Master's thesis

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

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Quantifying fairness in Local Energy Markets

Master's thesis in Energy and Environmental Engineering
Supervisor: Umit Cali
Co-supervisor: Marthe Fogstad Dynge
June 2023

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Abstract

The integration of renewable energy sources, vital for achieving United Nations Sustainable Development Goals (UNSDGs), presents challenges if not properly managed within the current power grid. Local energy markets (LEMs) emerge as a potentially effective tool in facilitating this transition. However, the establishment of a real-world LEM faces numerous challenges, especially the potential social consequences that could lead to greater societal disparities. This thesis employs lemlab, an open-source tool using agent-based modeling (ABM), to simulate varying scenarios of photovoltaic (PV) and battery deployments in LEMs, taking into consideration the unique characteristics of market participants.

Three key performance indicators (KPIs), Quality of Service (QoS), Quality of Experience (QoE), and Energy Index (EI), are used to measure market performance across these scenarios. Despite their widespread use, these KPIs had limited utility in the scenarios tested. QoS, mainly measuring equality rather than equity, failed to adequately capture perceived market fairness. Both original and modified versions of QoE proved resilient to changes across the different scenarios, due to minimal standard deviations of perceived prices compared to the difference between retail price and Feed-in Tariffs (FiTs). Meanwhile, EI emerged as a valuable tool for illustrating economic distribution within the market, highlighting disparities among households with varying demands or fixed generation capacities.

Importantly, this thesis proposes that subjective participant satisfaction in LEMs, drawing from philosophical and research-based definitions of happiness, could be a more significant factor in market acceptance than objective fairness. This stresses the importance of understanding motivational factors for participation in LEMs, taking into account cognitive biases when interpreting self-reported data. Future research is recommended to explore this area further, employing strategies to ensure a more accurate understanding of participants' experiences and perceptions of fairness in LEMs.

Sammendrag

Integreringen av fornybare energikilder, som er avgjørende for å nå FNs bærekraftsmål, byr på utfordringer hvis den ikke forvaltes riktig innenfor dagens strømnett. Lokale energimarkeder (LEMs) dukker opp som et potensielt effektivt verktøy for å lette denne overgangen. Etableringen av en virkelig LEM står imidlertid overfor en rekke utfordringer, spesielt de potensielle sosiale konsekvensene som kan føre til større samfunnsmessige forskjeller. Denne oppgaven bruker lemlab, et åpen kildekodeverktøy som bruker agentbasert modellering (ABM), for å simulere ulike scenarier for solcelle (PV) og batteridistribusjon i LEM-er, tatt i betraktning de unike egenskapene til markedsdeltakere.

Tre nøkkelytelsesindikatorer (KPIer), Quality of Service (QoS), Quality of Experience (QoE) og Energy Index (EI), brukes til å måle markedsprestasjonen på tvers av disse scenariene. Til tross for bruk i annen litteratur, hadde disse KPIene begrenset nytte i scenariene som ble testet. QoS, som hovedsakelig måler likhet i stedet for likeverd, klarte ikke å fange oppfattet markedsrettferdighet tilstrekkelig. Både originale og modifiserte versjoner av QoE viste seg å være motstandsdyktige mot endringer på tvers av de forskjellige scenariene, på grunn av minimale standardavvik for oppfattede priser sammenlignet med forskjellen mellom utsalgspris og innmatingstariffer. EI har vist seg å være et verdifullt verktøy for å illustrere økonomisk distribusjon i markedet, og synliggjøre forskjeller mellom husholdninger med varierende etterspørsel eller fast produksjonskapasitet.

Denne oppgaven foreslår at subjektiv deltakertilfredshet i LEM-er, basert på filosofiske og forskningsbaserte definisjoner av lykke, kan være en viktigere faktor for markedsaksept enn objektiv rettferdighet. Dette understreker viktigheten av å forstå motivasjonsfaktorer for deltakelse i LEM, og tar hensyn til kognitive skjevheter når man tolker selvrapporterte data. Fremtidig forskning anbefales for å utforske dette området ytterligere, ved å bruke strategier for å sikre en mer nøyaktig forståelse av deltakernes erfaringer og oppfatninger av rettferdighet i LEM-er.

Acknowledgments

This Master Thesis has been written at the Department of Electric Energy at the Norwegian University of Science and Technology (NTNU) and was concluded during the Spring semester of 2023. It was supervised by Professor Umit Cali and co-supervised by PhD candidate Marthe Fogstad Dynge.

Studying sucks, but being a student is incredible. Trondheim has given me the best five years of my life, and I will always look fondly back on the memories I have from here. The student voluntary culture has much of the honor for this. I want to thank all the wonderful persons I have met through UKA, EMIL-Link, NTNUstudent, Energidagen, NTNUI Calisthenics, Energi FK, and while on exchange at Universitat Politecnica de Valencia.

In the first years when I didn't feel accomplished at school, it was incredibly important to build confidence by gaining a sense of mastery in other areas. My volunteer work through student organizations often played that part.

I want to thank EMIL-18 for being an amazing class with so many wonderful and engaged people. And thanks to the people at Hovedbygget-salen for supporting me mentally when the times were tough while writing this thesis, and I couldn't compensate by participating in UKA or something like that.

To gutta i HUSET, you guys have played a crucial part in making studying here in Trondheim such a fantastic experience. I will greatly miss the everyday banter we had together.

On a more serious note, I want to express my gratitude to Marthe and Umit for being exceptional supervisors, I could not have done this without them. A special thanks to Marthe for always being available and being genuinely interested and engaged in supervising me. I am especially grateful that you have shown me that it is possible to combine technical studies with other topics such as psychology and social science. I found great joy in combing my field of study with the personal interests and skills I have developed during the last few years. The experiences gained during this last year from doing that will probably influence the challenges I embark on in the coming years.

Trondheim, 10.6.2023
Erlend Nilsen Anfinnsen

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Chapter 1

Introduction

1.1 Background and motivation

The energy system is moving towards decarbonization. It is needed to meet several of the 17 UN sustainable development goals (UNSDG). 7 - Ensure access to affordable, reliable, sustainable, and modern energy for all, 11 - Sustainable cities and communities, and 13 - Climate action all depend on an energy system adapted to deal with high penetrations of renewable energy [1]. Undoubtedly, it is important to reach these goals as quickly as possible, and it only gets more urgent with each passing day. Furthermore, several other goals rely on the electrification of industry and transportation, which will put the electricity grid under further pressure.

The growing trend of households investing in PV panels, and becoming prosumers, is increasing the complexity of local energy balancing markets due to the volatile nature of PV energy and the surplus it produces. The current electricity grid is ill-equipped to manage these challenges. Local Energy Markets (LEMs) are emerging as potential solutions, offering a decentralized trading platform that connects geographically close consumers, producers, and prosumers. While ample research exists on the technical aspects of LEMs, studies integrating both technical and social perspectives are less common, despite the potentially significant impact of LEMs on individuals and communities [2], [3], [4], [5].

The complexity and heterogeneity of actors in LEMs pose a unique set of challenges in evaluating their performance and impacts on various stakeholders. This calls for robust and nuanced analytical tools. One such tool is ABM, which captures the interactions among individual actors and their collective outcomes. The power of ABM lies in its ability to reflect the diversity and distinctiveness of the participants involved in energy markets, thereby providing an ideal platform for studying the social aspects of LEMs. Key Performance Indicators (KPIs), such as Quality of Service (QoS), Quality of Experience (QoE), and Equality Index (EI), are already tested tools for gauging the efficiency and efficacy of LEMs. However, these traditional KPIs might not fully capture the complexities of perceived fairness. This thesis aims to assess how well different KPIs perform across various LEM scenarios, explore the possibility of refining established KPIs to better measure perceived fairness, and examine the impacts of proposed pricing mechanisms on welfare distribution

Books based on academic research have been used in the discussion part to give a broader perspective of the interpretation of fairness in LEMs than what ordinary literature within the research field does. Those are Yuval Hararis Sapiens [6] and Daniel Kahnemans Thinking, Fast and Slow [7]. As of the author's knowledge, merging the insights from Kahneman's book in an Energy justice perspective has not been done before, but is highlighted as a strong tool to better understand the flaws of self-reported motivations and experiences of participating in a LEM, and how to avoid these. The author also provides specific recommendations to implement his theories. The author also employs insights from the books of Harari and Kahneman to present a unique perspective on the importance of perceived fairness in LEMs, a viewpoint that, to the author's knowledge, has not been previously discussed in the literature on this topic.

The aforementioned points guide the research questions in the following problem description.

1.1.1 Problem description

This paper aims to research the following questions:

- How do the different KPIs, QoS, QoE, and EI, perform across varying LEM scenarios?
- Is it possible to modify established KPIs to better capture the perceived fairness in the market?
- How does the proposed pricing mechanism affect the measured welfare distribution in our model?
- How can insight from social science literature be adapted to researching fairness in LEMs?

To answer these questions, a literature review will be conducted on LEMs, energy justice, ABMs, and how to measure fairness in LEMs. Further on, different scenarios are simulated in lemlab and the outputs are used to calculate the aforementioned KPIs. Modified versions of the introduced KPIs are proposed and analyzed as well.

1.1.2 Approach

In this thesis, lemlab an open-source tool that incorporates ABM, is used [8]. The tool allows us to simulate a range of scenarios within a LEM, considering different quantities of PVs and batteries, as well as the diverse willingness among participants to pay a premium for PV-produced energy. lemlab has been used for modeling, and extracting the output data and market plots. While Python has been used for plotting the KPIs.

1.1.3 Structure of the thesis

Chapter 1, *Introduction*: This chapter sets the stage for the research, establishing the background and motivation behind the thesis, and giving a brief description of the problems being addressed.

Chapter 2, *Decentralization of the power system and market*: This section provides an exploration of the concept of power system and market decentralization, discussing key components like distributed energy resources (DERs) and demand response (DR), the current state of the power system and market, and the emergence of LEMs.

Chapter 3, *Energy justice*: In this chapter, the thesis delves into the idea of energy justice, touching on academic definitions of fairness and the introduction of energy justice, as well as its various dimensions including distributional justice, recognition, and procedure.

Chapter 4, *Agent-based modeling*: This section introduces ABM and its relevance to the research. It also highlights some specific models and discusses the use of ABM in LEMs.

Chapter 5, *Methodology*: This chapter explores the research methods used, focusing on the application of lemlab, elaborating on the specific components of this approach, and detailing the different tested scenarios.

Chapter 6, *Results*: This section delivers the outcomes of the thesis, presenting findings on the quality of experience, equality index, quality of service, and market plots.

Chapter 7, *Discussion*: In this chapter, the results are examined and interpreted, providing insights into potential implications and real-world effects.

Chapter 8, *Conclusion*: The concluding chapter encapsulates the findings of the thesis, and suggests potential areas for further research in this field.

Chapter 2

Decentralization of the power system and market

2.1 Distributed energy resources and demand response

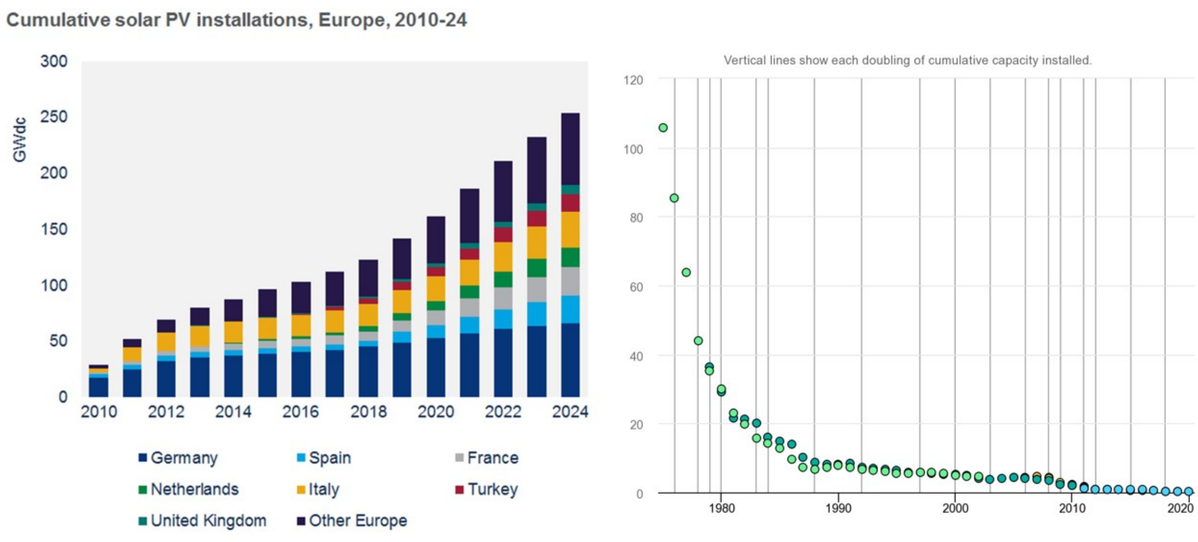


Figure 2.1: Development of PV sales and prices, taken from [9] and [10]

As much the theoretical foundation is closely related to previous work conducted by the author [11], the following sections are similar: chapter 2 and chapter 3, with the exception of section 3.7 and section 3.8 which were written for this thesis.

The definition of DER varies, but in general, it is defined as any source of electric power of limited capacity, directly connected to the electricity grid, close to where it is consumed by end users [12]. For regular households, DERs will usually be rooftop PVs, whose sales have increased drastically in the last decade due to large price reductions [13]. A household, or consumer, that has an installed production capacity, is defined as an *prosumer*. Ref. Figure 2.1 show the development of PV prices and installed capacity during recent years and estimated development in the coming years. The primary motivators for people to buy PVs are reduced electricity bills and to lower their own carbon footprint.

The repayment period will vary from geographical location and electricity prices, but in general, now the payback period is estimated to be 10-20 years with subsidization, while the expected lifetime of the products is a minimum of 25 years [14]. An example from [14] gave a payback period of 15 years, with public subsidies in Norway. Currently, several countries in Europe offer some subsidization for private persons investing in PV [15]. The increasing economic viability of rooftop PV has led to a massive deployment among households across Europe.

However, the increased penetration of DER also presents challenges to the distribution grid. Unregulated, DERs as PVs can have a negative impact on power quality, voltage quality, system stability, and protection systems due to the volatile nature of weather-based energy sources [16]. If not addressed in some way, increased PV penetration can lead to expensive investments to upgrade the existing grid. The key for the system operator is to regulate the PVs in a way that they can be a resource and not a liability to the grid.

DR is one of the solutions that can contribute to integrating more DERs into the current electricity grid. DR are all intentional changes to electricity consumption patterns done by end users regarding altering the timing, the level of instant demand, or total electricity consumption [17], often in response to a price signal given by the system operator. These measures can materialize themselves as waiting to turn on the washing machine to avoid peak load hours or reduce the heating during peak load hours. Lastly, the installation of DERs can reduce the demand for electricity from the grid. This is where PVs among end users come in. Being able to be self-sufficient during peak load hours contributes to lowering the grid load.

Usually, the distribution system operator(DSO) and transmission system operator(TSO) are the ones that invest in DR since they have the advantage of lowering the load on the grid during peak load hours. For example, in Norway, the grid tariff was changed by the DSOs to be priced based on the average of the three highest peak loads caused by each consumer separately [18].

2.2 The existing power system and market

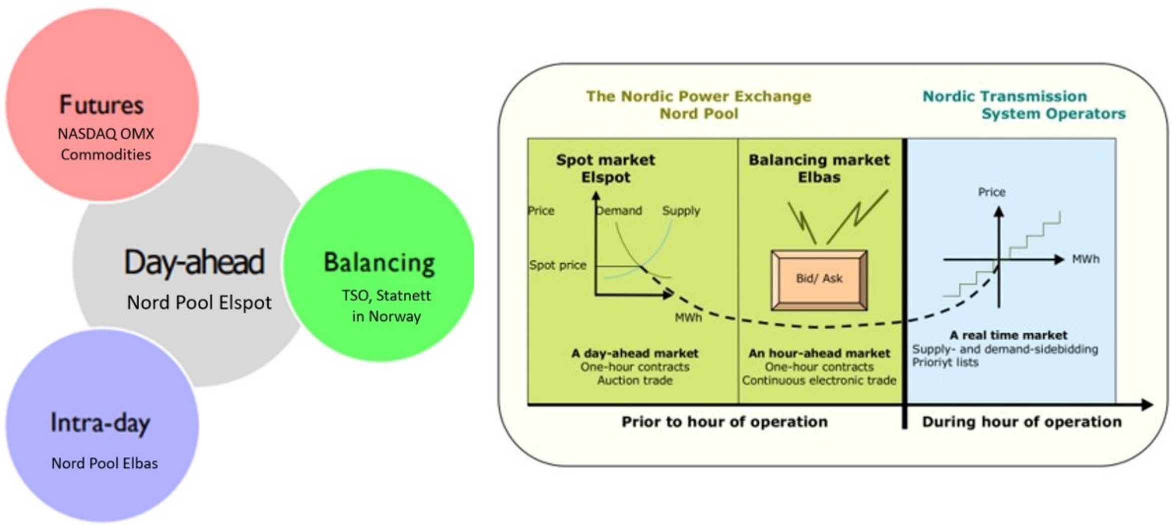


Figure 2.2: Illustration of the current electricity trading system. This figure is taken from [19]

The current energy market is a top-down-oriented solution. Figure 2.2 shows a visualization of the current system. Traditional energy generations such as hydropower, nuclear power plants, and fossil power are connected to the transmission grid run by the TSO [20]. The transmission grid can also be connected to other grid-scale generators such as grounded PV and wind farms and large consumers, such as power-intensive industries. Finally, most energy market trades are conducted through a trading platform. In a North European context, this is NordPool [21]. Further, the high voltage transmission grid is gradually transformed down to medium and low voltage distribution lines in the distribution grid, operated by the DSO. The DSO is responsible for distributing the electricity to end users such as households and smaller industrial customers [20]. At the distribution grid level, retail energy providers are located. They buy electricity at the wholesale market and sell it directly to the end users at prices they control. There can also be independent renewable energy producers, or DERs, who produce a smaller total effect and are therefore connected to the distribution grid. Finally, the DSO can cooperate with new energy providers. They can act as a community manager in a LEM, or just give other services such as home energy management.

Electricity trading markets are organized in different manners around the world, but as this thesis focuses on the Northern European continent, only the relevant structure of this market will be presented. In the northern European market, NordPool is the trading organization managing the matching of demand and generation. Figure 2.2 shows a visualization of the current trading system. The market is divided into several sub-markets. Firstly there is the futures market, which consists of financial contracts with time horizons of up to six years [19]. It is run by NASDAQ OMX Commodities, which is part of NordPool.

After that comes the day ahead (Elspot). It is a financial market, so no one is forced to generate or consume. It is a central trading solution, so all generation and consumption bids are placed at the same time anonymously to the market operator, which in a European context is NordPool. The market clearing algorithm matches the bids and offers. The market clearing price is decided from where the cost of bids and generation meets. This is seen today as the central instrument for the everyday matching of electricity supply and demand. The market is usually cleared 12-36 hours prior to actual operations [19]. On the other hand, the intra-day market (Elbas) is based on bilateral contracts that are centrally organized, instead of centralized trading. That's because of fewer market participants and less liquidity involved. The objective of this market is to adjust the production and demand between the day-ahead market and actual operations [19].

Lastly, there is the balancing market, which the regional TSO runs to maintain the security of the energy supply. It is used to adjust the imbalances of the day-ahead market clearing. This is the market of last resort since it's a real-time market. Together with the day-ahead and the intraday market, the balancing market makes up the *wholesale market*. Somewhere in this system, LEMs have to fit, but there is yet no common agreement where this will be[22]. The next section will present an introduction and literature review of LEMs, including proposed suggestions on where LEMs can fit into the existing power system and market.

2.3 What are local electricity markets?

Briefly put, a LEM is a decentralized trading solution that creates a connection between consumers, producers, and prosumers that often are geographically closely located.

The purposes of LEMs can be summarized to be the following [23], [20]:

- Balance local demand to match intermittent supply

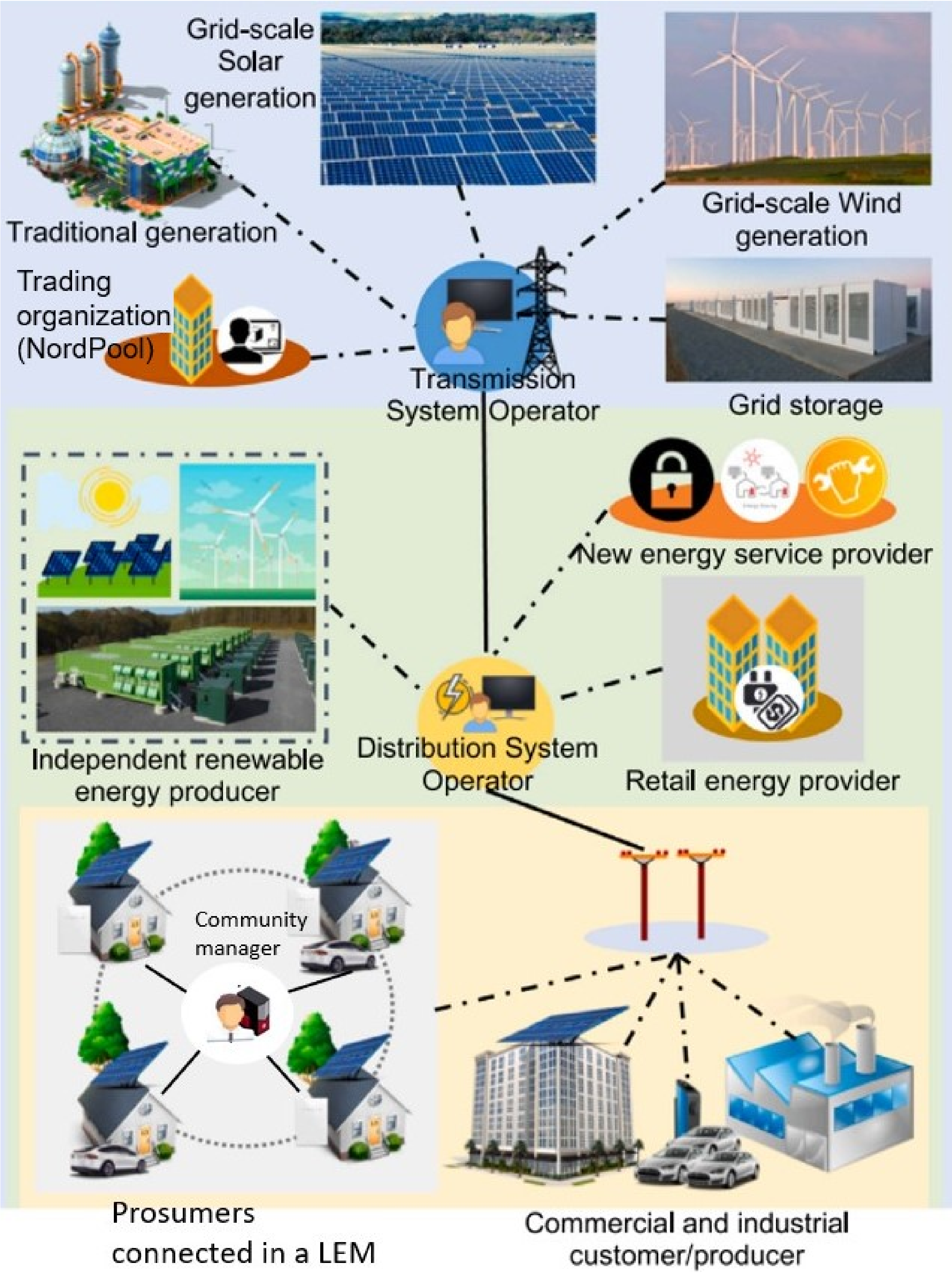


Figure 2.3: Illustration of the current energy system. This figure is inspired by: [20]

- Manage congestion and transmission/distribution constraints
- Replace/postpone grid investments with the utilization of local flexibility
- Increasing consumer participation and knowledge around environmental-friendly energy consumption
- Giving consumers a better choice of supply and the possibility to produce and sell their own energy
- Empowering consumers through a focus on trust, transparency, and openness

There exist several kinds of market designs for LEMs.[20] divides them into three different kinds of markets: full peer-to-peer (P2P) markets, community-based markets, and hybrid markets. These will be presented in the next three subsections.

2.3.1 Full P2P markets

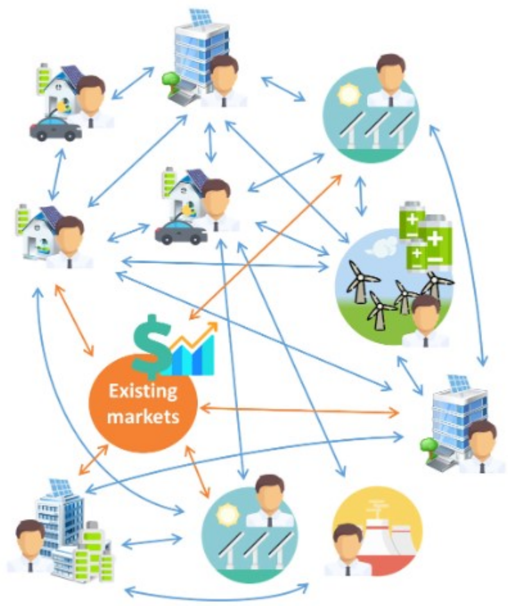


Figure 2.4: Illustration of a P2P market design. This figure is taken from [20]

A P2P market is based on peers that directly trade with each other, without the involvement of a third company. This is made possible through bilateral contracts between peers, which makes it possible for peers to prioritize their preferences on for example green or local energy. It exists several examples of tested models of full P2P markets. Ref. [24] created a P2P market consisting of bilateral trading between EVs, instead of charging them from the grid, like they usually do. These kinds of solutions are gaining traction. It's possible to describe how the market model works through an objective function, constraints and parameters, but in this text, this will only be done for the specific model to be analyzed later. Put briefly, the objective function of a P2P market will aim to minimize the cost of each individual peer, subject to individual and market-related constraints [25].

The challenge of full P2P markets is scalability due to the drastically increasing complexity of the negotiation process between peers when the market size increase. Also predicting the behavior of peers could prove to be a challenge due to the lack of centralized control [20]. But on the other hand, P2P markets have the advantage that it's easier to guarantee the privacy of the peer than other market models. This is because each peer only has to share the power and price that it wants to trade and not sensitive information like detailed consummation patterns [26].

2.3.2 Community based markets

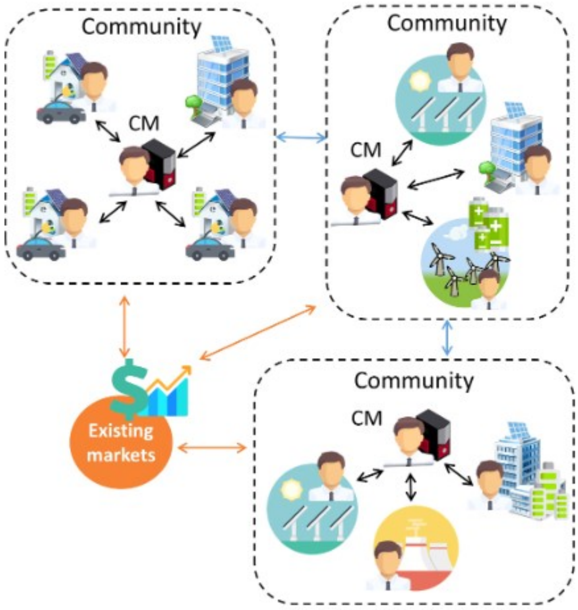


Figure 2.5: Illustration of a community-based market design. This figure is taken from [20]

Meanwhile, in a community-based market, there is a community manager(CM) that facilitates the trades between the peers and manages the LEM. These peers will usually be a group of neighboring prosumers and consumers due to their geographical closeness. It can also be community-based om members that share common goals, such as using more renewable energy instead geographical closeness. There are several entities that can take on the CM role. A possibility is a new energy service provider(NESP). The NESP, or another CM, will have to extend its operations towards the wholesale market to connect the market to the regular grid. Then they will function as an *aggregator* as well. A proposed solution would be for the aggregator to connect the LEM to the day-ahead market [20].

But the DSO could also branch out and take the role of a CM itself. This will be outside the usual operations of the DSO, but since it is in their interest to exploit the capacity of the grid in the best manner possible, they are also relevant for taking on this task [25]. Taking on this role also aligns with the interest of the DSO in facilitating DR.

Expressed mathematically, the objective function of a community-based market aims to minimize the total cost of the entire community and not just one peer. This can of course affects peers in different ways depending on how much potential they have to save [20]. To make this possible, the peer would have to share potentially sensitive information to the CM, such as consumption patterns. On the other hand, one certain advantage of the community-based market is that managing all the trades within the CM will greatly reduce the scalability problem compared to a full P2P market [26].

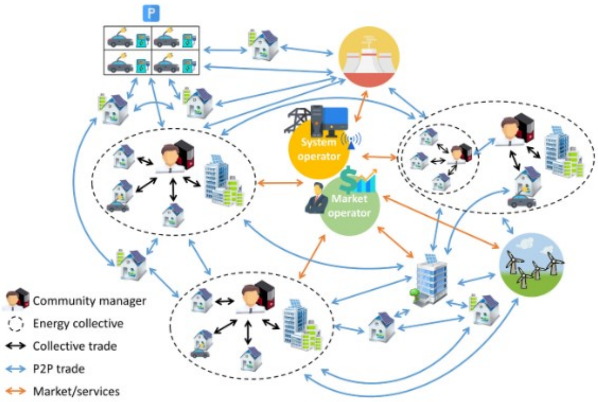


Figure 2.6: Illustration of a hybrid market design. This figure is taken from [20]

Market structure	Advantages	Challenges
Full P2P market	-(1) Empowering participants by giving them freedom of choice of energy source -(2) Less need for exhange of sensitive information	-(1) Cost more in term of scaling up due to the decentralized structure -(2) Harder for system operator to predict behaviors from the peers
Community-based market	-(1) Easier to scale up due to the centralized nature of the marker -(2) Facilitating cooperation and the relationship between the peers in height the community -(3) Potential new business areas for the DSOs working as a CM	-(1) Distributing the savings gained from the market evenly -(2) Sharing of potentially sensitive information with CM -(3) For the CM: aggregating and satisfying the demands of every peer
Hybrid market	-(1) Synergizes well with both of the other two market solutions Challenges	-(1) Coordinate trading between the submarkets and individual peers

Table 2.1: Main advantages and challenges associated with different LEMs structures

2.3.3 Hybrid P2P market

A hybrid market is a combination of a full P2P and community-based market. It can be seen as a layer-wise system where community-based markets and bilateral contracts co-exist between communities or other entities. There can also be smaller communities nested within larger communities. Some papers have started to look into this approach. Ref. [27] created a hybrid market where there are three different levels. The upper level divides the grid into cells where they trade with each other. At the second level, there is trading between the microgrids in this cell. At the third and lowest level, a community market is implemented for each microgrid.

The advantage of a hybrid market is that it synergizes well with both previously mentioned solutions, and can co-exist with one or both. On the other hand, it has to coordinate the trading between the submarkets and the individual peers [20]. The objective of the hybrid market will be to minimize cost for the different energy collectives and individual parties taking part in the trading market. Finally, Table 2.1 has been created to summarize the different advantages and challenges of the market designs.

2.3.4 Key challenges and opportunities

Several challenges upon realizing LEMs have been identified in the academic literature. Ref. [25] has done a comprehensive literature review of challenges LEMs potentially can face, and found 48 of them, which can be divided into 5 categories:

- Optimal utilization of distributed supply
- Optimal utilization of demand response
- Efficient and secure operation and technical implementation of localized markets
- Existing and emerging legal boundaries
- Socioeconomic aspects and human interaction

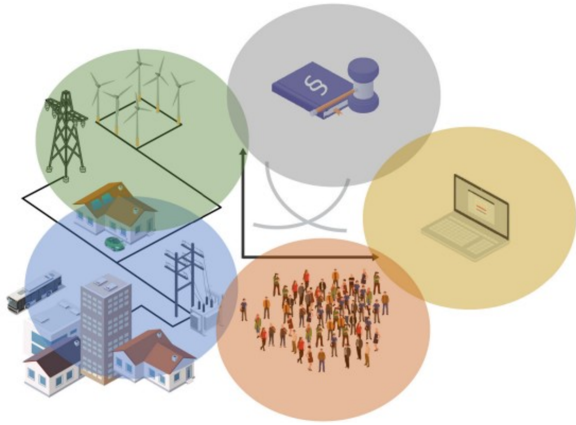


Figure 2.7: Main identified challenges in [25]. Distribution of generation(green), legal framework(grey), decentralization of markets(yellow), social aspects(red) and integration of demand response(blue)

Utilization of distributed supply

One of the objectives of creating LEMs is to utilize better, and incentive increased installed capacity, of local energy production from renewable sources. That will result in more DERs in a large number of locations in the grid. As discussed in previous sections, this presents several new challenges that must be overcome.

One of those is structural challenges. Distributed generation has a higher kW price than traditional localized generation [28]. Prioritizing to invest in distributed generation from an economic perspective is ineffective compared to centralized generation, and can be considered as wasting economic resources. This economic inefficiency of distributed generation poses a challenge.

Furthermore, higher penetration of distributed generation leads to challenges for the operations of grids. Ref. [29] and [30] list up changes in line losses, changes in voltage levels, changes in power quality (for example voltage flickering), changes in fault current levels, changes in requirements of protection systems and a potential reduction in system reliability. The traditional top-down approach to electricity production and consumption only flows one way. However, with a higher penetration of distributed production, this flow can, and will, go both ways and change continuously. This is one of the causes of the mentioned problems, and will mainly affect power quality in different ways, such as system frequency.

However, if implemented well and optimal utilization of distributed supply is achieved, several benefits for LEMs arise. It will be a big step towards the liberalization of energy markets. Furthermore, it will contribute to peak shaving opportunities, reliability, and power quality support. Finally, it facilitates the installation of more renewable generation in the grid [31].

Utilization of demand response

Managing demand response in LEMs can also be challenging. Especially with deferrable loads, for example, charging of EVs or water heaters. Large-scale aggregation of these loads through LEMs, combined with centralized pricing signals can give load kickbacks. This is caused by large numbers of electrical utilities simultaneously getting turned on. This effect has to be considered when aggregating demand response [25]. Another challenge is computational power. Ref. [32] found that utilities with storage capacities, such as EVs, local batteries, or water heaters have the highest economic benefits. Although these kinds of problems are very demanding computation-vice. This can cause difficulties when trying to find the global optimum, and then the best solution. There are other factors that also negatively affect computational complexity. Such as the fact that different forms of demand response require different measures [33] and that the algorithms solving the problem have to be able to perform real-time control [34].

Decentralization of markets

When creating a practical LEM, it's important to consider factors such as computational complexity, modeling the grid for decentralized power flow, and ensuring that all solutions work seamlessly together. Key components such as grid connection, the microgrid setup, the pricing and market model, the trading system, and the regulation behind it all have to work together. Whether this happens or not is decided by the actions taken by the market participants [35]. A concrete example of this would be the cooperation between the DSO and the TSO, which is vital for the stability of the grid. They will have to share forecasts and measurements, coordinate balancing services, and power quality control [36, 37].

Another factor is the start-up costs related to developing the needed information and communications technology (ICT) infrastructure to facilitate LEMs. In the physical layer, that usually means applications of smart grid protocols[38]. For the virtual layer, blockchain technology is looking like a promising solution [25]. Blockchains are the key enabling technology for crypto-currencies, which have gained popularity in recent years. Several papers argue that blockchain will play a key role in bringing the decentralized LEMs to life in the real world [25], [20], [39]. Blockchain technology presents a uniquely fitting solution for the evolving demands of LEMs due to its decentralization, transparency, and security features. Blockchain's ability to facilitate peer-to-peer energy trading without intermediaries can enhance overall efficiency while reducing transaction costs. Moreover, the transparency of blockchain, with its immutable ledger of transactions, fosters trust among market participants. All parties can independently verify energy production, consumption, and trading transactions, promoting fair and transparent pricing based on genuine supply and demand. Security is another crucial advantage. The cryptographic nature of blockchain, reinforced by consensus algorithms, makes it highly resilient to fraudulent activities and tampering, which is essential in a trading system where trust is paramount [25]. Even though many look at blockchains as the way to go in the future, it should be mentioned that LEMs can exist without this technology[20].

Legal framework

The EU Directive 2019/944 [40] allows the consumers to go together to form what the EU calls "citizen energy communities". This creates the legal foundation to make LEMs possible. On the other hand, the provisions adopted in the current EU directive are possible to interpret. This is because no "one size fits all" solution can be used to facilitate local energy trading [41]. This leaves room for interpretation that others can exploit. For example, stakeholders that profit from the existing power system can exploit this, or lobbying, to prevent the possible loss of power and influence [42]. In general, the reorganization of a highly regulated industry, such as the energy industry, is a highly challenging piece of work. It will need a wide range of real-world implemented case studies to be able to change the current system [43].

Furthermore, the trading of electricity within a LEM has to be legally allowed. For example in Norway, prosumers are currently only allowed to sell their surplus energy to retail energy providers. Even though the Norwegian Water Resources and Energy Directorate (NVE) recently announced it wants to test out energy exchange within housing associations and industry buildings [44], there is still a way to go for full legalization of electricity trading for private persons with each other.

Social aspects

The last main challenge mentioned is the social aspects. In a review of 48 papers done by [25] on the topic of key challenges for LEMs, only 8 papers addressed the social aspects of these markets, while in comparison 37 papers focused on the decentralization of markets. Additionally, the authors found that real-life projects focused on social justice within LEMs are in the minority, as seen in Figure 2.8. Other research has reached similar conclusions, highlighting the need for further study on the social aspects of LEMs [2], [3], [4], [5].

As the aforementioned texts notes, it is important to examine the social aspects of LEMs because these markets have the potential to significantly impact the lives of individuals and communities. The design and implementation of LEMs can either facilitate or hinder access to energy, which can have significant implications for issues such as overall quality of life[4]. Therefore, it is crucial to consider the social impacts of LEMs in order to ensure that they are designed and implemented in a way that promotes equity and benefits all members of the community. A failure to consider social factors in the design of LEMs could lead to unintended consequences and further exacerbation of existing social inequalities. This could also lead to a reduced willingness to participate in DR and decrease the motivation of people to participate in LEMs. These arguments will be elaborated upon in section 2.3.5.

Therefore, it is essential for researchers and policymakers to take an approach that considers both technical and social aspects when studying and implementing LEMs [5], [3]. This will be further explored in Chapter 4 - Energy justice.

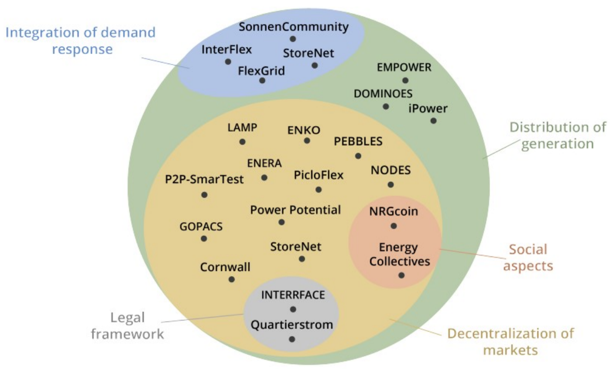


Figure 2.8: Challenges addressed in research and development projects. Taken from [25]

2.3.5 Pricing mechanisms and willingness to participate

A major challenge for the development of LEMs is that they need to recruit consumers and prosumers to engage themselves in joining these kinds of programs when they get available to the public. According to [46], peers who choose to engage themselves in research and development programs testing out different forms of LEMs are what [45] call innovators. They are the type of users that want to learn about cutting-edge technology and challenge the established standards. Usually, these are people coming from the upper socioeconomic classes. The challenge is to engage the subsequent

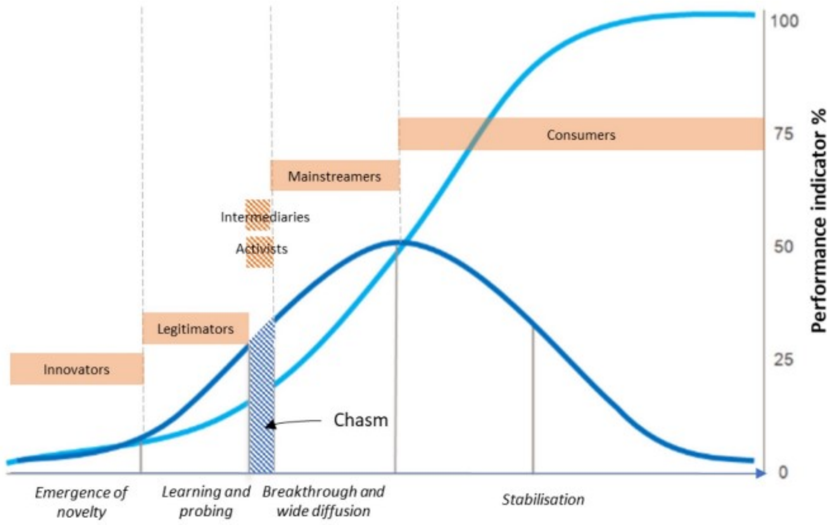


Figure 2.9: Categorisation of users along the innovation adoption bell curve. Taken from [45]

consumer groups seen in Figure 2.9. This is what [45] call crossing the chasm. Some kind of incentives has to be in place for this to happen. Usually, these are financial incentives through some kind of pricing mechanism. There exist several different mechanisms, some of the common methods are either auction-based, game theory-based, or rule-based[47]. Optimal pricing strategies, whether they are auction-based, game theory-based, or rule-based can promote active consumer participation by making it financially advantageous to do so. These incentives not only help in recruiting consumers and prosumers into the LEM but also encourage them to modify their consumption patterns in response to price signals, a cornerstone of DR. In a well-functioning LEM with effective pricing mechanisms, consumers are incentivized to reduce or shift their electricity usage during peak demand periods or when supply is limited. This shift in consumption patterns, facilitated by clear price signals, contributes to a more balanced and efficient grid, reducing the need for expensive power to cover peak load demand and lowering overall system costs. Moreover, these price signals can further encourage the use of DERs and the adoption of energy storage solutions. These technologies allow consumers to generate, store, and use their electricity, further reducing their dependence on the grid during peak times, which aligns with the goals of DR [47].

Auction-based

An auction is defined as a negotiation mechanism in which the negotiation is supported by an intermediary who could be a real agent and can be thought of as an automated set of rules [48]. There are several types of auctions and their qualities can categorize them. The most ordinary kind of auction is one-sided, where, in the electricity market only the buyer bids. Double/two-sided auctions exist, where both the buyer and seller participate. Ref. [49] proposed a LEM for electricity and hydrogen where market participants submit their offers and bids in a double auction to reach the maximum welfare.

Game theory-based

Game theory is defined as the formal study of the mathematical model of multiple decision-making players with possible cooperation and conflicting objectives. A cooperative game is a competition between groups of players with cooperative behavior, whereas a non-cooperative game is one in which players make decisions independently of each other [50]. In a LEM where the peers operate independently and only try to maximize their own profit, game theory is a well-suited approach to model their behavior [47]. Ref. [51] has done a review of game-theoretic approaches for local energy trading and reached several conclusions. They note that the market model has to be consumer-centric, which means that the consumers profit from the model. Further, it highlights the potential of high security and low computational complexity if a sound fusion of blockchains and game theory is achieved. Also, an advantage of some game theory types is that they can be modeled to properly deal with scenarios where some information is missing, which would otherwise reduce the performance of a LEM. One example is the Bayesian game, which can be modeled to work with incomplete game information [51].

Rule-based

In several rule-based models, the market price is decided post-event, which means the costs are allocated within the community after the trades have taken place. Ref. [52] introduces a *supply-demand ratio* parameter, which is defined as the ratio of total energy surplus to the total energy requirement in the local market. This is used to define the trading price somewhere in the range between the feed-in tariff(FiT) and the wholesale market price. The FiT is the price prosumers receive for exporting surplus energy back to the grid. Currently, the FiT tends to be notably lower than the wholesale market price [52]. Ref. [53] compared the supply-demand ratio method with two other methods, called Bill-sharing and Mid-market. In their comparison, the supply-demand ratio method yielded the best results. The paper also found out that some community members are not always better off with one of these methods compared to traditional trading with the supplier. It, therefore, suggests a second stage of the centralized cost-sharing process. With this new mechanic, none of the community members faced increased costs.

Non-economic motivation

Currently, the motivational strategies are mostly limited to pricing mechanisms through economical and technical incentives[25]. There can be a lot of reasons for this, which may differ from country to country. Ref. [2] explains a Norwegian example: within the energy industry consumers are still being modeled in the same way as they were in the 70s. They assume that they are economically rational beings with motivation and knowledge deficits. If this is true, then it makes sense to only look at financial tools for affecting user patterns. The way consumers are viewed has also possibly affected the lack of communication with the public regarding the imagined future of the electricity grid[2].

Several papers, such as [54] and [2] highlight the benefits of informing the consumers about the motivations, beyond the economic part, to join LEMs. As [54] states, in a survey conducted among private householders and energy systems developers, lots of consumers want to be informed about why there is a need for change in the current energy system. Especially, they expressed interest in the reasoning behind the need for the active participation of private persons. Others wanted to know why the grid operators don't just upgrade the electricity grid instead. Engaging consumers to participate in LEMs without just economic incentives demands information from the public. Also, several participants expressed scepticism about who profits from consumers engaging themselves in flexibility work. They did not like the thought of the energy industry, being grid companies or third parties, gaining economic profit from their flexibility. On the other hand, engaging in flexibility efforts for the sake of the environment, local community, or society in general, where deemed as acceptable reasons.

Chapter 3

Energy justice

3.1 Academic definitions of fairness

Aristotle's approach to justice is based on the idea of virtue ethics, which holds that the goal of human life is to develop good character traits and habits of action, such as generosity, courage, and honesty. For Aristotle, justice is a virtue that involves giving people what they deserve based on their individual merit and worth [55]. Rawlsian theory of justice is based on the idea of a "social contract" and the "original position." Rawls argues that people in the original position, who are unaware of their own social position or personal characteristics, would choose principles of justice that ensure a fair distribution of resources and opportunities in society. Rawls emphasizes the importance of equal basic liberties and the difference principle, which states that inequalities should be arranged to benefit the least advantaged members of society [56]. Varian's approach to fairness is based on the concept of "envy-freeness." He argues that an outcome is fair if no individual would prefer to switch positions with any other individual. This definition of fairness is often used in the context of economic and social policy, where outcomes are evaluated based on the satisfaction of individual preferences [57].

While these three approaches to fairness are different, they share a common concern with ensuring that decisions and actions are fair, just, and impartial. They also all recognize the importance of considering the distribution of resources and opportunities within a society, and the need to address issues of inequality and discrimination.

Equity and equality are two related but distinct concepts that are often used in discussions of fairness and justice. Equality refers to the idea of treating everyone the same or providing everyone with the same resources or opportunities. The goal of equality is to eliminate discrimination and ensure that everyone has access to the same opportunities and resources. For example, in the context of education, equality might involve providing all students with the same textbooks, facilities, and teaching staff [58]. Equity, on the other hand, refers to the idea of treating people fairly based on their individual needs and circumstances. The goal of equity is to address systemic inequalities and provide everyone with an equal opportunity to succeed. For example, in the context of education, equity might involve providing additional resources and support to students who face barriers to learning, such as students from low-income families or students with disabilities [58].

The Aristotelian, Rawlsian, and Varian views of fairness can all be related to the concepts of equity and equality. Aristotle's focus on individual merit and worth can be seen as a form of equity, as he emphasizes the importance of treating people fairly based on their individual characteristics and achievements. Rawls's theory of justice as fairness can be seen as emphasizing the importance of equality, as he argues that a fair and just society should ensure that everyone has access to the same basic liberties and opportunities. Varian's concept of envy-freeness can be seen as emphasizing the importance of equity, as it seeks to ensure that everyone has access to the resources and opportunities they need to achieve their goals.

3.2 Introduction to energy justice

Decarbonization of the current energy system is a task of grand proportions and is heavily linked with several of the UNSDGs as mentioned in chapter 1. The goals mentioned there only relate to the technical and environmental aspects of the energy system. The energy system is now so interwoven in our daily life, that such a drastic change needed to decarbonize it, will affect several other aspects of our life as well. *Energy justice* is connected to various UNSDGs, such as 10 - Reduce inequalities, 8 - Promote sustained, inclusive and sustainable economic growth and 1 - End poverty [1]. There are a few aspects of everyday life that do not get affected by such a drastic change in the energy system. Energy justice is a tool for not miss-using the enormous power and dependency energy has over us.

More specifically, energy justice is a social research agenda seeking to apply justice principles to energy policy, energy production and systems, energy consumption, energy activism, energy security, the political economy of energy, and climate change. Energy justice aims to find [4]

- Where injustices emerge
- Which affected sections of society are ignored
- Which opportunities exist to reveal and reduce injustices

This list motivated the authors of [4] to divide energy justice into three tenets, (1) distribution, (2) recognition, and (3) procedure. The thought is to first understand the injustice that has to be dealt with (1), then identify who it affects(2) and lastly, find strategies to amend what's done(3).

In this chapter, the three different tenets will be further explained, then energy justice in a LEM context will be reviewed and lastly, KPIs will be introduced to evaluate how just energy models are.

3.3 Distributional justice

Distributional justice assesses the physically uneven allocation of environmental advantages and disadvantages, and the responsibility that follows with them [59]. This can e.g. be an uneven distribution of renewable energy due to geographical limits within a country combined with a CO2 tax mostly affecting the other part of the country. With this example, there is a possibility to do empirical research on how the location of energy infrastructure causes distributional injustices.

A concrete example is *Energiewenede*, the German imitative of an energy strategy transformation. The objective is the decarbonization of the German energy sector, also removing nuclear power. To help this transition, they have introduced a special FiT. This tariffs grant priority access and advantageous electricity prices for producers of renewable energy. The cost of these FiTs is financed through an extra payment made by the electricity consumers. This results in an unequal economic burden for lower-income people who pay relatively more of their income than others to fund this [4]. Also in Germany, much of the renewable energy is produced in the north, while the energy-demanding industry is located in the south. This imbalance requires improvements to the electrical grid to be able to facilitate the transportation of renewable energy to the industry. However, the state of Bavaria stopped the building of new power lines due to the overwhelmingly negative response of the public. This led to suggestions of electrical tariff zones within Germany, which would cause the South to pay more [60]. If this happens, that would further create an uneven financial burden for low-income persons caused by the Energiewende, especially for people in the south. Even though the intentions of the Energiewende are good, it creates complex distributional justice problems.

3.4 Recognition

Recognition justice states that individuals must be fairly represented, be free of physical threats, and be granted complete and equal political rights [61]. A lack of acknowledgment can manifest in cultural and political dominance, insults, humiliation, and devaluation. It can show as both a failure to recognize and a misrecognition or distortion of people's opinions that appear humiliating or disgusting [61]. As a result, it includes requests to recognize differing perspectives rooted in social, cultural, ethnic, racial, and gender diversity [62]. Ref. [62] highlights three categories of misrecognition: cultural domination, non-recognition, and disrespect. Further on in this section, an explanation of the latter two will be paired with an example from the UK.

3.4.1 Non-recognition

The policy in the UK has lately begun to acknowledge that some social groups, such as the elderly, the infirm, and the chronically ill at times have different needs than other social groups. For example, the need for higher than average room temperature [63]. This movement is in contrast to a long-standing tradition of modeling the "energy poor" and their "inefficient" use of scarce energy and financial resources. Government-sponsored programs have traditionally considered the "energy poor" as having a knowledge deficit, with projects focusing on the provision of objective information, economic subsidies, and other ways of boosting the energy efficiency of the housing stock and electrical equipment. However, few attempts were made to understand the motivations behind consumption patterns or to interact with their interpretation of energy-related concerns, as well as what kinds of solutions and methods they would imagine [64]. This inability to recognize certain groups not only causes injustice but may also result in the loss of potentially helpful knowledge and stories as we lose the perspectives of marginalized social groups.

3.4.2 Disrespect

Further on in the UK, developers and investors for renewable energy often blame local opposition against wind farms as "not in my backyard" protests by misinformed and self-centered individuals[65]. This is followed by the belief that individuals have a knowledge and motivational benefit as previously mentioned. Although, there is little systematic evidence that the top-down information about economic benefits, climate mitigation and moderate noise levels, changes opinion in the *short term* [4]. The lack of results from the information campaigns about economic benefits for the local communities makes the developers and investors believe that the knowledge of the people is both insufficient and incorrect [65]. This perception is backed when it comes to subjective meanings used to counter technical arguments. Examples are perceived noise levels, wind turbine aesthetics, and doubt about the economic beneficiaries of the project. When the developers and investors compare this resistance with public opinion surveys about wind power that generally show positive support, they conclude that all of the local opposition is rooted in the "not in my backyard"-phenomena [66]. Assuming this is tearing all opposition with the same brush. It may also misrecognize the sincere concern of the affected locals.

3.5 Procedure

Procedural justice relates to access to decision-making processes that concern the aforementioned distributional justice. It is the need for fair procedures that engage all involved parts in a non-discriminating way [59]. It can be applied to class, gender, and religion [4]. Procedural justice is dependent on access to well-working legal systems, but also less rigid regulations as practices, values, and behaviors [63], [5]. To elaborate on this, one of the main mechanics from [4] will be highlighted with a concrete example. Harvesting local knowledge has been identified as a significant motivator in the literature for pursuing the involvement and engagement of impacted societies [4]. The concept is most strongly associated with indigenous peoples. An example is with the Sami people and Finnmark Kraft AS in Norway. A proposed project threatened to hinder the reindeer husbandry in the area, so the project developers sought advice from the Sami council about construction details such as location [67]. It shows that procedural justice is more than just inclusion, it also involves the active mobilization of local knowledge.

3.5.1 Integration of social factors

As several papers note, quantifying and integrating these social aspects into energy models is one of the key challenges modelers face [68], [69]. Both [69] and [3] call attention to the fact that modelers should not only model what is easily quantifiable, and instead find ways to quantify social aspects. Ref. [3] does acknowledge the difficulty of this task and notes that quantifying qualitative narratives is a key challenge for modelers. Access to better empirical data on the subject can make this task easier. The current shortcomings of modeling these problems cause modelers to include social aspects "on top" of existing models [3], especially in qualitative storylines, but also through adjustments in scenarios and input variables. That means social factors are included through external assumptions not directly affecting the model. E.g. by doing a brief analysis of how the end results of a model affect social aspects. Neglecting social aspects like this can cause inaccurate models that have limited usefulness for decision-makers. Most analyzed models are made with a techno-economic approach, meaning they seek to reduce the total cost. As [3] notes, the "least cost future" might not be the most desirable by society.

Ref. [3] suggests three ways to increase social factors' integration in energy models. Firstly, social factors must be represented further in models than just with exogenous assumptions. Modelers must be willing to break up the existing modeling structure, add necessary modules, and find a new way to put it together. Also, explore new ways to formulate equations to describe social factors with mathematical expressions better.

Second, modelers have to work closer with social scientists than what they are doing right now. Several of the analyzed models in [3] lack any interdisciplinary collaboration between modelers and social scientists. Modelers must be more open to working with other research fields, and social scientists must conduct research that better fits modeling work.

Third, it is clear from the results of [3] that not one model single-handedly can fit every social aspect into it. Each model type has different capabilities to represent these factors. Therefore [3] suggests utilizing several models together to understand the whole picture better.

3.6 Frameworks for integrating social factors

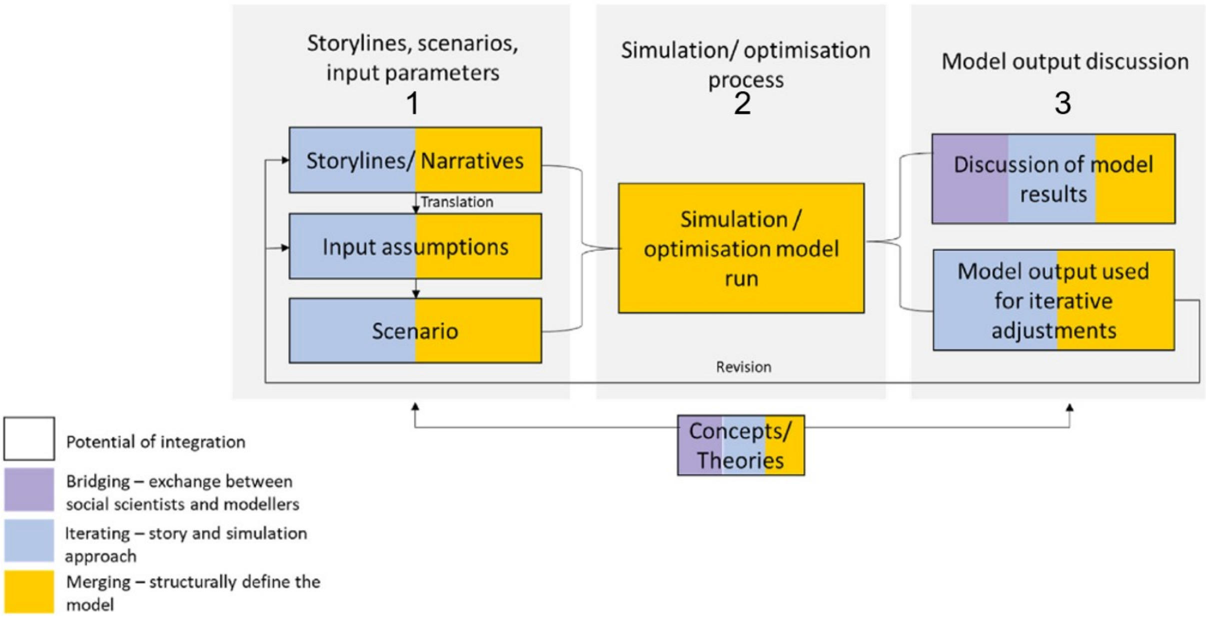


Figure 3.1: Potential of integrating social aspects in LEM models, taken from [3]

KPIs are often used to quantify the performance of LEMs and can also indicate the level of fairness in a LEM. As noted in subsection 3.5.1, the implementation of KPIs in LEM models is usually limited to simple variables calculated from the model results, but there is a need for deeper integration of fairness factors, or KPIs, in the models. Ref. [3] proposes a framework for integrating along three modeling steps: (1) storyline, scenario, input parameters, (2) simulation/optimization process, and (3) model output discussion, as shown in Figure 3.1.

The first step of the process is developing external storylines and translating them into input parameters that become part of the scenario. The integration of modeling and social science can be done in a number of ways, with the "bridging" strategy being the softest way of doing it. This approach involves bringing together concepts and theories from both fields. Another option is the "iterating" approach which involves using empirical data to add more detail to the input assumptions, specifically related to social aspects. Finally, the "merging" approach involves jointly developing or adapting a model with input parameters that are specifically designed to incorporate both modeling and social science. In the simulation/optimization process, an integration of fairness factors signifies that they are part of the mathematical formulation that structurally defines the model. This is a part of the "merging" strategy.

The last step in the suggested framework of [3] is the output discussion. This step involves discussing the model results in the context of a specific social aspect, such as the potential for increased wind energy use in residential areas. This discussion does not affect the actual model results, but it does influence how the results are interpreted and discussed. It is also possible that this discussion could lead to adjustments in the storylines, using either an "iterating" or "merging" strategy.

Justice in LEMs can be more than KPIs as well. As [54] notes, the difference in the understanding of end-user flexibility between the end users and system operators is also a problem. From a system operator perspective, the peak load hour is a pressing problem for the grid, but end users have untapped flexibility potential that must be used, which can be achieved through engaging end users in a LEM. On the other hand, the end users want information on why they should join a LEM. They are skeptical about who profits from it and seem more motivated to help solidarity for the environment or the local community than to help the grid operator [54]. A failure to recognize these aspects will make it harder to bridge the gap between end users and the grid operator when creating a LEM.

3.7 Definitions of fairness in a LEM context

To comprehensively discuss fairness in a LEM, it is essential to consider various aspects contributing to the issue's complexity, as highlighted by [70]. One must consider market participants' diversity, innovative technologies' integration, the regulatory environment, and the need for transparent pricing mechanisms. Different definitions of fairness may be appropriate, depending on the market's objectives.

Firstly, the heterogeneous nature of market participants plays a crucial role in defining fairness. A LEM can be comprised of residential, commercial, and industrial consumers, as well as prosumers, energy service providers, and grid operators. Each stakeholder has unique needs and priorities, which should be reflected in the market design to ensure that all participants are treated equitably. For instance, residential consumers may prioritize affordability and reliability, while prosumers may seek incentives to invest in distributed energy resources and grid-connected assets.

Secondly, integrating innovative technologies such as smart grids, energy storage systems, and renewable energy sources requires a fair market design that accommodates these advancements. The market should offer equal opportunities for early adopters of these technologies, while also providing a level playing field for traditional energy sources. This approach fosters technological innovation and contributes to achieving broader environmental and sustainability goals.

The regulatory environment is another key aspect influencing the perception of fairness in a LEM. Policymakers and regulators should ensure that market rules and regulations are transparent, consistently applied, and adaptive to the evolving energy landscape. Regulations should facilitate a competitive environment that balances the interests of various stakeholders, prevents market manipulation, and promotes long-term market stability.

Lastly, pricing mechanisms are vital in shaping a fair LEM. Transparent and dynamic pricing structures should reflect the true cost of energy production, distribution, and consumption. By incorporating factors such as e.g. time-of-use pricing, peak demand management, and locational marginal pricing, market participants can make informed decisions that align with their individual objectives and contribute to overall market efficiency.

3.8 Analyzed Key Performance Indicators

The objective of the introduced KPIs in this thesis is to look at LEMs as a way to encourage the adaptation of distributed energy resources while simultaneously supporting energy democracy. Prosumers who help meet local energy needs should be acknowledged and rewarded, without disadvantaging those market participants who can't contribute at the same level. As a result, the definition of fairness leans toward equity rather than equality.

Ref. [71] applies fairness factors defined by [72], which have traditionally been used in communication services. They are QoS and QoE. The QoS is based on Jain's index, which is a mathematical measure typically used to determine the uniformity of resource distribution in computer networks. For an energy system, equal exchanged quantities may not be the system's primary objective, but low QoS levels show that some peers have a greater influence on the community than others. QoE has a more user-centric perspective and is based on the standard deviation of the perceived cost of each market participant. If all participants have a similar access to the different products (energy from prosumers and the retailer), they will experience a similar price, and the market can be perceived as fair. When the QoE is equal to one, everyone experiences the excact same price.

From economics, the EI is also introduced. The EI is an adaptation of the Gini coefficient, which measures the deviation of peers' income distributions from an ideal distribution in a market. [73]. Equal income distribution is a significant consideration in many aspects of human society, including the energy sector. Pronounced inequality can disrupt harmony within a community and impede the acceptance and implementation of the establishment of a LEM. The mathematical definitions of these KPIs are introduced in chapter 5

Chapter 4

Agent based modeling

4.1 Modeling social aspects

In this section, social aspects and energy justice will be introduced in the context of general energy models and LEM models. Ref. [3] has done a throughout review on the current representation of social factors in energy models. There are several types of energy models, such as Energy system models (ESM), integrated assessment models (IAM), ABM, and computable general equilibrium (CGE) models. ABMs are usually used when modeling LEMs because it allows the simulation of autonomous entities interacting with their environment [74], [75]. Since the methodology part of this thesis is based on an ABM, there is a dedicated section to further explain ABMs in these contexts.

Briefly put, ABM considers the agents' decision-making about the given problem and can be used to analyze complex social behavior [76]. It makes ABM well-suited to represent social phenomena at a microeconomic level. They are often based on game theory, social scientific theory, etc., and not so often on optimization. There are several different social aspects that can be focused on in an energy model. Ref. [3] has the general objective of modeling social aspects related to *socio-technical transitions* and therefore looks at a broad range of social factors. Through a review of several papers regarding the issue, the following factors are highlighted:

Behaviour and lifestyle [76],[77], [78], [79], [80]. This factor considers the behavior and lifestyle of peers involved in transformations and how this influences the development of the energy transition [77]. For example, changes in behavior can change the demand curves of individuals, and then again influence the optimal development and allocation of DERs.

Heterogeneity of actors [76],[77], [78]: This factor is related to the concept of "heterogeneity across societies" [78], such as the difference between consumers and producers in different stages of the energy transition. Also, the heterogeneity and behavior of individuals in groups affect the speed of the transition [76]. These are contextual and environmental factors, distributional impacts of environmental change and policies, and socio-economic conditions [78].

Public acceptance and opposition [77], [78], [80], [81], [82]: This factor relates to the public acceptance and opposition against energy infrastructure and can influence the speed of renewable energy deployment [3]. Ref. [82] suggests the dimensions of social acceptance: socio-political acceptance, community acceptance, and market acceptance.

Public participation and ownership [3] [83], [84]: Community acceptance is based on the amount of public participation and ownership[3]. Ref. [84] considers this to be a main driver of the energy transition since it facilitates people to affect and participate in the local energy transition. Participation can e.g. be financial transfers of local wind farms' profit to nearby cities.

Transformation dynamics [77], [76]: This factor is concerned with transformation dynamics at different scales and in time, including the pace of forms, path dependencies, and the quality of various system states.

After analyzing 13 models included in modeling projects openENTRANCE and SENTINEL, [3] conclude that ABMs are good at representing social aspects, but also noting that ESM, IAM, and CGE to some degree include behavior and lifestyle well. In general, they note that modelers usually include socio-economic factors that are easily quantifiable, such as parameters that account for social acceptance and opposition. While the difficulty of modeling actor heterogeneity caused it only to be addressed in ABMs. It was the only model able to represent different groups and their interactions. Ref. [76] also reaches the conclusion that ABM is one of the more promising modeling approaches in this context. That is the motivation for choosing to work with an ABM in this thesis.

Summary of representation of social aspects in the analysed models.

Social aspect	Potential of Integration	Model type			
		ESM	IAM	ABM	CGE
Behaviour and lifestyle	1	x	x	x	x
	2	x		x	x
	3	x	x		
Heterogeneity of actors	1			x	x
	2			x	
	3				
Public acceptance and opposition	1	x		x	
	2				
	3	x		x	
Public participation and ownership	1			x	
	2			x	
	3			x	
Transformation dynamics	1				
	2				
	3				

Figure 4.1: Comparison of modelling literature reviewed by [3]. For an explanation of potential of integration, see Figure 3.1

4.2 Introduction to agent-based modeling

In this section, literature regarding the use of ABMs in an energy context will be elaborated upon as the methodology in this thesis is based on an ABM. The agents in an ABM can represent a wide range of entities, such as individuals, households, companies, or regulatory authorities [3], [76]. The model works by creating a virtual environment and populating it with agents that have specific characteristics and rules for interacting with each other and their environment. The agents in an ABM can be programmed with a variety of behaviors and decision-making processes, which can be based on factors such as their environment, social network, or individual preferences. For example, in an energy model, the agents might represent households that make decisions about how much energy to consume based on factors such as the weather, energy prices, or the behavior of their neighbors [3], [76]. During the simulation, agents interact with each other and their environment, creating a dynamic system that can produce emergent behaviors and patterns. ABMs can be used to study how changes in the behavior of individual agents or the environment might affect the overall system, and to test different scenarios and policies [79]. One advantage of ABMs is that they can capture the complexity and heterogeneity of real-world systems, and can be used to model systems with many interacting parts that are difficult to analyze using other analytical techniques. However, they can also be computationally intensive and require significant amounts of data and parameter tuning [3], [76] There are several different kinds of ABMs, and [3] looks at two of them in their work of mapping modeling of social aspects in the energy transition. These are *Agent-based Technology adOption Model*(ATOM), and *Business Strategy Assessment Model* (BSAM).

4.2.1 Agent-based Technology adOption Model

ATOM is designed to incorporate social parameters such as agents' initial beliefs, resistance, probability to invest, and social learning. It consists of three modules to assess agents' behavior and preferences. The first module defines the key set of parameters and the calibration process for the quantification of behavioral uncertainty of the agents based on historical data and observations by specifying the appropriate ranges of the values. The second module is a sensitivity analysis to quantify uncertainties related to the characteristics and decision-making criteria of the agents. The third module encompasses the scenario analysis of different policy schemes to study and simulate the behavior under consideration of the socioeconomic and geographic context.

ATOM can be used to simulate the technology adoption of PV systems and to quantify the behavioral uncertainty of consumers regarding the decision-making criteria and agents' preferences. Ref. [85] used it in a participatory transdisciplinary way with other models to explore the development of PV and dynamic adaptive policy pathways in Greece, considering interactions between the agents and policy context.

In the context of a LEM, an ATOM is especially well-equipped to simulate the adaptation process of a LEM in e.g. a neighborhood and quantify the uncertainty related to the adaptation. As [3] notes, motivation to join these markets and the establishment of them are as important to understand as well, not just the workings of a fully established market.

4.2.2 Business Strategy Assessment Model

BSAM is the second type of ABM that is covered by [3]. It is a power sector model that primarily focuses on the anticipated behavior of power generators by simulating power bidding and investment decisions. The model allows for the evaluation of the microeconomic and economic implications of being a prosumer and explores the macro-socioeconomic consequences and social risks associated with the transition towards solar-based energy. Ref. [86] employed a BSAM to analyze the barriers to and the repercussions of an energy transition in Greece, together with MEMO, a computable general equilibrium (CGE) model.

BSAM can take into consideration various public perspectives, such as public acceptance and opposition, and public participation and ownership, in its scenarios and discussions regarding the output of the model. It employs historical data and projections that are in a constant state of change, including data that contain electricity demand, renewable energy generation, hydro generation, electricity import prices, and fuel prices. Furthermore, BSAM integrates data that is changing slowly or not at all, such as technical and economic characteristics of thermal resources, market-related data, and interconnection capacities with neighboring countries, as well as RES subsidies [3].

The output of BSAM includes system marginal price (SMP) in an hourly resolution, total electricity costs when subsidies are taken into account, electricity mix, generation schedule of all resources, profit/loss of each power producer, and the level of curtailment applied to renewable energy generation. The model utilizes a participatory scenario definition approach to evaluate uncertainties in the energy transition and involves stakeholders in the assessment of associated risks and dynamics.

In a LEM context, BSAM could be applied to simulate the behavior of local power generators and consumers, and with the incorporation of relevant economic and regulatory factors, BSAM could provide insights into the likely outcomes of different scenarios, such as the impact of changes to local energy policies, the introduction of new technologies such as improved batteries, or changes in consumer behavior.

4.2.3 Emerging challenges and possibilities

[79] has identified challenges of modeling social changes with ABMs and suggests doable actions that can be implemented in the near future. They highlight the need to improve current modeling approaches by going beyond a narrow focus on outcomes and instead capture what are the drivers of social change. This can be achieved by enhancing the modeling of actor heterogeneity and integrating approaches from different disciplines. The paper identifies several opportunities for improvement, such as combining different models and enriching scenarios with elements from transition studies and applied economics. They also suggest deepening engagement between quantitative system modeling and social science approaches, including transition studies and initiative-based learning. The paper identifies challenges related to making models more realistic, including the lack of agent heterogeneity, weak empirical foundation for behavioral patterns and rules, stylized representations, decision mechanisms driven by techno-economic relationships and rational choice paradigms, and the assumption of perfect knowledge. Low-hanging fruit for improvement include increasing actor heterogeneity by differentiating regional and demographic dimensions, soft-linking ABMs and IAMs, using material from social learning initiatives to improve learning dynamics in IAMs, improving the representation of institutions with the help of applied economics, and standardization through common agreement of concepts, parameters, metrics, and data. The authors caution that the increased complexity of models and input data can restrict the model's applicability to smaller fields. Finally, the paper suggests increasing actor heterogeneity by improving the representation of culture and social contacts in models.

4.2.4 Use of ABM in LEMs

In recent years, there has been a growing body of literature focusing on the application of ABMs in LEMs. This section aims to review specific case studies of LEMs that have employed ABMs and summarize the key findings from a comprehensive literature review done on this subject.

[87] uses ABM to investigate the economic interactions between autonomous PV system owners in a local energy microgrid comprising 48 households. The objective is to understand the effects of different factors on profitability and energy self-sufficiency. The study varies the number of PV owners (investors) and their pricing behaviors across different scenarios. The study demonstrates a potential for an average self-sufficiency of approximately 24%, an achievement reached without the requirement for incentives or electric storage. A central finding in the study is the impact of varying the number of investors. As the number of investors decreases, the remaining investors witness an increase in their earnings, ranging from 8% to 74% of the baseline. This is an advantageous development for those investing in the system as it presents a self-generating incentive to invest whenever someone is unwilling to participate.

Another key finding concerns the pricing strategy of an agent. There is substantial potential for improvement even without knowledge of the demand of others, avoiding any privacy infringements. The study introduces a simple dynamic pricing strategy, where agents sell excess power at a very low price when their balance is above average and at the highest possible price when their balance is below average. This strategy, despite its simplicity, was able to outperform those actors trying to sell at lower prices in the market to gain an advantageous position. The research concludes that high prices within the microgrid might lead to a more equal distribution of risks and benefits. However, households are unlikely to move towards a high price equivalent to the grid price. In real-life scenarios, some households may refuse to invest in the shared PV system. Yet, this might result in increased revenues and savings for the other groups, thereby improving the Compound Annual Growth Rate (CAGR) for those who own a PV system. To conclude the study highlights the benefits of demand aggregation, the effects of pricing strategies and the impact of different investor scenarios on profitability and self-sufficiency. However, it also emphasizes the need for further exploration into financing and risk distribution solutions.

[88] employs ABM to simulate a LEM, focusing on the role of trust in market negotiations. A Trust model is proposed to evaluate participants' proposals based on forecasting mechanisms that attempt to predict their expected behavior. In addition, a case study is undertaken to assess how well this trust model can evaluate participants who submit false negotiation proposals. The proposed trust model calculates a trust value for each participant considering their historical data, contextual factors such as weather data, and forecasting methods to anticipate their expected behavior. The trust value evolves over time, reflecting the participants' market submissions, forecasting of those submissions, and the disparity between these values. The case study further tests this trust formulation's effectiveness using realistic consumption data and introducing biases in the form of false value submissions. By employing different forecasting methodologies and various levels of accuracy and precision, the study provides an evaluation over a 24-hour period and 15-minute market negotiation period duration. The findings reveal that the choice of forecasting methodology significantly impacts the trust formulation's performance. Poor forecasting methods result in unsatisfactory trust evaluations. Also, as expected, the study finds that the more false values a participant submits, the lower their trust value becomes. The study concludes by emphasizing that an ABM simulation of the LEM, integrated with a trust model, can be a powerful tool to ensure trust in LEM negotiations.

Given the advancements necessary for smart grids' evolution, exploring business models for novel energy services is crucial. Ref. [89] and [90] concentrate on the integration of RES generation into the market. They examine the role of new intermediaries exploiting various policies implemented in Germany to accomplish this. To ensure a reliable and economically efficient incorporation of RES into the electrical system and market, Germany has been gradually transitioning its support mechanisms. These transitions include moving from fixed feed-in tariffs to incentivizing market-oriented production and feed-in strategies. One such adjustment, an optional market premium for the direct marketing of RES electricity on the power exchange, is the core of the authors' analyses. In order to properly establish and calibrate the agent-based simulation model, the authors conduct a comprehensive actor analysis. They employ what they call an AMIRIS model (Agent-based Model for the Integration of Renewables Into the Power System) which focuses on the implementation of new intermediaries for direct marketing of renewable electricity.

The model includes various types of intermediaries that offer corresponding remuneration options for plant owners' electricity. These options could be maintaining the fixed feed-in tariff or opting for the dynamic market premium. Plant owners choose to enter into contracts with the intermediaries based on the expected profitability of these options. The paper concludes that agent-based perspectives on the integration of renewables into markets can yield innovative computational analyses of the relationships between relevant actors. This approach, encapsulated in the AMIRIS simulation model, enables the examination of the impacts of different market designs at both macro and micro scales, a necessary step in creating effective support schemes that promote market development without enabling windfall profits for certain actors. For future work, the authors suggest focusing on a more dynamic sampling of the agents and the model itself, as many parameters can change over time but are currently set externally.

[91] has done a comprehensive literature review of ABM in LEMs and notes that while ABM provides a rich empirical framework, it's still faced with a few challenges. Upholding general research standards, such as model description and validation, can increase the quality and acceptance of the research. ABM is flexible but also prone to excessive complexity and inaccurate precision. Consistency is vital for enhancing comparability within ABM-based research, alongside other approaches and empirical observations. ABM techniques have been used to study the electricity system in two main ways. The first is through Agent-based Computational Economics (ACE), which focuses on analyzing economic systems. The second is agent-based control strategies, which are intended for designing real-world systems. In terms of future research, local market concepts should take into account broader system integration and the acceptance of such participation schemes among initially inexperienced agents. Storage systems are particularly noteworthy given the flexibility they bring to smart grids. A comprehensive understanding of interactions with centralized markets and the role of intermediaries is necessary, along with an evaluation of their business models. Finally, [91] notes that increasing the degree of multidisciplinary research to incorporate technical, social, economic, political, and environmental aspects could further improve future ABMS-based research of smart grids and markets. This approach could provide valuable input for stakeholders' decision-making processes and policy formation.

Chapter 5

Methodology

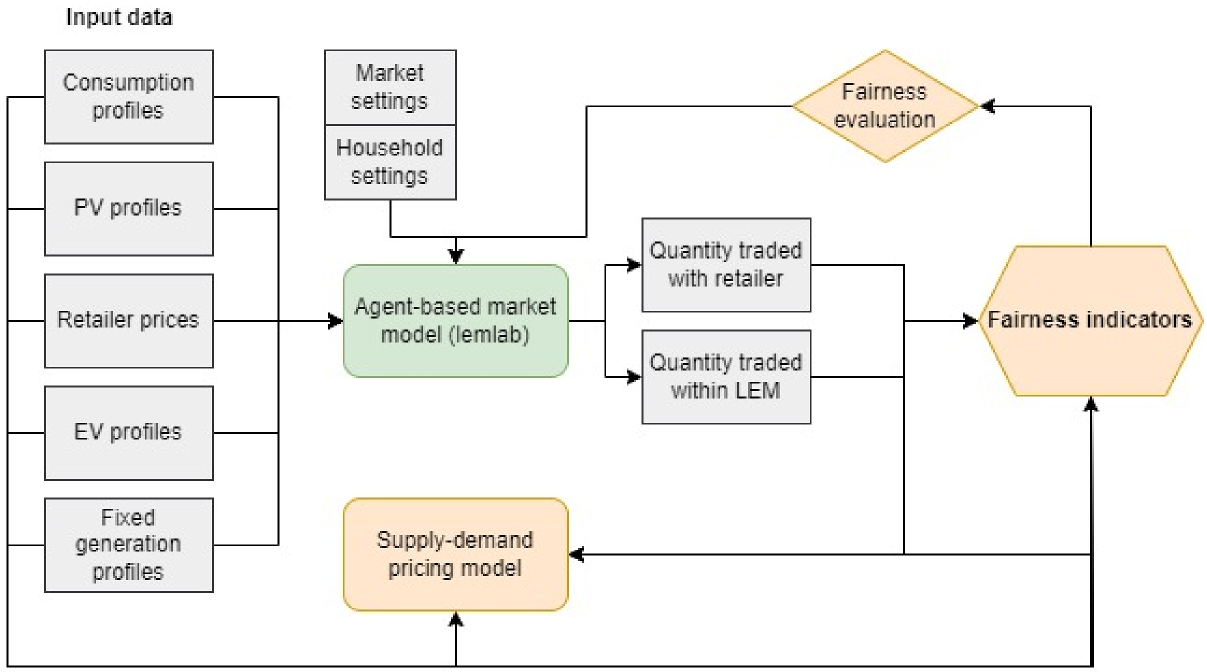


Figure 5.1: Overview of thesis methodology

Before starting this section, a clarification of what is done by the author and what has been done by external help will be presented. lemlab has been developed by researchers at the Technical University of Munich. In this thesis, this tool has been used to configure new scenarios and run the simulations of a LEM. The author of this thesis has processed the input and output data provided by lemlab and its developers to fit the KPI analysis done in this thesis. The KPIs are taken from other papers within and outside LEM research and are modified by the author with the intention of better capturing different fairness aspects of the simulated LEMs. This is followed up with a discussion of the strength and flaws of both the original and modified KPIs.

5.1 Introduction to lemlab

To do ABM simulations of a LEM, lemlab has been used, which is an open-source tool developed by the Chair of Energy Economics and Application Technology of the Technical University of Munich [8]. This software employs a combination of Gurobi, an optimization solver, Python and PostgreSQL, a database system to run simulations-

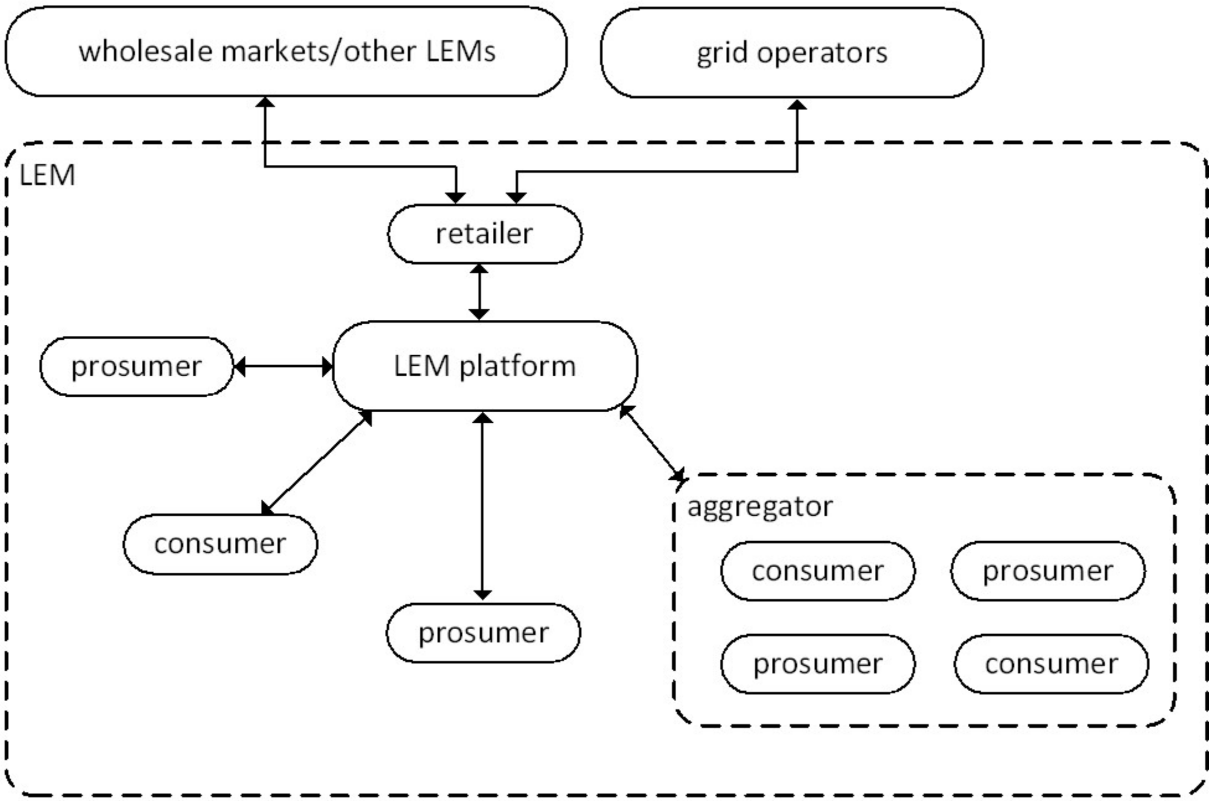


Figure 5.2: Overview of the LEM-structure used in lemlab. Taken from [8]

Lemlab's LEM structure consists of prosumers and retailers, with the former trading energy on their own behalf and the latter serving as the link to the wholesale market. Notably, the functionality for an aggregator, an entity that trades on behalf of a group of prosumers, is currently not implemented in the software.

The workflow in Lemlab is divided into four primary time segments. Initially, all participants register before trading begins. Afterward, the software enters a recurring rolling horizon market sequence for each delivery period. Each day is divided into a number of periods, or timesteps, for each energy exchange, $ts_{delivery}$, typically marked as the interval between t_d and $t_d + T$. These periods are often 15-minute windows (T=900s), as the energy market in Germany operates in 15-minute intervals. Since lemlab is developed in Germany, it also intends to simulate a typical German energy market

The operations within each timestep are divided into several parts as follows:

- **Pre-exchange-activities**
  - Pre-clearing-activities (takes place for each n clearing periods):

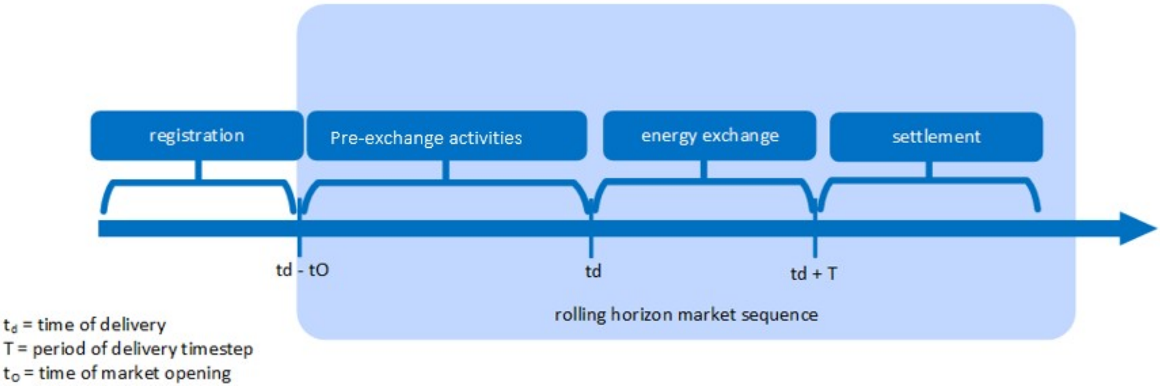


Figure 5.3: Overview of the timeline of the market operations in lemlab. Taken from [8]

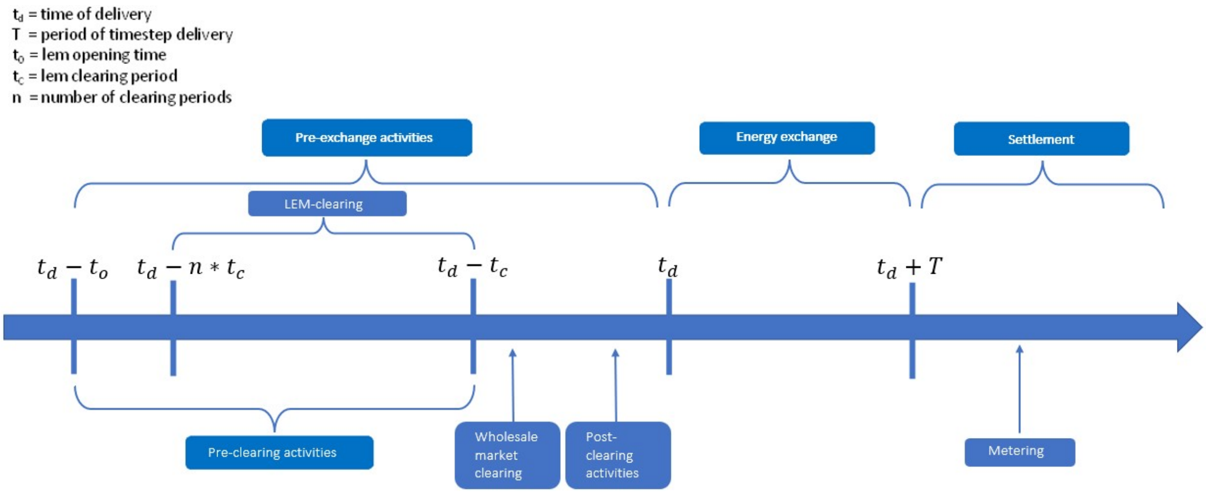


Figure 5.4: A more detailed view of the timeline of the market operations in lemlab. Inspired by [8]

- Prosumer:
  - real time controller execution
  - logging of metering values
  - forecasting
  - predictive control
  - market trading
- Aggregator:
  - Forecast aggregated loads
  - Post buy and sell positions on the LEM

- LEM-clearing: Takes place during some or all of the n periods.
- Wholesale market clearing: Takes place after LEM clearing
- Post-clearing activities: Takes place right before energy exchange and typically include checking of clearing market results.

- **Energy exchange**: During this time, the physical flow of energy takes place

- **Settlement**:
  - Validation of and post-processing of metering data
  - Determining balancing energy, which is deviation from ex-ante market results
  - Calculating ex-post market prices and labelling (community markets that don't rely on ex-ante trading)
  - Calculating settlement prices (balancing prices and levies) either in advance or ex-post
  - Calculating the value of and logging transactions based on the aforementioned points

5.1.1 Object function and constraints

In the presented model, the aim is to minimize the net costs of the grid interaction over the simulation time period. The objective function, therefore, accounts for the energy fed into the grid and the energy drawn from the grid. The grid feed-in is valued at the predicted price, while grid consumption is valued at the predicted price plus fixed levies. Non-degeneracy of the Mixed Integer Linear Problem (MILP) is ensured by adding small quadratic terms to the objective function for both power fed into and drawn from the grid.

The objective function is defined as follows:

$$\min \quad \sum_{t=0}^{T}\Big(G^{out}(t)\cdot(-p(t)+p^{+}(t)) \quad + G^{in}(t)\cdot(p(t)+p^{-}(t)) \quad + \delta\cdot(G^{out}(t))^{2} \quad + \delta\cdot(G^{in}(t))^{2}\Big) \tag{5.1}$$

where:

$G^{out}(t)$ is the power fed into the grid at time step j, $G^{in}(t)$ is the power drawn from the grid at time step j and $p(t)$ is the market price at time step t. $p^{+}(t)$ and $p^{-}(t)$ are the positive and negative energy levies at time step t, and δ is a small constant ensuring non-degeneracy of the MILP problem.

$$\begin{aligned} p_{\text{load}}(t) + \sum_{pv} P_{PV}(p,t) + \sum_{wind} P_{Wind}(w,t) + \sum_{bat} P_{BatOut}(b,t) - \sum_{bat} P_{BatIn}(b,t) \\ + \sum_{ev} P_{EVOut}(e,t) - \sum_{ev} P_{EVIn}(e,t) + \sum_{fixedgen} P_{FixedGen}(f,t) + \sum_{hp} P_{HP}(h,t) \\ = P_{GridOut}(t) - P_{GridIn}(t) \end{aligned} \tag{5.2}$$

The power balance constraint is denoted in Equation 5.2 for each time step t. This constraint ensures that the total power produced and consumed by all components in the system is balanced at all times.

$$SOC_{\text{Bat}}(\text{b},t) = SOC_{\text{Bat}}(\text{b},t-1) + \eta_{\text{charge}}\cdot P_{\text{BatIn}}(\text{b},t) - \frac{1}{\eta_{\text{discharge}}}\cdot P_{\text{BatOut}}(\text{b},t) \tag{5.3}$$

$$SOC_{\min} \leq SOC_{\text{Bat}}(\text{b},t) \leq SOC_{\max} \tag{5.4}$$

The constraints for the battery power flow are defined in Equation 5.3 and Equation 5.4. These constraints ensure that if a battery is discharging, it cannot be simultaneously charged, and vice versa.

Category	Symbol	Description
Set	i	Index set for batteries
	t	Index set for timestep
	j	Index set for grid
	h	Index set for household
	e	Index set for electric vehicles
Scalar	A_{pv}	Area of photovoltatic plant
	SOC_{min}, SOC_{max}	Min/Max State Of Charge (SOC)
	H	Number of households in the LEM
	η_{charge}, $\eta_{\text{discharge}}$	Battery efficiencies
	FiT	Feed-in-Tariff
	r	Retail price on electricity from grid
	η_{EVcharge}, $\eta_{\text{EVdischarge}}$	EV charging/discharging efficiencies
	SOC_{EVmin}, SOC_{EVmax}	Min/Max SoC for EV
Parameter	$p(t)$	Market prices at timestep t
	$p^{+}(t)$, $p^{-}(t)$	Energy levies at timestep t
	$P_{\text{grid\_outMax}}(t)$, $P_{\text{grid\_inMax}}(t)$	Max grid power out/in at timestep t
Variable	$G^{out}(t)$	Grid power output at timestep t
	$G^{in}(t)$	Grid power input at timestep t
	$M^{grid}(t)$	Binary variable for grid power flow at timestep t
	$L_{elec}(t)$	Sum of household electrical loads at timestep t
	$L_{therm}(t)$	Sum of household thermal loads at timestep t
	$B^{in}(i,t)$	Power into battery i at timestep t
	$B^{out}(i,t)$	Power out of battery i at timestep t
	$M^{bat}(i,t)$	Binary variable for battery i power flow at timestep t
	$P_{pv}(p,t)$	Power from photovoltaic (PV) plant p at timestep t
	$P_{fixedgen}(f,t)$	Power from fixed generator f at timestep t
	$P_{hp}(h,t)$	Power from heat pump h at timestep t
	$Q_{hp}(h,t)$	Thermal power (heat) from heat pump h at timestep t
	$P_{wind}(w,t)$	Power from wind plant w at timestep t
	$P_{ev\_out}(e,t)$	Power out from electric vehicle e at timestep t
	$P_{ev\_in}(e,t)$	Power into electric vehicle e at timestep t
	$hp_{\text{p}}(t)$	Heat pump's power at timestep t
	$hp_{\text{cop}}(t)$	Coefficient of performance of the heat pump at timestep t
	$SOC_{ev}(e,t)$	State of charge of EV e at timestep t
	$S(t)$	Solar irradiance at timestep t
	$W(h)$	Willingness to pay for desired energy quality t
	$x(h,t)$	Energy sold within the market by household h in timestep t
	$b(h,t)$	Energy bought within the market by household h in timestep t
	$E(h,t)$	Energy exported to grid by household h in timestep t
	$GI(h,t)$	Energy imported from grid by household h in timestep t
	$y(h)$	Revenue of household h from participating in the LEM relative to only participating in the wholesale market

Table 5.1: Nomenclature

$$P_{\text{GridOut}}(t) \leq P_{\text{GridOutMax}}(t) \tag{5.5}$$

$$P_{\text{GridIn}}(t) \leq P_{\text{GridInMax}}(t) \tag{5.6}$$

Equation 5.5 and Equation 5.6 are constraints ensure that power can either flow into or out of the grid, but not both simultaneously.

$$P_{\mathrm{PV}}(\mathrm{p}, t) \leq S(t) \cdot A_{\mathrm{pv}} \tag{5.7}$$

For each PV plant p and each timestep t, we have a constraint that limits the power output of the plant to the predicted value, if the plant is controllable.

$$P_{HP}(hp, t) \geq HP_P(t) \tag{5.8}$$

$$Q_{HP}(hp, t) = -COP(t) \cdot P_{HP}(hp, t) \tag{5.9}$$

The Heat Pump (HP) constraints are defined above: The first equation ensures that the power consumed by each heat pump hp at any given time step t is at least as great as the minimum power requirement $HP_P(t)$ for that heat pump to operate. The second equation is an expression of the energy balance in the heat pump

$$P_{ev\_out}(e, t) \geq 0 \tag{5.10}$$

$$P_{ev\_in}(e, t) \geq 0 \tag{5.11}$$

For power flow constraints, Equation 5.10 and Equation 5.11 are defined to ensure that if an EV is discharging, it cannot simultaneously charge, and vice versa.

$$P_{ev\_in}(e, t) \cdot P_{ev\_out}(e, t) = 0 \tag{5.12}$$

Equation 5.12 enforces that only one of the P_{EVIn} or P_{EVOut} can be non-zero at any time step.

$$SOC_{\mathrm{EV}}(e, t) = SOC_{\mathrm{EV}}(e, t-1) + \eta_{\mathrm{charge}} \cdot P_{ev\_in}(e, t) - \frac{1}{\eta_{\mathrm{discharge}}} \cdot P_{ev\_out}(e, t) \tag{5.13}$$

The SOC of the EV at time step t is affected by the power flow into and out of the EV. If SOC of the EV is dentoed as $SOC_{EV}(e, t)$, it can model it as seen in Equation 5.13.This equation implies that the SOC at time t is equal to the SOC at the previous time step, plus the energy added by charging (taking into account charging efficiency η_{charge}), minus the energy removed by discharging (taking into account discharging efficiency $\eta_{discharge}$).

$$SOC_{\mathrm{min}} \leq SOC_{\mathrm{EV}}(e, t) \leq SOC_{\mathrm{max}} \tag{5.14}$$

Furthermore, the SOC should not exceed the capacity of the EV, and should not fall below a minimum, as illustrated in Equation 5.14: This constraint ensures the SOC stays within a permissible range.

5.1.2 Pricing mechanism

In Lemlab, the price is set according to the supply-demand ratio within the LEM for each time step. The utilized supply-demand ratio for this thesis is shown in 5.2. Each supply-demand ratio corresponds to a LEM-price. The LEM-price for each kWh is interpolated using the two nearest values whenever the ratio resides between two explicitly defined ratios. The LEM-price is represented in (€/kWh) while the supply-demand ratio is unitless.

Supply-Demand Ratio	0	0.1	0.2	0.6	0.7	1	1.1
LEM-price (€/kWh)	0.08	0.074	0.068	0.044	0.038	0.02	0.02

Table 5.2: Supply-demand ratio utilized in the market simulations

5.1.3 Input data

Since lemlab intends to simulate a typical German energy market, the FiT tariff (0.01 €/kWh) and the price from the wholesale market (0.48 €/kWh) are set as fixed prices. The levy- and balancing prices are also set as fixed eur/kWh prices. The balancing price is baked into the retail price to make extraction of the output data used to plot the KPIs possible. Since the balancing costs anyways reflects a cost for using the grid, it was deemed as an acceptable solution.

The participants in the market can either be pure consumers or prosumers. It is possible to edit both the numbers of participants and equip them with the following technologies: PV, batteries, heat pumps, small-scale wind, a fixed generation (to simulate CHP or run-of-the-mill hydropower), and EVs with or without vehicle-to-grid (V2G) connection.

The batteries are set to only charge from prosumer produced energy. In a scenario with spot prices this could cause be assumed as unrealistic, but with fixed prices there are no reasons to charge the batteries from the grid. The batteries have an initial SOC of 10% and are scaled to have the same size of their accompanying PVs. The PVs are again based on the annual demand of each household. The demand of the households are based on German load profiles. The annual demand of each household vary between roughly 3000 - 4000kWh, and a PV production between 2.5-4-5kWp.

5.1.4 Forecasting

Forecasting plays an important role in the price setting of the market and the adjustment that has to be done underway to align production and imported electricity from the grid with the demand of the LEM. Several things are forecasted, such as household loads, PV production, EV availability, small-scale wind production, and heating demand for heat pumps. Lemlab has various options for different types of forecast models, including a seasonal autoregressive moving average (SARMA) model, perfect knowledge, naive forecasting, moving average, electric vehicle realistic forecasting, neural network, and weather forecasting. But currently several of these forecasting methods are not fully implemented in lemlab. Until this was found out, the plan was to combine forecasting with varying degrees of accuracy to see how this affected the results. But in practice, there is little forecasting in the simulated scenarios. The following variables have a perfect forecast: household demands, PV production, HP production, and CHP production. For the perfect forecast, the function returns the values from the specified file for the given horizon. The forecasting of the availability of EVs is set to be perfect knowledge of the current availability cycle once the vehicle arrives.

5.1.5 Key performance indicators

In this section follows the mathematical definitions of the KPIs introduced in section 3.8.

$$QoS_t = \frac{[\sum_{j=1}^{H} b(h,t) + x(h,t)]^2}{H \cdot \sum_{j=1}^{H}(b(h,t) + x(h,t))^2} \tag{5.15}$$

QoS indicates the amount of energy traded within the community. Following QoS, the system is 100% fair when the amount of traded energy in the collective is equal for all peers. Equal traded amounts are not necessarily a goal for the system, but low QoS values indicate that there are peers with a larger impact on the community than others.

As highlighted in research co-authored with this thesis supervisor [92], a challenge using QoS is that equal traded amounts of energy can be a faulty measurement of fairness. In cases where there is only one, or few, households with production capacity, they will naturally demonstrate high "market power" Therefore, in this thesis. *QoS prosumer* and *QoS consumer* are introduced to calculate only the QoS for the prosumers and consumers separately. Also, as noted in section 3.8, this thesis is more focused on equity rather than equality. Assessing QoS separately for consumers and prosumers aligns with the goal of measuring equity because it enables a comparison between households that share a more comparable reference point

$$\lambda(h,t) = \frac{FiT \cdot E(h,t) - (r) \cdot GI(h,t) - p(t) \cdot (b(h,t) + x(h,t))}{E(h,t) - GI(h,t) + b(h,t) + x(h,t)} \tag{5.16}$$

$\lambda(h,t)$ is calculated as the sum of costs, or revenues, from trading within the community or with the system operator divided by net consumed or produced power and can be interpreted as the *perceived price* of energy consumption. Further on σ is the standard deviation of the prices $\lambda^{(h)}$ and $\sigma_{max} = r - FiT$ is the maximum price deviation. A lower price variation results in a fairer energy market according to the QoE. A QoE equal to 1 signifies that all prosumer prices, $\lambda^{(h)}$, are the same. QoE is proposed by [93] as:

$$QoE = 1 - \frac{\sigma}{\sigma_{max}} \tag{5.17}$$

When the market price is linearly determined between the retailer's buying and selling price based on a supply-demand ratio pricing mechanism, everyone in the LEM pays the same price when trading under a uniform pricing structure. As [92] notes, when all household follows this uniform pricing structure QoE is relatively robust to change across scenarios. In an attempt to capture the differences across scenarios, the original definition of QoE is elaborated upon to make use of lemlabs ability to account for heterogeneity of actors. Each household's willingness to pay a premium for the desired energy quality reflects a preference for a certain energy quality. To account for the possibility that consuming more energy of desired quality reduces the "perceived cost" of consumption, *QoE New* is introduced. The goal is to see whether or not QoE New will better capture deviations in the perceived costs of participating households.

In lemlab, the energy qualities are Grid, Local and Green Local, where Local is energy from Fixed Gen and Green Local is energy from PV and batteries. In QoE New, the perceived cost for each household of each timestep is reduced with W if the consumed energy is of the desired quality, defined in

		House																			
PV	**Bat.**	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
16	10	✓✓		✓	✓		✓✓	✓	✓✓		✓✓	✓	✓	✓	✓✓	✓	✓✓		✓	✓✓	✓✓
10	4	✓✓		✓ ✓		✓✓		✓	✓				✓		✓			✓	✓		

Table 5.3: Distribution of PVs (orange) and batteries (green) in the cases analyzed.

Equation 5.18. With W being the percentage of how much more they are willing to pay for the given energy quality. Using lemlab's ability to account for actor heterogeneity to reduce perceived price in QoE is an attempt to bridge subjective preferences, actor decisions and economic outcomes. This is aligned with literature from subsection 3.5.1 highlighting the need for tighter cooperation between researchers with technical and social focus to create models that more realistically catch the correlation between both aspects

$$\lambda(h,t) = \lambda(h,t) \cdot W(h) \tag{5.18}$$

The EI is defined in Equation 5.19:

$$EI = 1 - \left(\frac{2\sum_{h=1}^{H} h y_h}{H\sum_{h=1}^{H} y_h} - \frac{H+1}{H}\right) \tag{5.19}$$

Where H is the total number of market participants and y_h is the revenue of household h from participating in the LEM relative to only participating in the wholesale market, ranked ascendingly. In contrast to the conventional Gini index, the index has an inverted definition, meaning that a number nearer to 1 denotes a more equal distribution of income. This is done to make the results easier to read and to correlate with the definitions of the other indexes in this work.

To compare the economic distribution separately between consumers and prosumers, EI consumer and EI prosumer are introduced in the same way, and with the same motivation, as with QoS prosumer and consumer.

Furthermore, *Absolute EI* is introduced to evaluate the income distribution in the LEM without considering the costs of non-participation in a LEM. This Absolute EI is identical to the original EI, but the variable y_h solely reflects the real costs associated with participating in the LEM, as opposed to being based on the cost difference between participating and not participating in the LEM, as it is in the original EI.

5.1.6 Scenarios

For this thesis, eight different scenarios have been simulated to test the proposed KPIs. There are four different combinations of PV and batteries that have been tested, combined with two different preference scenarios to make eight simulations in total. The preference scenarios is denoted with two different willingness to pay a premium for the desired energy quality, as seen in Table 5.4. In both scenarios, everyone has a preference of green local energy, which without wind generation present means PV produced energy and batteries. Willingness is measured in how much more than the market price households are willing to pay to satisfy their energy preference. Regular preference and Green Preference are the names of the two different preference scenarios simulated in this thesis.

Household ID	Regular Preference (%)	Green Preference (%)
1	30	40
2	30	40
3	20	30
4	0	10
5	0	10
6	0	10
7	10	20
8	0	10
9	20	30
10	30	40
11	0	10
12	0	10
13	0	10
14	0	10
15	0	10
16	0	20
17	10	10
18	10	20
19	30	40
20	10	20

Table 5.4: Willingness to pay a premium for the preferred quality of energy (here being green local energy). Willingness is measured in how much more than the market price households are willing to pay to satisfy their energy preference. Regular preference and Green Preference are the names of the two different preference scenarios simulated in this thesis.

The full setup of the market with EVs, fixed gen and HPs included as well can be seen in Figure 6.1. These three do not change across the different scenarios. Wind generation was decided not to include to make it easier to analyze the impact of different numbers of PV in the market. While writing the discussion section, the need to simulate a scenario where PV production does not saturate the market arose. Therefore an extra scenario identical to the others, but with only 2 PVs and 0 batteries was simulated.

Chapter 6

Results

This section presents the values of the KPIs from chapter 5 and explains trends in the results that will be explained in chapter 7.

6.1 Market plots

These market plots are used to accompany the discussion and explanation of the results of the KPIs in chapter 7.

Figure 6.1 shows the balance of market participants in the scenario with 10 PVs and 2 batteries. As the demand of each household is relatively similar, the installed technology has the biggest effect on the economic outcome. The consumers with HPs have an additional large load to cover and therefore have the highest costs. Household 7 with a constantly producing fixed gen is able to export during the entire simulation period and naturally gains on this. As the market is saturated with green energy during midday, not all prosumers are able to sell their surplus PV production. This leads to differences between the prosumers with only PVs as well.

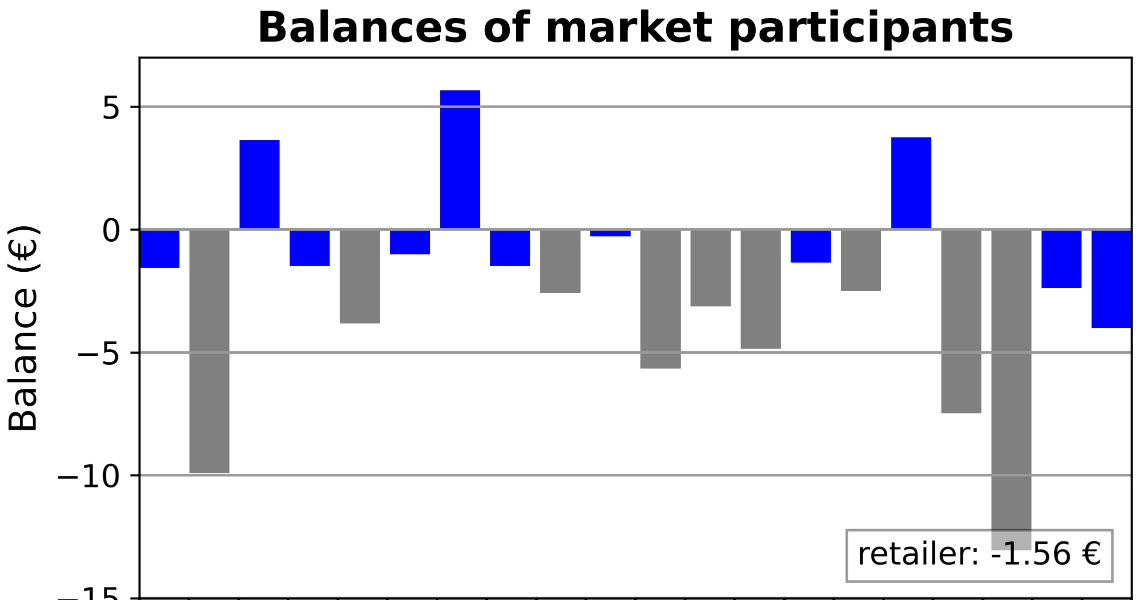
Figure 6.2 shows the balances of market participants in scenario 10 with PVs and 2 batteries if they were to not participate in a LEM. As there is only the possibility to sell excess energy for FiT-price, all comes economically worse out of this scenario. Since all PV-equipped prosumers only can sell to the retailer and have similar production capacities, they now have more equal costs.

Figure 6.3 shows the energy quality and market price during the simulation period in the scenario with 10 PVs and 2 batteries. The local energy is solely from the fixed gen of household 7. During midday, the LEM is saturated with green local energy from PV production. This surplus pushes down the LEM price during these hours.

Figure 6.4 shows the total positive, negative, and net flow of the LEM during the simulation period. The negative load comes from household demands, while the positive flow is the product of PV production. It is worth noting that the households have an even demand curve during the entire day.

6.1.1 Market plots of scenario 2 PVs and 0 batteries

With only 2PVs present in the LEM there is no longer a saturation of PV energy. This leads to higher prices during midday as more of the consumption has to be covered with imports from the grid.



	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	#11	#12	#13	#14	#15	#16	#17	#18	#19	#20
PV	✓		✓	✓		✓		✓		✓				✓		✓			✓	✓
Battery	✓					✓														
EV							✓				✓				✓			✓	✓	
Heat pump		✓															✓	✓		✓
Wind																				
Fixed gen							✓													

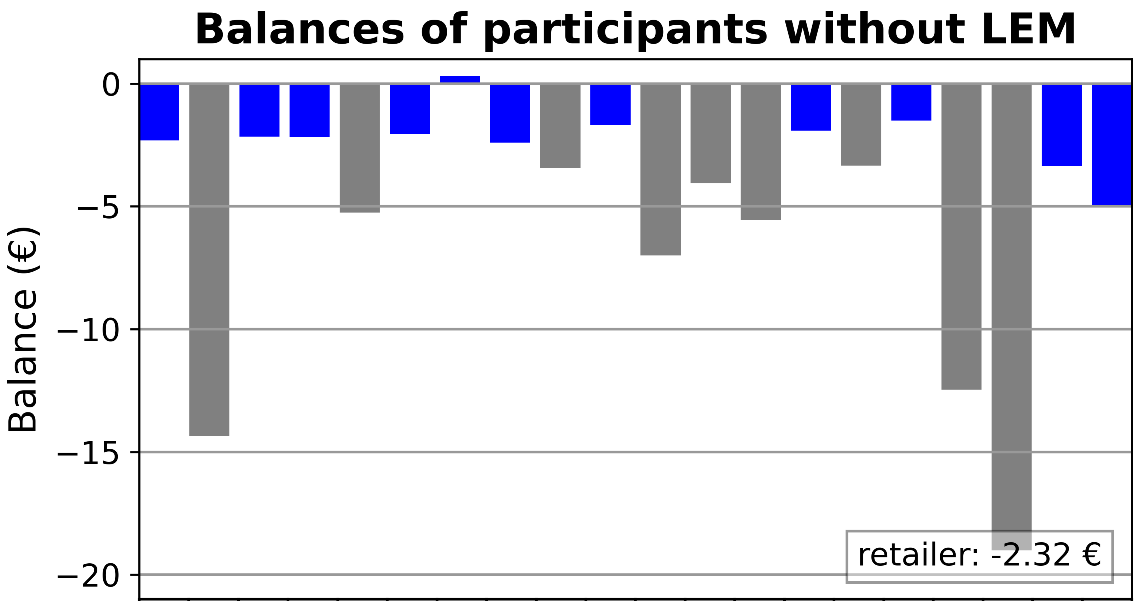
Figure 6.1: Balance of market participants in the scenario with 10 PVs and 2 batteries. Prosumers marked in blue.

The number of batteries has not made a substantial impact on the QoS or any other KPIs. As demonstrated in the referenced comparison in Figure 6.6 of power flows for the same prosumer with and without a battery, the battery's usage is minimal. This trend is consistent across the entire market. When looking at scenarios featuring 10 PVs and varying battery quantities—2 and 8, the total market savings throughout the simulation period see a minor increase of just 0.08 euros. As PV production saturates the market and drives the prices down, it becomes more economical to satisfy a greater demand at low solar prices rather than fulfilling a marginally smaller demand at slightly higher prices.

6.2 Quality of Experience

The QoE-results can be seen in Figure 6.7 There is close to no variance in the different QoE values across the different scenarios and they are overall high.

Across various scenarios, QoE remained consistently close to 1 in all scenarios tested, indicating that all participants, regardless of their size or transaction volume, faced the same electricity price. There was also close to no variance in the results, illustrated in Figure 6.7. This can be seen in relation to the saturation of green local energy observed in Figure 6.3 in the scenario with 10 PVs and 2



	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	#11	#12	#13	#14	#15	#16	#17	#18	#19	#20
PV	✓		✓	✓		✓		✓		✓				✓		✓			✓	✓
Battery	✓					✓														
EV							✓				✓				✓			✓	✓	
Heat pump		✓															✓	✓		✓
Wind																				
Fixed gen							✓													

Figure 6.2: Balance of market participants in the scenario 10 with PVs and 2 batteries without LEM. All excess PV production is exported for FiT-price, and all demand not covered by PV production/battery is imported from the grid

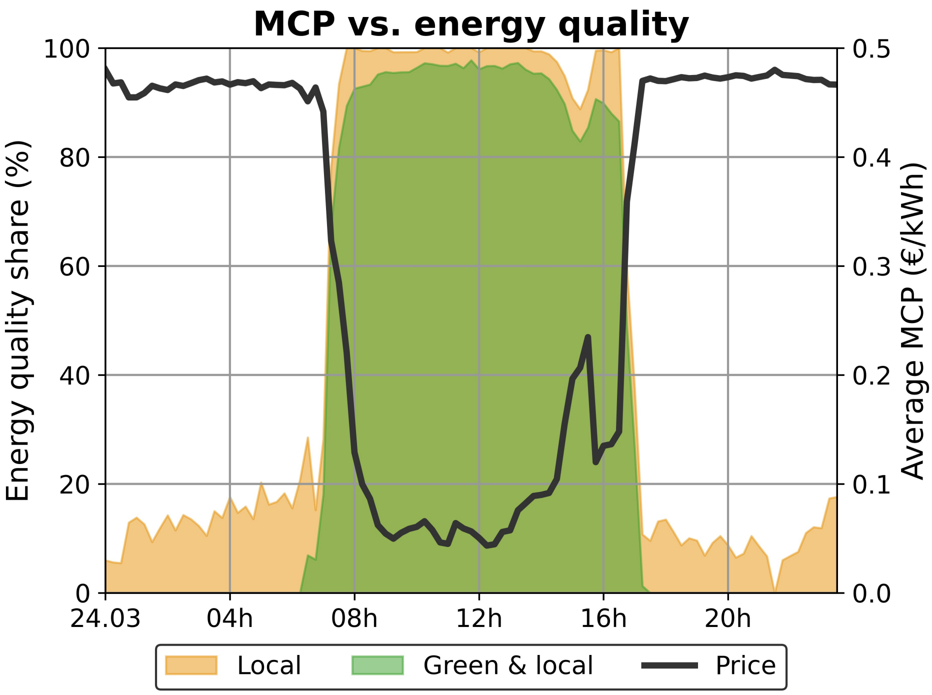


Figure 6.3: Energy quality and market price during simulation period in the scenario with 10 PVs and 2 batteries. What is not covered by local or green local is covered by energy imported from the grid.

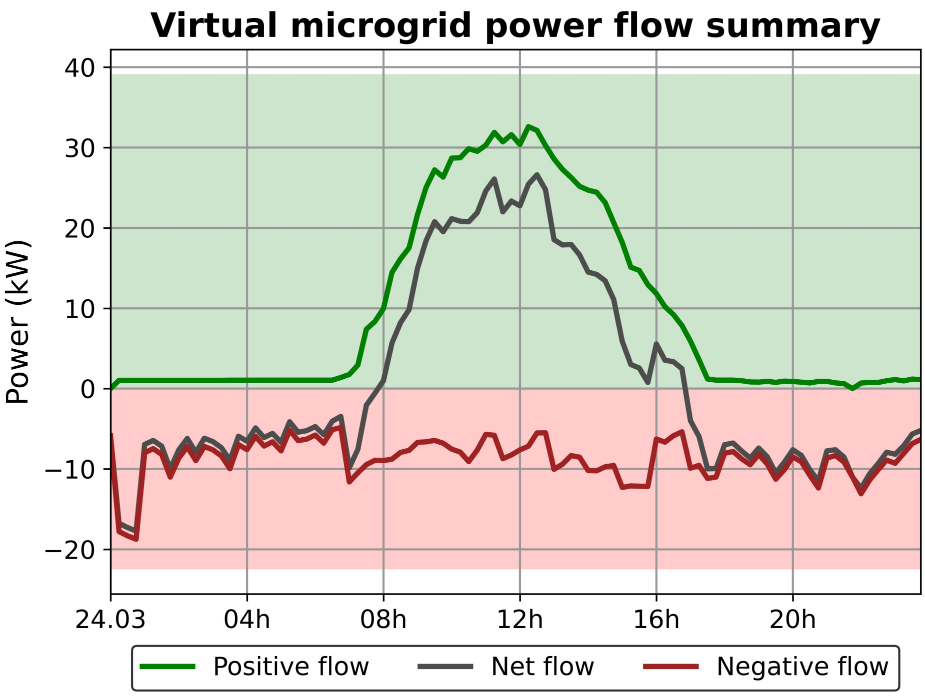


Figure 6.4: Net power flow from the LEM during the simulation period in the scenario with 10 PVs and 2 batteries.

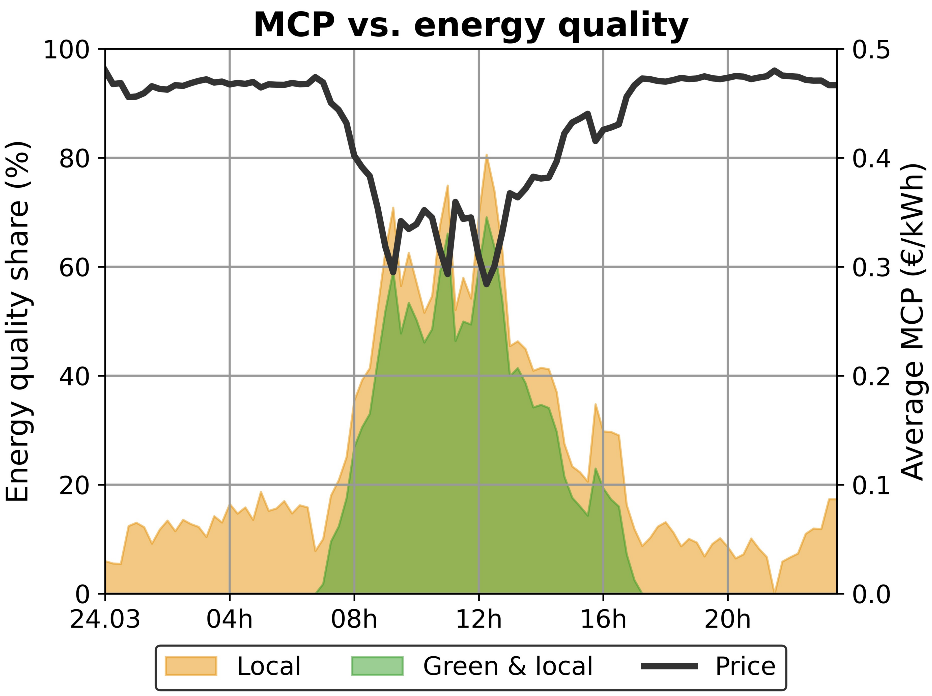


Figure 6.5: Energy quality and market price during simulation period in the scenario with 2 PVs and 0 batteries. What is not covered by local or green local is covered by energy imported from the grid.

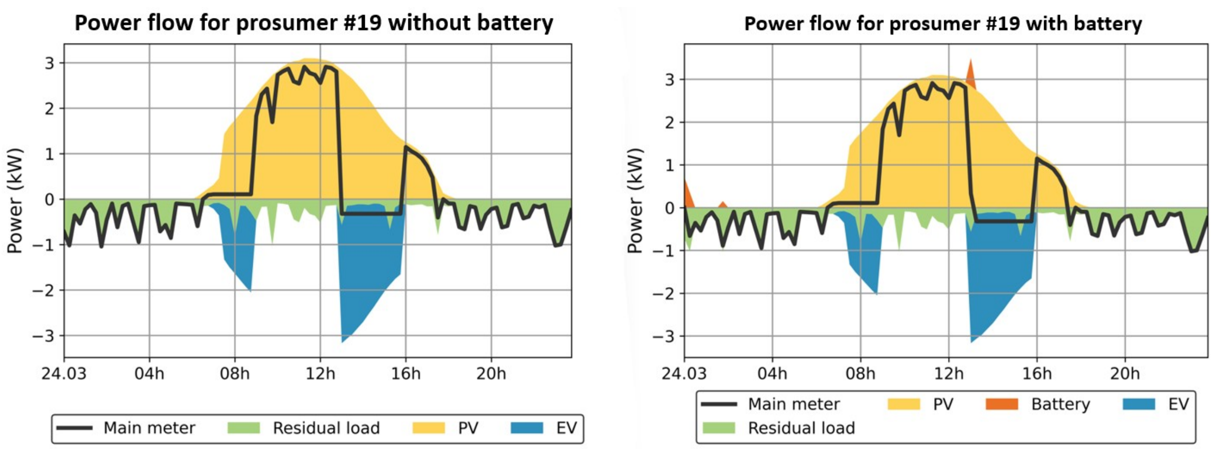


Figure 6.6: Power flow of household 19 during the scenario with 10 PVs and 2 batteries and 10 PVs and 8 batteries.

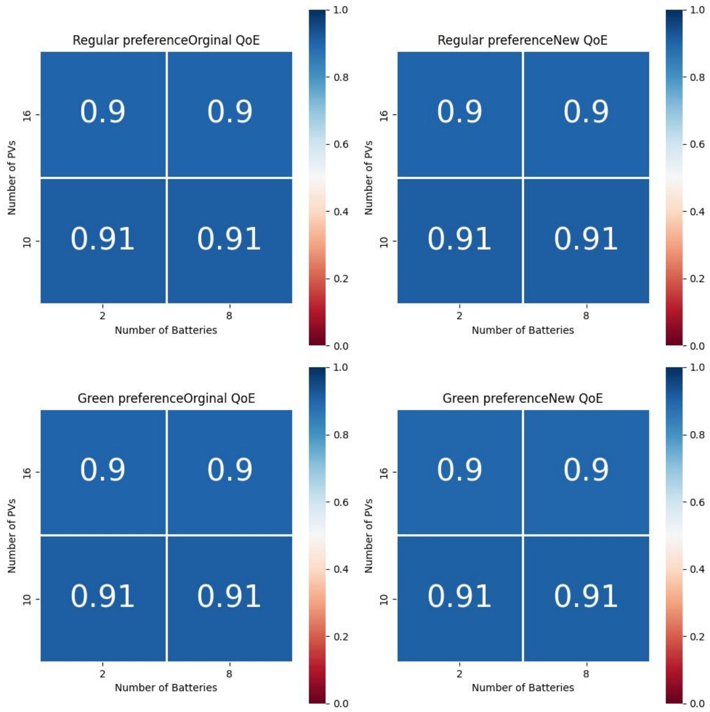


Figure 6.7: Comparison of the two versions of QoE across the different scenarios

batteries. To further check QoE in a non-saturated market, a scenario with 2 PVs and 0 batteries was simulated as well. This yielded around 50% coverage of green local energy during midday but did not affect the QoE or the new QoE in any way. They both clocked in at 0.91.

The introduction of the green preference scenario was especially with the new QoE in mind since it adjusts for a reduced perceived price if the desired energy quality is acquired. Nevertheless, it yielded no changes. This, and the aforementioned trend will be investigated further in chapter 7 with visual help from the net market flow in Figure 6.4 and the PV production and prices in Figure 6.3.

6.3 Equality Index

Since EI is a purely economic KPI, it is directly linked with the balances of each market participant seen in Figure 6.1 and Figure 6.2. Nevertheless, the increased willingness to pay for green local energy in the green preference scenario did not seem to impact the EI. This again is linked to the surplus of PV production in the market during midday. It is also debatable whether or not an economic KPI is the best measure to include in a scenario based on subjective preferences.

Apart from that, the EI is the KPI demonstrating the greatest variance in value across the different scenarios. The original EI tends to decrease when more households with PVs participate in the market. This is primarily due to a larger reduction in the prosumer EI, which outweighs the gain in consumer EI for these scenarios. How absolute EI can be interpreted and used relative to the other EIs will be done in subsection 7.4.1 with the help of the insight drawn from the books of Harari and Kahneman.

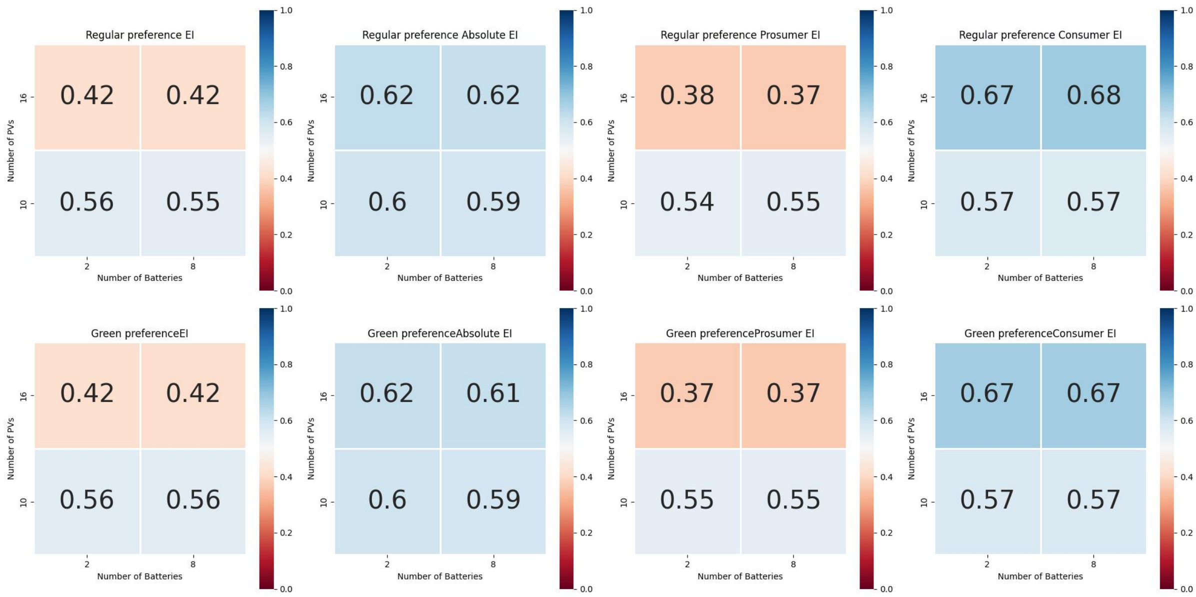


Figure 6.8: Comparison of the different versions of the EI across the different scenarios.

6.4 Quality of Service

QoS measures the equality of the amount of traded energy by each household in the market. When comparing the Regular and Green preferences the QoS remains unchanged across the scenarios. In a centrally cleared LEM with linear supply-demand pricing, it's always beneficial for market participants to purchase as much PV energy as they can. Thus, comparing QoS at different willingness-to-pay levels yields no difference in the results. And when comparing the QoS of prosumers and consumers, it's observed that as the number of prosumers in the market rises, there is a corresponding decrease in prosumer QoS and an increase in consumer QoS. This is due to the increased competition between the added prosumers and reduced competition between the consumers that are left. Both QoS and EI express this trend when comparing prosumers and consumers. In general, the QoS values are low due to the differences in production capacity and demand between the households. This will be elaborated on in chapter 7 and used to argue against its utility of measuring equity in a market.

6.5 KPIs of scenario 2 PVs and 0 batteries

The KPIs of the scenario with 2 PVs and 0 batteries are presented in Table 6.1.

In this scenario, QoE was more or less unchanged, experiencing a slight increase. In this scenario around half of the participants were unable to buy energy from the LEM. Nonetheless, this did not reflect on the QoE or new QoE. This is because the difference in the standard deviation of the retail price and FiT and the perceived price are too low to make an impact in the calculation of QoE. Furthermore, the QoS is 0.26. With two households having PV and one with fixed gen, they naturally have high market influence. This again shows the lacking ability of the QoS to measure the equity in the market.

The original EI is relatively unchanged in this scenario but with greater changes in absolute, con-

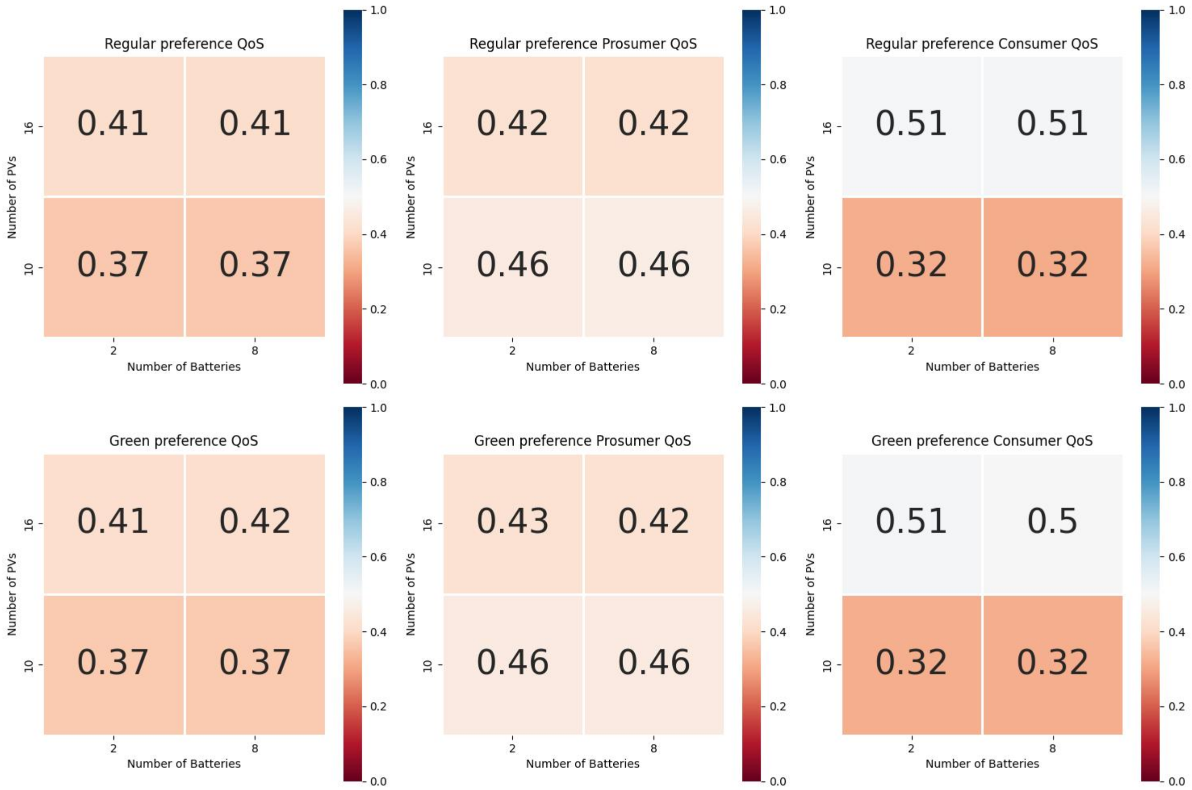


Figure 6.9: Comparison of QoS, and QoS for only prosumers and consumers across different scenarios

KPIs of scenario 2 PVs and 0 batteries and regular preference	
QoS	0.26
Prosumer QoS	0.61
Consumer QoS	0.25
Orginal QoE	0.95
New QoE	0.95
EI	0.37
Absolute EI	0.64
Prosumer EI	0.80
Consumer EI	0.49

Table 6.1: KPIs of the additional scenario, 2 Pvs and 0 batteries

sumer, and prosumer EI. With less competition among the prosumers, their EI will be high and conversely, the consumer EI will be lower. The Absolute EI scores high at 0.64, while the original EI is 0.37. This discrepancy likely arises from the fact that when comparing the savings between participating and not participating, the two prosumers will gain more than the consumers.

Chapter 7

Discussion

7.1 Quality of Experience

When QoE is equal to one, it implies that every participant, regardless of their size or the volume of their transactions, experiences the same price for electricity. This is the essence of a uniform pricing scheme that acts as a hallmark of equity in the electricity market.

To illustrate this, one can refer to Figure 6.7. As the data suggests, the QoE is consistently close to one across all scenarios. In these cases, the QoE might be better suited to identify if all households are able to participate in buying energy from the prosumers in the market. In the scenario with the least production capacity, 10 PVs and 2 batteries, there is still enough local or green local energy to cover all the demand in the market alone, as can be seen in Figure 6.3. Everyone gets to buy energy for the same price. Since the other scenarios have the same market coverage, the QoE will be the same for them as well.

On the other hand, it could be expected that in a different scenario where there is not enough coverage of renewables for everyone in the market, the QoE would change more. To test this hypothesis, an extra scenario consisting of 2 PVs and 0 batteries was tested. In this scenario, there was only around 50% coverage of green local energy during the middle of the day, as seen in Figure 6.5. This led to around half of the participants being unable to buy energy from the LEM. Nonetheless, this did not reflect on the QoE or new QoE of the scenario, which remained more or less unchanged. This is due to the differences in the standard deviation of the retail price and FiT and the perceived price, which is used in Equation 5.17. Since the retail price and FiT are based on fixed prices, it will always be 0.47 in this scenario. Even though there are notable differences in the perceived price within the LEM, the standard deviation of the perceived price is too small (around 0.035 in the scenario with 2 PVs) compared to the difference in retail price and FiT to make a visible impact on QoE. Therefore, in scenarios with these kinds of differences, QoE is not even a usable indicator of market coverage. However, it could be more useful in LEMs with individual prices, typically based on auction or distributed optimization, or where the production portfolio is more varied.

Furthermore, the modification of the new QoE yielded no change in the results across all scenarios. This is probably a result of several factors. The savings from the "perceived reduction" of the cost of buying energy of the desired quality is relatively low. As seen in Figure 6.3, during the hours of coverage with green local energy, the market price is already so low that, e.g. a 30% reduction in the perceived price does not alter much. Especially considering that the household's energy demands do not increase during daytime, as seen in Figure 6.4.

7.2 Equality Index

As EI is a purely economic KPI, it is directly linked with Figure 6.1 and Figure 6.2. Similar to the case with QoE, there is a negligible difference between the regular and green preferences. This can be attributed to the same reasons discussed in section 7.1. Given that there is sufficient green local energy for everyone during midday, paying a premium for access is unnecessary. Furthermore, even if there were a shortage of green local energy, any increased willingness to pay would not significantly impact the EI due to the relatively low prices of green energy. While this may not be the case in different market setups or scenarios, it's important to note that the EI is a purely economic KPI. Since the willingness to pay a premium is based on subjective preferences, the EI may not be the most suitable KPI for comparing results across different levels of willingness to pay. It won't be able to capture whether or not a household is happy to pay a premium needed to consume a higher share of green energy. Subjective preferences can vary widely based on numerous factors such as environmental consciousness, financial capacity, or other beliefs. These subjective aspects may not be accurately captured by a purely economic measure like the EI, making it less effective for comparative analysis across diverse willingness-to-pay scenarios. Hence, other KPIs that can factor in these subjective elements might be more appropriate for such comparisons.

Turning the attention to differences between the overall EI, and the prosumer and consumer EI, the overall EI tends to decrease when more households with PVs participate in the market. This is primarily due to a larger reduction in the prosumer EI, which outweighs the gain in consumer EI for these scenarios. The decrease in prosumer EI arises from increased competition among households with PV capacity, which means not everyone can sell surplus energy. Consider households 3 and 4 in Figure 6.1 and Figure 6.2, both equipped with a PV (with capacities of 5.691kWp and 4.669kWp respectively) and having almost identical demand (annual consumption of 3594kWh and 3517kWh). Without a LEM, their costs during the simulation period are almost identical. However, with the introduction of a LEM, household 3 gains significantly more than household 4 from participating, as the saturated midday market prevents household 4 from selling its surplus. This example, taken from the scenario with 10 PVs and 2 batteries, illustrates how competition intensifies with more prosumers, as seen in Figure 6.8. Conversely, the remaining consumers in the market benefit from more available PV surplus and fewer buyers.

Regarding the general values of the different EIs, despite most households having similar load profiles and PV production capacities, there are notable differences. Some households have HP, resulting in a significantly larger demand than other households. Conversely, one prosumer has a fixed generation, which can always sell all its surplus during hours without PV production, as shown in Figure 6.3. These disparities are fairly well reflected in the EI values being around 0.5. While it could be argued that a prosumer investing in greater PV capacity, as household 3 compared to 4, should receive more compensation, given the low investment costs of slightly better PVs, it is important to balance the benefits received from investing in slightly better equipment. It may be perceived as unfair by household 4 if only household 3, out of the two, is capable of selling energy to the. On the other hand, the fixed generation is supposed to represent a CHP plant or run-of-the-mill hydropower. Considering the high investment cost associated with this, it's possible to argue that the discrimination the household with fixed generation faces matches its contribution, or that it should receive even greater benefits. Again, matching the advantages received against the contribution of a prosumer is of paramount importance. Developing a KPI that captures this aspect would be interesting for further work. Furthermore, this thesis assumed perfect knowledge of load and production profiles. In real-world situations, this might not be the case. Future work could investigate the effects on the economic distribution in the market by introducing forecasting errors or uncertainties in load and production profiles. This would make the setup more reflective of real-world conditions where accurate forecasting is a challenge.

The results of absolute EI will be addressed in subsection 7.4.1

7.3 Quality of Service

The first thing to notice across all versions of QoS is that it does not change between the regular preference scenario and the green preference scenario, as can be seen in section 7.2. This is due to the fact that QoS only address the amount of energy traded, not its price. With a centrally cleared LEM priced based on a linear supply-demand ratio, it will always be advantageous to buy the amount of PV energy that is possible for each market participant. Therefore, in these scenarios comparing the QoS across different levels of willingness to pay has little utility.

Similar to prosumer and consumer EI, the prosumer and consumer QoS are respectively reduced and increased with a higher amount of prosumers in the market, as seen in Figure 6.9. It can be explained similarly by the higher competition explained in section 7.2. Another factor explaining that could affect this is the definition of QoS, as seen in Equation 5.15. Since it is based on the absolute values traded energy by each household, it does not account for the varying demands of the households. This could lead to abrupt changes in QoS when increasing the numbers of prosumers, just because the households that are left by chance have more similar demand curves, which will materialize itself as a consumer QoS closer to one. In the simulated scenarios of 10 and 16 PVs, this is not the case, the standard deviation of the demands of the consumers that are left actually decreases a bit when 6 more households are equipped with PVs. Even though it could be argued that the consumer and prosumer QoS have some utility as it identifies the increased/reduced competition between prosumers and consumers across scenarios the division of EI into consumer and prosumer EI gives exactly the same insights. QoS can in some cases be used to expose households that demonstrate high "market power". As seen in Table 6.1, in the scenario with 2 PVs, the QoS is 0.26. With two households having PV and one with fixed gen, they naturally have high market influence. The QoS capture this with a low value. In the simulation done in the thesis, there is a centrally cleared market, which means that market abuse should not occur. This assumption is based on the fact that batteries are a part of the market clearing mechanism, and therefore not controlled directly by an end user. If market participants have the ability to strategically control their storage, they may potentially manipulate the market by strategically reporting their input to the central authority. Without having a lot of context about the market, this can be hard to tell from only looking at the QoS if market abuse happens or not.

Of the three analyzed KPIs in this thesis, this is the one with the least utility. If adjusted for the demands of the different households, maybe it could prove greater worth. Since QoS measures equality and not equity, and the thesis leans towards a preference of equity rather than equality it's logical that it does not describe the perceived fairness in the market in a satisfying way.

7.3.1 Lack of impact on KPIs from batteries

Across all scenarios and KPIs there is no visible impact of adding more batteries to the LEM. This comes from the fact that the batteries are used minimally during the simulation period, as seen in Figure 6.6.

The lack of noticeable impact on KPIs when adding more batteries to the LEM can be attributed to several interconnected factors. Firstly, an abundance of solar energy leads to an excess supply during daylight hours, thereby driving prices to a very low level. In comparison, the batteries are unable to produce a similar surplus to exert the same downward pressure on prices within the LEM. Thus, when the objective is to minimize total market costs, it becomes more economical to satisfy a greater demand at low solar prices rather than fulfilling a marginally smaller demand at slightly higher prices. Secondly, the batteries do not significantly influence the overall market dynamics, including the price or total trade volume. For example, in scenarios with 10 PVs, the addition of six extra batteries (totaling eight) only realizes a total saving of 0.08 euros compared to scenarios with only two batteries. This negligible economic benefit suggests that the added batteries do not bring substantial value to the market. For future research, it is recommended to explore scenarios where the role and impact of batteries in the energy market could be more pronounced. This might involve adopting spot prices instead of fixed retail prices or utilizing a different market clearing mechanism. If spot prices are adopted instead of fixed retail prices, this could introduce more variability and unpredictability in energy costs. In such a scenario, batteries could play a strategic role in storing energy when prices are low and discharging when prices rise. Such investigations might offer fresh perspectives on the strategic role and value of batteries in energy markets.

7.4 Potential loss of perceived fairness

As mentioned earlier, fairness must align with the participant's motivations to join in establishing a fair market. Several aspects of motivation are hard to quantify but nevertheless should be attempted, as previously mentioned. Contributing to helping the environment is one of them. Probably the most obvious advantage of investing in a PV or participating in a LEM is to be able to facilitate the installment of more green energy in the local areas. But an advantage that is probably overlooked by many is the environmental impact of contributing to reducing grid congestion. In the uttermost consequences, measures like this can postpone grid expansions. Which in non-urban areas hurt nearby nature, need raw materials for production, and are a source of pollution in both the production and transportation phases. Minimizing grid expansion can have just as much positive environmental effect as installing micro-production of PV. However, when the participants of a LEM do not know about this climate advantage, there is a "potential loss" of perceived fairness among the participants motivated to join for environmental purposes. In theory, this means increasing the perceived fairness in a LEM would be possible by informing future participants about the non-economic benefits of participating in a LEM, like the positive effects on the grid. This aligns with the findings of [54] and [2] about the benefits of informing consumers about the motivation to join beyond the economic part.

This could explain why the early adaptors mentioned by [46] in 2.3.5 are technically competent and engaged in more than just their short-term economic gain of participating. This also follows the experience done by the author through interviews during an internship for Elvia, a DSO in Norway, while researching the motivation to install a self-regulated water heater was examined among seven pilot program participants. The only participants showing some interest in taking part other than their short-term economic wins were a farmer and a mechanic that displayed an understanding of the grid-helping features the load shifting the water boilers could provide. These reductions in the perceived price caused by local and green local energy should be further investigated in a specific LEM context to accurately depict the gains of experienced fairness. Challenges related to this are further discussed in section 7.6.

On the other side, there are challenges to this suggested solution. One potential counterargument or challenge to the idea that increasing awareness of non-economic benefits will lead to increased perceived fairness is that not all consumers will be equally motivated by environmental and social factors. For some participants, the primary concern may still be economic gain, and they might not place significant value on the broader impacts of their participation in a LEM. As a result, the effectiveness of informing consumers about the non-economic benefits may vary depending on the target audience. Moreover, there is a risk of overselling the environmental benefits of LEMs, which could lead to skepticism and distrust among consumers. Therefore, it is essential to ensure that the information provided to potential participants is accurate, transparent and that any claims about the environmental and social benefits of participating in a LEM can be substantiated.

Another challenge is the cost and effort of providing this information to consumers. Marketing and educational campaigns can be expensive, and LEMs might struggle to find the necessary resources to communicate the non-economic benefits of participation effectively. Additionally, not all consumers may be receptive to the information provided, and it may require a sustained and targeted effort to shift consumer attitudes and preferences successfully.

7.4.1 The utility of absolute EI

In the context of this discussion, absolute EI can be seen as the observed reality that participants will use to judge the market after participating for some time. However, the original EI values could be interpreted as those that potential participants would initially consider when deciding to join the LEM. Given our argument that demonstrating fair results is more crucial for motivating people to join than long-term fairness, the original EI becomes more important.

Another perspective is how the LEM is presented to potential new participants after some time of operation. There's the possibility of showcasing the results of an established market to make the LEM more attractive. For instance, in the scenario with only 2 PVs, the Absolute EI stands at 0.64, while the original EI is at 0.37, as seen in Table 6.1. This discrepancy likely arises from the fact that when comparing the savings between participating and not participating, the two prosumers will gain more than the consumers. However, one could argue that this is fair, as there should be an incentive for early adopters to invest. If this perspective is agreed upon, utilizing the Absolute EI as a means of presenting the market's performance to potential early adopters could be a valid approach.

On the other hand, in scenarios where an established market with a high number of prosumers already exists, the deliberate use of Absolute EI could potentially mislead new participants. As seen in Figure 6.8, the EI for prosumers is the lowest among all the metrics. Therefore, using the Absolute EI to showcase the performance of this market to potential participants might paint a more favorable picture of the market from a prosumers perspective than what is actually the case.

To wrap up this segment of the discussion, it is the author's belief that the Absolute EI can be a useful tool in certain scenarios to motivate households to participate. However, it should not be used in a manner that could be perceived as deceptive. Doing so would contradict the argued need for market transparency.

7.5 Exploring the diminishing significance of equity in local energy markets through the lenses of Harari and Kahneman

Drawing from the insights provided by Yuval Harari in "Sapiens" [6] and Daniel Kahneman in "Thinking, Fast and Slow," [7] it could be suggested that the measurement of fairness in a LEM may be of limited significance when the assumption is that participating in a LEM is invariably advantageous compared to not participating. This assumption comes from using a linear supply-demand ratio where the LEM price will always lay between the retail price and the FiT. Then a participant will, in a worst-case scenario not save anything, but most likely save something. Harari proposes that an individual's happiness is contingent not exclusively on objective conditions such as wealth, health, or community but rather on the relationship between these objective conditions and subjective expectations. He also notes that this definition of happiness as the relation between objective conditions and subjective expectations is established both among researchers in the field and historical philosophers. Applied to the context of a LEM, this suggests that if the subjective expectations of participants are met or exceeded, they are likely to experience satisfaction or contentment, independent of the objective fairness of the market. Consequently, when LEM participation consistently yields benefits compared to non-participation, the assessment of fairness could be deemed less relevant, as participants' expectations are already being met through the inherent advantages of LEM involvement.

Kahneman's observation that "the luxuries of today become the necessities of tomorrow" implies that individuals adapt to novel comforts and eventually come to regard them as indispensable. With respect to LEMs, as participants become accustomed to the benefits they derive from the market, such as reduced energy costs and access to clean, local energy, these advantages may become their new baseline expectations. Given that LEM participation consistently results in benefits, the sustained satisfaction of participants might render the evaluation of fairness less critical. As participants adjust to the benefits, they might no longer perceive them as luxuries but as standard aspects of their energy consumption, thereby diminishing the importance of fairness as a factor influencing their overall satisfaction.

This statement acknowledges that the argument presented in the previous response relies on two key assumptions. First, it assumes that as long as participants receive benefits from the LEM such as reduced energy costs and access to clean and local energy. And second, if their subjective expectations are met, then the measurement of fairness might be of limited significance. However, it is essential to recognize that these assumptions may not hold true in all cases. There could be situations where participants' satisfaction might be affected by their perception of fairness, even if they are experiencing benefits from the LEM. E.g., they might perceive the distribution of benefits among participants as unequal or believe that certain participants are unfairly advantaged. In such cases, their perception of fairness could influence their overall satisfaction and expectations of the LEM, despite receiving benefits.

Another way of interpreting the logic presented by Daniel Kahneman, it can be argued that to motivate individuals to join a LEM, it is essential to provide tangible evidence of a fair market or a market that aligns with the expectations of potential participants. However, as time progresses, the significance of fairness may diminish, as participants may eventually take the market for granted. Initially, when individuals consider joining a LEM, their expectations and perceptions of fairness play a crucial role in shaping their decision-making process. Demonstrating tangible results that prove a fair market, such as equitable distribution of benefits, transparent decision-making processes, and equal opportunities for all participants, can effectively address these concerns and motivate individuals to join the LEM. Providing this evidence aligns with participants' expectations, leading to increased satisfaction and a higher likelihood of joining the market. Nonetheless, their perceptions may change as participants become accustomed to the LEM and its benefits. Kahneman's observation that "the luxuries of today become the necessities of tomorrow" suggests that, over time, participants adapt to the market and its benefits, eventually considering them as essential components of their energy consumption experience. As a result, the importance of fairness might gradually decrease as participants begin to take the market for granted and focus on the perceived necessities provided by the LEM.

7.6 Challenges of self-assessed well-being

The willingness to pay a premium defined in Table 5.4 was chosen based on what the author assumed was reasonable for the two scenarios. To find out how much participants actually value the option of paying a premium for green local energy, more studies have to be conducted. Not only for this purpose but there is a need to find out how much households value other aspects of participating in a LEM. This affects both the motivation to join and the perceived fairness of participating. In Thinking Fast and Slow, Daniel Kahneman investigates the challenges of quantifying self-assessed well-being and happiness. This section will briefly summarise Kahnemans points and then discuss how this relates to the challenges of quantifying fairness and motivational factors for participating in LEMs

Kahneman introduces the concept of the two selves - the Experiencing Self and the Remembering Self. The Experiencing Self, as the name implies, is in the present, experiencing events as they occur in real time. The Remembering Self, on the other hand, reflects on past experiences and shapes our overall assessment of life.

A key illustration of the divergence in the interests between these two selves lies in the 'Peak-End Effect' and 'Duration Neglect'. For instance, consider a patient who undergoes a surgical procedure. If the surgery was prolonged but ended on a relatively painless note, the Remembering Self might view this experience as less painful, disregarding the duration of the operation - this is the Duration Neglect. Likewise, if the pain peaked at a significantly high level towards the end of the operation, the Remembering Self might remember the experience as extremely painful, despite an overall manageable level of pain - this is the Peak-End Effect. Similarly, in a marriage that was joyful for years but ended in a bitter divorce, the Remembering Self might cast a shadow over the many years of happiness, emphasizing the painful end.

This discrepancy between the two selves presents substantial challenges in measuring self-assessed well-being. A person with higher education, for instance, may rate their life highly due to the societal prestige associated with education, reflecting the perspective of the Remembering Self. However, the Experiencing Self may not necessarily feel more joyful or content day-to-day, thus not showing an increase in experienced well-being. He also discusses how individuals often employ heuristics when answering questions about general life satisfaction. For instance, someone who found a coin right before answering a survey may report higher life satisfaction due to the 'mood heuristic'. They have let their immediate, positive mood influence their overall assessment of life. This phenomenon is underpinned by the 'focusing illusion', which stipulates that nothing is as important as you think it is when you're thinking about it. For instance, if a person just got a promotion, they may overestimate its long-term impact on their overall happiness.

When considering the challenges of quantifying perceived fairness in LEMs, these psychological principles are of paramount importance. Participants' reports about their motivations for joining, or their perceptions of fairness in these markets, could be heavily influenced by the same biases. They could, e.g., disproportionately focus on recent experiences or particular incidents (positive or negative peaks), and this could influence their overall assessment of fairness in the LEM. Consequently, this could lead to misconstrued insights when designing LEMs or integrating these perceptions into models aimed at accounting for fairness in LEMs. For instance, if they have recently read about the positive impacts of renewable energy or the devastating effects of a climate disaster, these events may create an immediate focus on the importance of an even distribution/high consumption rate of renewable production capacity in the LEM. This heightened focus could inflate what factors affect the perceived experience of fairness, thereby leading the survey makers to think this is of great importance to potential participants of a LEM.

However, as the focusing illusion suggests, this perceived significance may not persist in the long term. Once the immediate focus is removed, the importance of fairness may lessen in the individual's eyes. They may become more concerned with the practicalities of participating in the LEM, such as cost savings or convenience, as these factors become more relevant to their everyday experience. This could also happen the other way around. If there are high electricity prices when the surveys are conducted, this could lead to the belief that a fair economic distribution is of great importance. But some years later, when LEMs are actually implemented in real life, headlines regarding the climate situation might dominate and change the expectations of LEM participants in another direction.

This dynamic becomes even more complex when considering the potential conflicts between the Remembering Self and the Experiencing Self in the context of LEMs. Imagine a participant who's been active in a LEM pilot project for some time. Over the course of their participation, they have navigated a range of experiences - some challenging, others rewarding. Their Experiencing Self went through the ups and downs of participating in the LEM, dealing with technical difficulties, learning new systems, and also reaping benefits such as cost savings or a sense of community involvement.

Now, this participant is asked to reflect on their experience in the LEM. Their Remembering Self, which is in charge of forming an overall assessment, comes into play. As per the 'Peak-End Effect' and 'Duration Neglect' discussed earlier, the Remembering Self might focus on the most intense (peak) and recent (end) experiences. E.g., if they recently encountered a technical issue that temporarily disrupted their energy supply, their Remembering Self might overly focus on this negative event, even though their overall experience has been largely positive. On the other hand, if their most recent experience was receiving a significantly reduced energy bill, they might overlook past challenges and rate their overall experience highly. This discrepancy between the continuous experience of the Experiencing Self and the selective memory of the Remembering Self might lead to an over- or underestimation of the value they derived from participating in the LEM. This can pose challenges when trying to gauge participant satisfaction or gather feedback to improve the LEM, as these cognitive biases might skew the feedback.

It is, therefore, critical to take into account these potential cognitive biases when interpreting self-reported data and ensure measures are in place to gain a more accurate understanding of participants' experiences and perceived fairness in LEMs. This could involve a range of strategies, from structuring surveys to minimize the impact of recent events (e.g. by designing surveys to recall a range of experiences, not just the most intense or recent), to interpreting data in a way that accounts for the potential influence of peak experiences and the focusing illusion.

Chapter 8

Conclusion

The necessity to incorporate more DERs to meet the UNSDGs poses substantial challenges if not properly integrated. LEMs emerge as a promising tool to aid this transition, but practical implementation, and more importantly, the social implications of such a shift, demand further research. Literature recognizes ABM as an effective tool to address these concerns, which inspired the selection of lemlab, an open-source tool, for this thesis. Scenarios with varying quantities of PVs and batteries were simulated along with the combination of varying willingness to pay a premium for PV produced energy from the prosumers within the market. The perceived price in QoE was modified to reflect a reduced perceived price if desired energy quality was bought. This approach aligns with the literature's call for better integration of technical and social aspects.

When it comes to the performance of the KPIs, QoS demonstrated the least utility. If adjusted for the demands of the different households, maybe it could prove greater worth. Since QoS measures equality and not equity, and the thesis leans towards a preference of equity rather than equality it's logical that it does not describe the perceived fairness in the market in a satisfying way. As demonstrated by other literature, QoE tends to be robust to changes across scenarios of different deployments of PVs and batteries. This thesis found the same results, and the new suggested QoE was not able to change this. Despite differences in perceived price within the LEM, the low perceived prices caused minor standard deviation of the perceived price, compared to the difference between retail price and FiT. Even in the scenario with 2 PVs and lower market coverage, was both original and new QoE as high as before. In the utilized market setup in this thesis, both the new and old QoE was an insufficient indicator of market coverage. However, in LEMs with individual pricing or a more diverse production portfolio, typically based on auction or distributed optimization, QoE could prove more useful.

The modification of the new QoE didn't affect the outcomes due to low savings from the perceived reduction in energy cost. As market prices during green local coverage hours were already minimal compared to retail prices, even a significant reduction, such as 30% in perceived price, didn't substantially influence the results, especially given the consistent household demand being the same at daytime as during the night. The EI value provides an economic depiction of the local energy market, shedding light on the distribution dynamics among prosumers and consumers. When more households with PVs enter the market, overall EI tends to decrease due to increased competition reducing prosumer EI, while consumer EI gains are offset. Additionally, despite similar load profiles and PV production capacities, EI values can illustrate differences among households, such as those with higher demands or fixed generation capacity. This demonstrates the value of dividing into prosumer and consumer EI, as it allows a more nuanced view of the economic distribution within the market.

When it comes to the comparison of the KPIs across different levels of willingness to pay, both QoS and EI was deemed irrelevant the simulated scenarios. Due to the EI being a purely economic KPI, it is not suitable for comparing subjective preferences, as different levels of willingness to pay for green energy. The QoS only address the amount of energy traded, not its price. Therefore, with a centrally cleared LEM priced based on a linear supply-demand ratio, it will always be advantageous for market participants to buy the amount of PV energy that is possible. So in these scenarios comparing the QoS across different levels of willingness to pay has little utility.

Applying the established definition of happiness—across both research and philosophy—objective conditions vs. subjective expectations—to LEMs offers a unique perspective. If LEMs meet or exceed participant expectations, satisfaction increases and fairness perception becomes less crucial. As they adjust to benefits, these become standard, decreasing fairness's role in satisfaction. Fairness in LEMs, therefore, is argued to be a critical participation motivator, not a constant requirement. Understanding participation motivations, often derived from pilot experiences, is important. The book Thinking, Fast and Slow by Daniel Kahneman underlines the need to account for cognitive biases in self-reported data. Accurate insights into participants' experiences and LEM fairness perceptions may be gained through well-structured surveys and data interpretation that minimizes the impact of recent events and accounts for cognitive biases such as peak experiences and the focusing illusion.

8.1 Future work

Based on the discussion in chapter 7, here are four suggestions for future work:

Different market clearing mechanisms: QoE could be significantly impacted by different market clearing mechanisms. As our results indicated, QoE may not be a reliable indicator in scenarios with negligible price variations. Therefore, using individual pricing strategies, such as auction-based or distributed optimization mechanisms, could be explored. This could be particularly insightful in LEMs with more varied production portfolios.

Realistic forecasting: This thesis assumed perfect knowledge of load and production profiles. In real-world situations, this might not be the case. Future work could investigate the effects of introducing forecasting errors or uncertainties in load and production profiles. This would make the setup more reflective of real-world conditions where accurate forecasting is a challenge.

Development of new KPIs: It would be interesting to develop a KPI that captures the contribution of prosumers in the market and the advantages they receive. A KPI that reflects this balance could offer a more nuanced understanding of the economic dynamics within LEMs.

Role of batteries and variable pricing: The role of batteries in the LEM and their impact on energy costs could be more pronounced in scenarios with variable pricing, such as spot prices. Future research could explore such scenarios, focusing on the effects of introducing more cost variability and unpredictability. A different market clearing mechanism could also be utilized in these scenarios to better understand the consequences of battery use in LEMs.

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