedures, lack of relevant competences, and contradicting or unclear regulations. Solution to these causes are out of 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-reinforcements. 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 [106] can be done for this purpose.

Furthermore, there exist 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, DSOs can distribute connection capacities by auctions or grandfathering and then the allocated connection capacities can be traded between the end-users on shorter time-frames such as a day or a week. Similar ideas have been discussed in [107]. A potential challenge for this alternative is consumer discrimination regarding capacity prices at different geographical locations. Besides the above-mentioned market-based solutions, tariff-based solutions also exist. There are 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. Such discrimination is not an issue for LFMs since the flexible end-users are rewarded instead of inflexible users being penalized. 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. Furthermore, tariffs are indirect incentives and their impact on the behavior of agents are uncertain which can affect the reliability of such solutions.

The most suitable congestion management solution depends on the context including various parameters such as the size of grids 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. Therefore, LFMs need to be put into context and evaluated in comparison to other solutions in each context to find the most suitable solution or mix of solutions.

4.3 RQ1.3: Evaluation of the LFM design

With regards to RQ1.3, the aim has benn to evaluate the proposed LFM design and compare it to other congestion management solutions. The work is ongoing for this research question; however, a toolbox for the comparison is proposed in **Paper IV** to enable both qualitative and quantitative comparisons with other congestion management solutions. Moreover, Chalmers Campus testbed is improved (**Paper V**) to host the close-to-real-life demonstrations. In this section, the modeling and demonstration platform for evaluating the design is explained. Moreover, the improvements in the testbed that is required for evaluating the LFM design are explained. In addition, the most recent evaluation results are presented in Section 4.3.1.

The proposed comparison toolbox in **Paper IV** enables a systematic comparison of different congestion managements solutions for local system challenges. It consists of two parts: i) a qualitative analytical framework to identify the barriers of implementing different solutions over regulatory, technical, cultural, and complexity aspects; and ii) a scalable and extendable modeling platform called LESOOP to quantitatively assess the 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 4.4 presents the overview of the domains and examples of their content as a Unified Modeling Language (UML) diagram. The content of the solution domain can be different depending on the solution and thus it is shown as an empty block. The abstract classes can be seen on the higher levels of hierarchies in each domain. For example, the Agent super-class can have sub-classes 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 sub-classes such as residential, industrial, and commercial end-users that can have their specific methods and DERs. The domains are connected with 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.

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

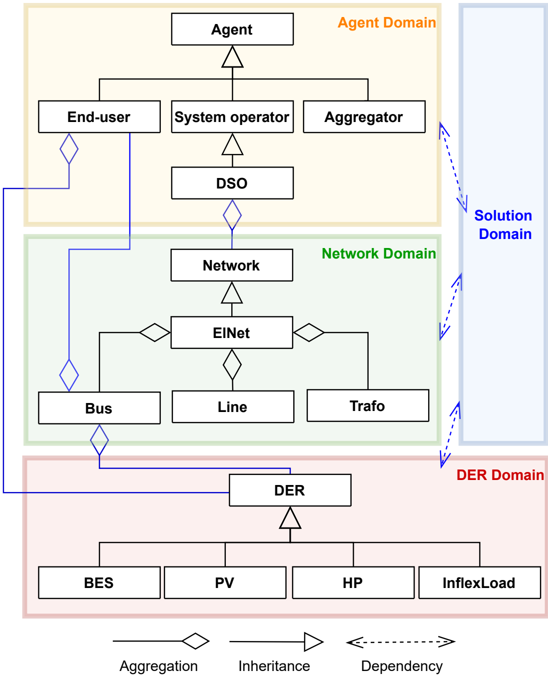

Figure 4.4: Overview of the domains and examples of their content in the form of a UML class diagram

Control or a congestion forecast study, sub-classes 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 reusablity, some tools are composed of a group of methods and are written as generic as possible to be independent from a specific application.

The improvements of Chalmers Campus testbed are presented in **Paper V**. They include developing and integrating the required tools for the demonstration in LESOOP. The tools are, for example, load, PV, and congestion forecasting, energy management systems (EMSs), and bidding algorithms to enable evaluation of the proposed LFM under more realistic conditions. The overview of integrating these tools in LESOOP including their communication and related applications are presented in Figure 4.5.

4.3.1 The most recent evaluation results

In this section, the most recent results on the evaluation of the LFM design is presented where LESOOP and the setting explained in 3.3 is utilized. 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. 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 is presented in Figure 4.6. 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 4.7 shows that the two LFM-related cases have higher occurrence of loadings right below the line capacity compared to the other two cases. This is due to activation of LFM that has shifted the overloadings to values less than the line capacity.

Since the focus of the evaluation is the LFM design, the overloading events for the LFM-related cases are further analyzed. Based on the analyses, the overloading hours for these cases can be divided into two groups: 1) the

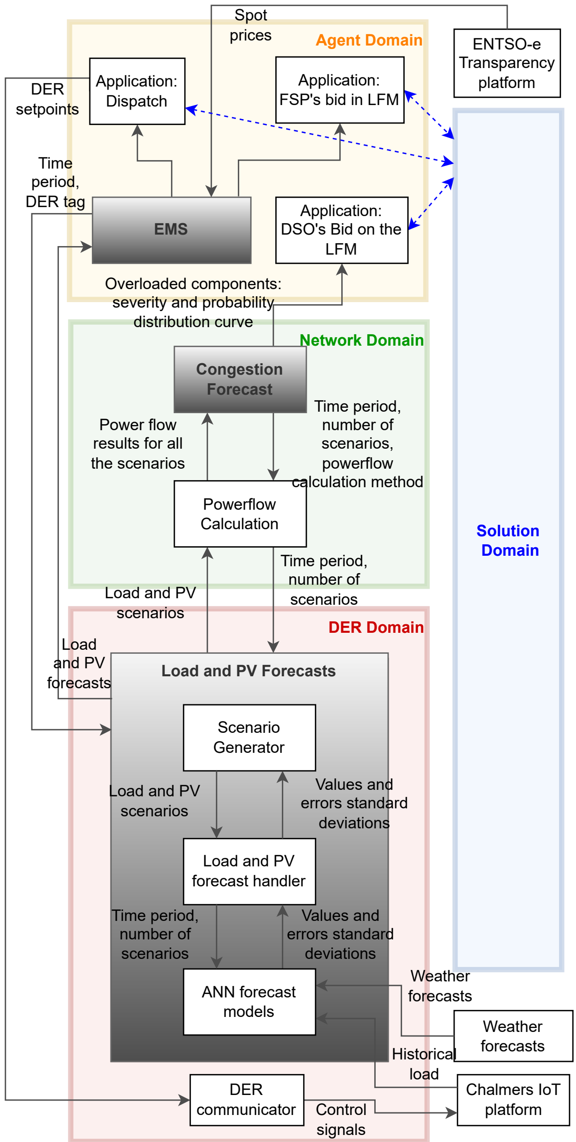

Figure 4.5: Overview of the required tools for demonstrating LFMs in Chalmers Campus testbed

overloadings due to neglecting grid losses in the procurement procedure of the CL product, and 2) overloadings due to rebound effects from activating the LFM.

The first group of overloadings in the LFM-related cases include the loadings slightly over 1.0 p.u. of loading (Figure 4.6). This group consists of 2 hours in case LFM+PT+ET, and 5 hours in case LFM+ET. The reason is that grid losses are not presented in the current setting for procuring CL products. In the current test-system, the losses are very low due to the grid being strong besides 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 3.5 of Paper III.

The second group of overloadings in the 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 congestions 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 for delivering the product for the cleared hours in these days. Compared to the original schedule, the rescheduling include a total increase of 51-63 kW in the loading from the batteries for case LFM+ET. The increase is 18 kW for the hour in case LFM+PT+ET. Since the only varying factor between cases LFM+PT+ET and LFM+ET is inclusion of power tariffs, the results suggest that deploying power tariffs besides the presented LFM design could have reduced the rebound effects in this study.

As an example of the supply-demand curve, hour 11 on the 14th of Feb. in case LFM+PT+ET is presented in Figure 4.8. The cleared CL-cap quantity in this hour is 2118 kW which corresponds to sum of all the connection capacities down the line (3000 kW) minus the line capacity (882 kW).

The flexible agents' dispatch plans on the same date and case are provided in Figures 4.9 and 4.10, where the following are presented: 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}) where positive and negative values represent charging and discharging respectively, the state-of-charge of BES (SoC_{bes}), and the generated power from PV (p_{pv}). The figures show

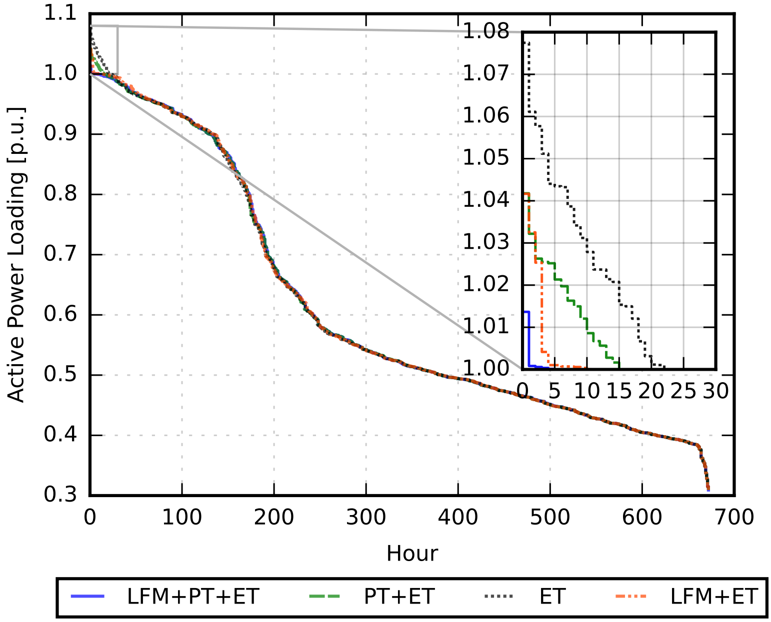

Figure 4.6: The active power load duration curve of the line between buses 07:8.1 and 07:8.1.2 for four cases: LFM+PT+ET: LFM, power tariffs, and energy cost, LFM+ET: LFM and energy cost, PT+ET: power tariffs and energy cost, ET: only energy cost.

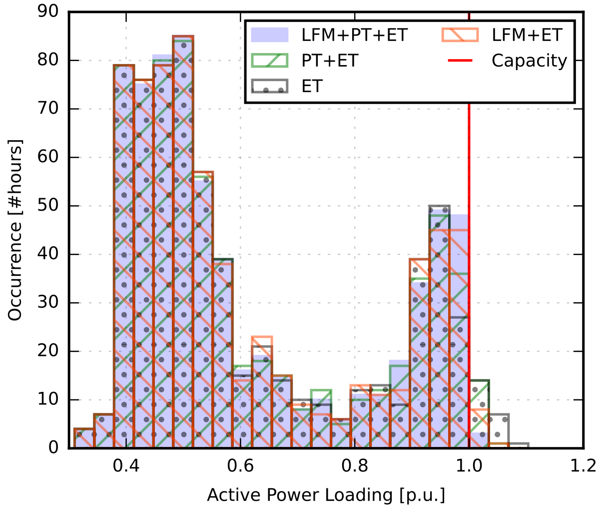

Figure 4.7: The histogram of active power loading in the line between buses 07:8.1 and 07:8.1.2 for four cases: LFM+PT+ET: LFM, power tariffs, and energy cost, LFM+ET: LFM and energy cost, PT+ET: power tariffs and energy cost, ET: only energy cost.

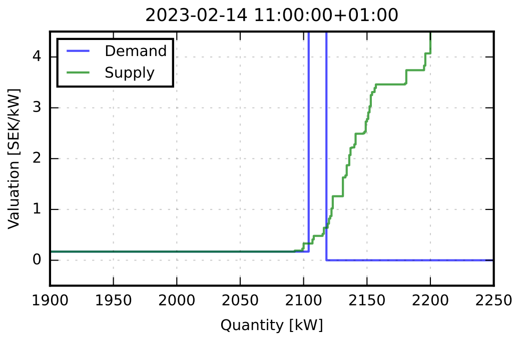

Figure 4.8: Supply and demand curves at hour 11 on the 14th of Feb. for case LFM+PT+ET

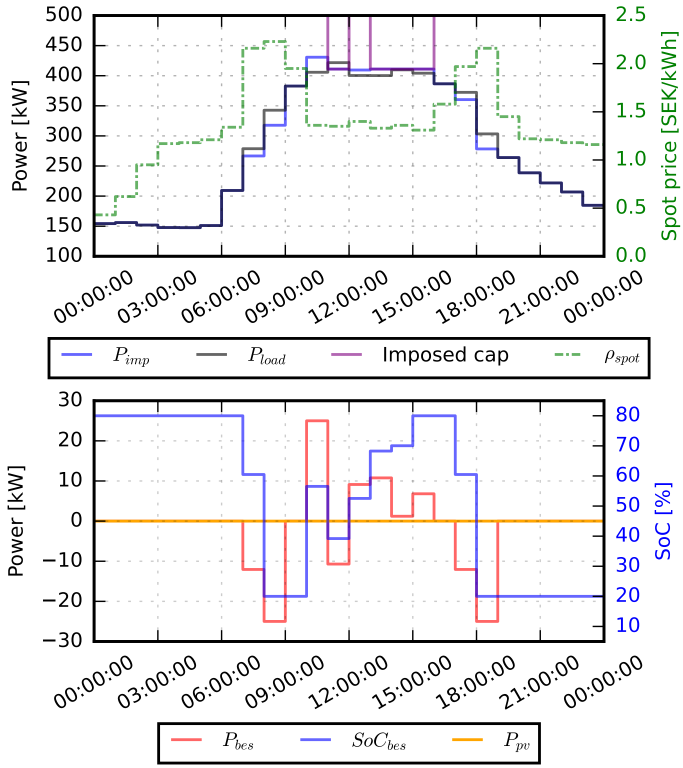

Figure 4.9: Operation of agent $\text{bld}_{07:28}$ on the 14th of Feb. for case LFM+PT+ET

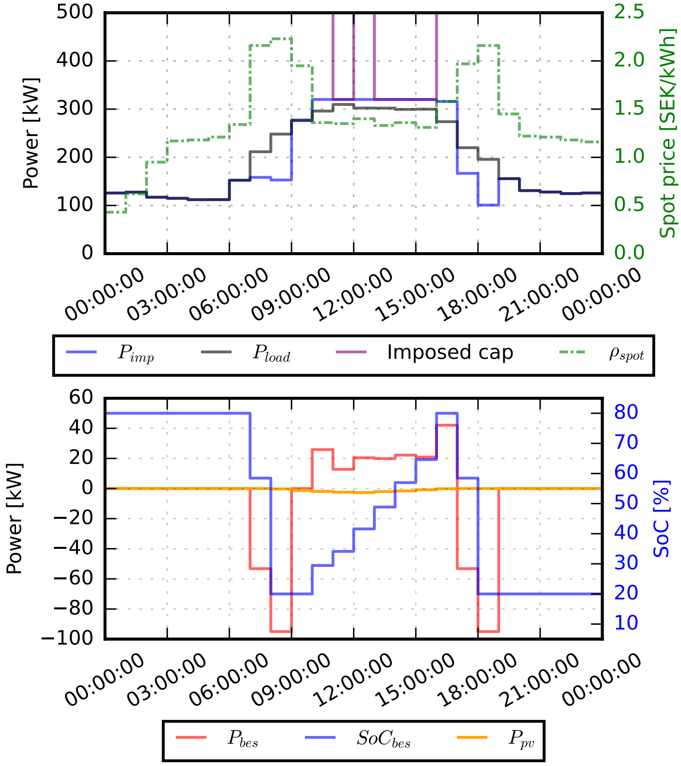

Figure 4.10: Operation of agent $\text{bld}_{07:11\text{B}}$ on the 14th of Feb. for case LFM+PT+ET

how the agents keep their net-loads below the cap imposed 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 a reschedule of the battery belonging to agent $\text{bld}_{07:28}$.

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

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

The results of the case study shows that, by utilizing all identified abatement strategies, a 20.8% emission reduction could be achieved with a 2.2% increase in cost. The identified abatement strategies include: more usage 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 more dispatch of the higher efficiency heat pumps. Furthermore, the utilization of the combined heat and power (CHP) unit showed 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.

This analysis demonstrates that across all abatement strategies the total carbon dioxide abatement cost is 36.6–100.2 (€/tCO_2), which is higher than both the average carbon price in EU Emission Trading Scheme and carbon tax prices in Sweden in 2019, but at the same level as similar pilot projects in Sweden.

The results can provide insights to local MES operators who aim to reduce their carbon emission footprints regarding the strategies and consequent costs. Moreover, similar studies can provide insight to 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.

CHAPTER 5

Conclusions and Future Work

This chapter concludes the thesis by providing the key takeaways from the results besides providing the future research direction of my studies.

5.1 Key takeaways

This thesis has aimed at adding insights on two use cases of flexibility from local resources: 1) incentive mechanism-driven congestion management in distribution networks by local flexibility markets, and 2) individual-driven carbon emission reduction in local multi-energy systems by multi-objective operation planning. In Section 1.3, four research questions were defined for this aim 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 about the design challenges and key factors/trends for the future of LFMs. Incorporating design aspects that support 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 interests and high administrative costs of delivery validation related to baseline-based products. In addition, products that require sub-meter measurements and a more complex communication infrastructure for delivery validation can hinder the adoption of LFMs.

RQ1.2 was about proposing an LFM design that considers the challenges in RQ1.1. A design with a triple horizon market structure including reservation, activation, and adjustment horizons 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 algorithms proposed in Paper III 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**, about the evaluation of the design, it is important to consider that the most suitable congestion management solution is dependent on the context including parameters such as the size of grids and DSOs, regulations, social aspects, the load patterns and its expected rate of increase, lead-time and cost of grid reinforcements, and 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, 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 a part of the answer to this RQ.

Four cases of LFM+PT+ET, LFM+ET, PT+ET, and ET were quantitatively compared using the introduced toolbox on a sub-area of Chalmers campus testbed. The most recent results showed that case LFM+PT+ET (i.e., considering LFM, power tariffs, 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 the agents' assets after the LFM clearing results are published. The comparison of cases LFM+PT+ET and LFM+ET suggested that enforcing power tariffs besides the LFM could reduce the number of congested hours due to rebound effects in this study.

Regarding **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 more usage of biomass boilers in heat production, substitution of district heating and absorption chillers with heat pumps, and higher utilization of storage unit. The analysis showed that the cost of strategies was between 36.6 to 100.2 (€/tCO_2).

The results from this thesis can be useful to system operators, flexibility asset owners, policy makers, and researchers who are dealing with the discussed use cases for local flexibility resources. The thesis can provide insights to these actors by contributing to a better understanding of the challenges, and proposing potential solutions and toolboxes for implementing and evaluating these use cases.

5.2 Future research direction of my PhD studies

For the continuation of my PhD, two paths are considered. First, the presented toolbox and demonstration testbed is to be used for evaluating further the proposed LFM design. This work is essential for a complete study on the proposed LFM design. Second, the power use case of local flexibility for balancing purposes can be an attractive revenues stream for local flexibility assets owners such as energy communities and aggregators. Therefore, studying the potential revenues and algorithms related to participating in frequency regulating markets can contribute to achieving a more complete view on the use cases of local flexibility resources.

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] 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.

[19] I. Bouloumpasis, N. Mirzaei Alavijeh, D. Steen, and A. T. Le, "Local flexibility market framework for grid support services to distribution networks," *Electrical Engineering*, pp. 1–19, 2021.

[20] N. Mirzaei Alavijeh, D. Steen, A. T. Le, and S. Nyström, "Capacity limitation based local flexibility market for congestion management in distribution networks: Design and challenges," *International Journal of Electrical Power and Energy System*, 2023.

[21] 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.

[22] R. Sharma, N. Mirzaei Alavijeh, M. Mohiti, D. Steen, L. A. Tuan, and P. Löveryd, "Flexigrid tools for real-life demonstrations of local energy system concepts at chalmers campus testbed," in *2023 IEEE Belgrade PowerTech*, 2023.

[23] 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, ISSN: 1996-1073.

[24] 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.

[25] 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.

[26] 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.

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

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

[29] 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.

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

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

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

[33] 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.

[34] 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.

[35] 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.

[36] 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.

[37] 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.

[38] 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.

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

[40] 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.

[41] 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.

[42] 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.

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

[44] 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.

[45] 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.

[46] 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.

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

[48] 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.

[49] 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.

[50] 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.

[51] 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.

[52] 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.

[53] 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.

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

[55] 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.

[56] 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.

[57] 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.

[58] 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.

[59] 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.

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

[61] 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.

[62] 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.

[63] 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.

[64] 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.

[65] 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.

[66] 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.

[67] 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.

[68] 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.

[69] 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.

[70] 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.

[71] 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.

[72] 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.

[73] 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.

[74] 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.

[75] 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.

[76] 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.

[77] 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.

[78] 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.

[79] 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.

[80] 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.

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

[82] 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.

[83] 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.

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

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

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

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

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

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

[90] 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.

[91] 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.

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

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

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

[95] 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.

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

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

[98] 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.

[99] 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.

[100] 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.

[101] 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.

[102] 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.

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

[104] 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.

[105] 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.

[106] 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.

[107] 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.