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Price formation in Local Electricity Markets

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Price formation in Local Electricity Markets

Master Thesis

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Abstract

This thesis aims to identify suitable price formation mechanisms for Local Electricity Markets (LEMs). The methodology of the thesis consists of a literature review, Multi Criteria Mapping and an assessment of the performance of the mechanisms through the simulation of a real-life case study.

The literature review explores the reform of electricity markets through European directives, emphasising local participation from prosumers in the distribution grid. Active participation can be facilitated by Local Electricity Markets, which allow for the trading of energy volumes by decentral market participants within the distribution grid. Three price formation mechanisms are identified: auction-based mechanisms, negotiation-based mechanisms, and system-determined mechanisms.

Stakeholder involvement plays a crucial role in identifying the definition of 'suitable' in the context of price formation mechanisms and is performed using Multi Criteria Mapping, which maps five stakeholder perspectives. The analysis of the perspective of the network operators, public sector, market sector, cooperative sector and academic sector indicates the preference varies between the auctions and system-determined mechanisms. Both mechanisms allow for fair and transparent price formation, whilst system-determined mechanisms are also conceptually simplistic. In addition, the stakeholders raise concerns relating to the operation of the mechanisms in LEMs with market power and low liquidity conditions.

In the analysis of the Local4Local BioZon pilot, the first project in which electricity is locally sold for the cost price, the performance of the mechanisms are analysed through a simulation. The findings show that the local market conditions should be monitored to assess market dominance, efficiency, transparency, and fairness. If the market conditions are sub-optimal, for example, due to high market concentration, a stable, disclosed, and transparent system-determined mechanism should be implemented until effective price formation by an auction-based mechanism can be facilitated.

Incorporating stakeholder perspectives is essential in designing market structures and the large-scale implementation of LEMs. The thesis recommends that further research is necessary to define locality, identify tipping points for price formation mechanisms, and establish the necessary regulatory frameworks.

Preface

It is with great pleasure that I present this master thesis, which is the result of the last part of my Master Sustainable Energy Technology (SET) at Eindhoven University of Technology (TU/e). The thesis was conducted under the supervision of Dr. ir. Phuong Nguyen, Prof. dr. ir. Anna Wieczorek, and ir. Sjoerd Doumen, who provided me with valuable guidance and support throughout the process.

I would also like to extend my gratitude to Daan Rutten and Emmanuel van Ruitenbeek from ENTRNCE International for their guidance and feedback throughout the writing of the thesis. Their vast expertise and insight in the field of (local) electricity markets was proven very helpful for my academic work.

Furthermore, I would like to express my sincere appreciation to all those who participated in the interview process for my thesis. Without their participation, the research would not have been possible.

Lastly, I would like to thank my family, friends, and girlfriend for their support and encouragement throughout the writing of my thesis.

I hope the thesis contributes to the energy transition and the global challenge of addressing climate change, which is ultimately achieved by taking collective action towards a more sustainable future.

Pepijn van de Water

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Nomenclature

μ_{buy}	Bid price
μ_i	Individual Clearing Price
μ_{p2p}	Clearing price negotiation-based mechanism
μ_{sell}	Offer price
μ_{wavg}	Weighted average price
σ_{std}	Volatility
BRP	Balance Responsible Party
CDA	Continuous Double Auction
D	Order book depth
$DERs$	Distributed Energy Resources
DSO	Distribution System Operator
HHI	Herfindahl–Hirschman index
k	Price coefficient
LEM	Local Electricity market
MCM	Multi Criteria Mapping
MCP	Marginal Clearing Price
MCV	Marginal Clearing Volume
N	Number of market participants
$n_{cleared}$	Number of cleared orders
OTC	Over The Counter
$P2P$	Peer-to-peer
PDA	Periodic Double Auction
PV	Photo Voltaic

q_{clear}	Cleared volume
q_{demand}	Demand
$q_{imported}$	Imported volume
q_{ti}	Volume
q_{trade}	Trading volume
RES	Renewable Energy Sources
s_i	Market share per participant
T	Clearing period
t	Clearing interval
TSO	Transmission System Operator

Chapter 1

Introduction

1.1 Background

In the sixth assessment report from the Intergovernmental Panel on Climate Change (IPCC) a comprehensive assessment of the current state of knowledge concerning the observed impacts and potential risks of climate change was conducted. A significant interaction between natural, climate and social systems was confirmed. In addition, the report underlined that widespread adverse impacts to both nature and people have been caused by human-induced climate change [59].

In an effort to reach a sustainable, equitable and fair world it is important to limit global warming to 1.5 °Celsius. The climate change problem is a threat to both the planet and human well-being and the window for global anticipatory action is closing [59]. In the Paris Climate Accord from 2015 it was agreed upon that global heating should be limited to less than 2.0 °Celsius with reference to pre-industrial levels. In response to the Paris Climate Accord, the Dutch Government set the target to reach a 49% greenhouse gas reduction in reference to 1990 in 2030. In addition to this central target, the Dutch Government aims for a greenhouse gas reduction of 55% in Europe [103].

Concretely, in 2030 a total of 84 TWh of electricity should be produced from renewable energy resources. To achieve this target, agreements and goals are set for sustainable energy production on land and at sea. In total, land-based renewable energy resources should account for 35 TWh and offshore wind for 49 TWh in 2030 (49% reduction target). In reference, 1 TWh is equal to the annual electricity consumption of the city of Den Bosch. Consequently, 84 TWh is equal to around 70% of the current annual electricity consumption in the Netherlands. In the year 2017, the total renewable electricity generation accounted for 17 TWh [35].

The transition towards a sustainable electricity system will impact the existing energy system and stakeholders, and can be characterized using the four D's as driving forces [72]:

- **Decarbonisation**: To reach carbon neutrality in the year 2050, a carbon-free electricity system should be implemented. Consequently, existing fossil-based energy sources will be replaced by renewable energy sources such as wind and solar PV. Other sectors, such as mobility, agriculture, the built environment and industry will also see further electrification with the aim to meet the greenhouse gas emission reduction targets for 2030 and 2050 [103];

- **Decentralisation**: The decentralisation of energy generation is a driver that impacts the transition of the electricity grid, which is traditionally designed for central production and transport of energy. In distributed generation, energy is produced at the distribution part of the energy system. The generated energy through distributed units is smaller as compared to central production units, however, the share of decentralised energy sources connected to the grid is expected to increase. In general, distributed energy sources demand for an alternative control paradigm as compared to centralized control that is applied with central power plants. Centralized control will ultimately reach the limits of computational complexity, scalability and communication and therefore requires an intelligent, decentralized approach [69]. Decentralisation also allows for more active participation of citizens in the energy transition, for example through participation in energy communities or cooperatives. These public institutions could allow for a transition towards public ownership of the renewable energy infrastructure, which was previously owned by centralised commercial actors, thereby indicating an institutional change [107].

- **Digitalisation**: Digitalisation plays a crucial role in the integration of decentralized assets into the energy system. As described in the EU Action plan on digitalising the energy system, digitalisation will enable interactions between the different actors in the energy system. Ultimately, as the result of decentralized energy generation, more grid decisions will be taken at the edges of the energy system which demands more flexibility from the electricity grid. Flexibility can be provided through flexible management of decentralized energy assets by prosumers and active consumers. Through flexibility, the possibility to adjust the electrical consumption or production of an installation or process can be unlocked. A prerequisite for the integration of flexible and decentralized assets into the electricity grid are shared data infrastructures and digital tools, which can be enabled through digitalisation initiatives [43];

- **Democratisation**: The fossil-fuel-based energy infrastructure relies on centralised control, which differs in several social aspects from the decentralised nature of renewable energy systems. Through renewable energy generation, individuals, households, energy communities and municipalities can actively participate in the energy system. Consequently, local and distributed ownership and control are new aspects of the future energy system. In addition, as the main energy resources for renewable energy generation (sun and wind) are widely available and accessible, there is less need for competition allowing for a more inclusive energy system. Ultimately, local ownership, decentralized control, accessibility and inclusiveness allow for the democratisation of the energy system [110].

1.1.1 Impact of driving forces on the electricity markets

The four driving forces of the energy transition impact the existing electricity grid, that was traditionally built in a centralized, vertically-integrated manner. Through decentralisation and democratisation, smaller actors will participate in the electrical system, however, the access and participation in the electricity markets for smaller producers is still limited [118]. In traditional electricity markets, electricity trading is performed on a large scale in wholesale markets, in which retailers, generators and industrial users are the main actors. The principles of traditional electricity trading can consequently not directly be applied in local energy trading markets that fundamentally differ from the wholesale markets [61].

Different entry barriers for the participation of decentralised actors in wholesale markets can be identified. In the wholesale markets, centralized power plants with high power output capacities must generate a minimum power output (0.1 MW at EPEX Spot) to be eligible to sell their electricity on the market. Smaller, decentralized energy production units may, however, not be able to generate this minimum amount of electricity in order to participate in the wholesale market, thereby creating a barrier to entry. Furthermore, expertise is crucial in order to trade energy on the wholesale market, which is an additional entry barrier for decentralized prosumers [78]. Lastly, all transactions on the wholesale market must be facilitated by a licensed supplier, and consumers can only have one supplier, thereby setting a regulatory entry barrier to market participation for actors without a license or the facilitation of trades between actors with different suppliers [14].

As described in the Clean Energy for All package by the European Union, the final consumer is perceived as a crucial participant in the electricity market of the future, in which they should actively participative in the system. Ultimately, it is the goal that 'final consumers can become self-generators (prosumers) of renewable energy, for example, by installing rooftop panels, managing their storage and other load flexibilities, and even participating in local collective self-consumption (CSC) and energy communities' structures, where local electricity markets (LEM) mechanisms can help them to sell their energy surplus or find local supply to their needs' [82][p.1].

These 'consumer-centric' approaches are prone to different characteristics as compared to the traditional commercial market actors that operate on the wholesale markets. Energy communities are for example organised around certain principles such as ownership, control and governance by non-professional actors, non-commercial purposes and open and voluntary participation. As a result of these characteristics, entities such as energy communities face inherent challenges with reference to technical and financial resources, placing them in a different situation as compared to traditional market actors. Energy communities that seek to supply their members with locally generated electricity face barriers related to financial and administrative requirements, such as the need for a license to supply energy, which is a crucial barrier for bottom-up initiatives as a consequence of the regulation of existing energy systems and centralised design. However, looking at the EU legal principle of equality, renewable and citizen energy communities should be able to act on a level playing field with reference to commercial actors, with non-discriminatory, fair and transparent procedures [41].

Market access and engagement for small and medium users in the energy system, such as prosumers or energy communities, can currently be achieved in two ways: the actors can control their renewable assets by optimising self-consumption (no-direct market access) or they can access the market through an intermediary, that has a licence to supply energy (such as a supplier), to indirectly access the electricity markets [25]. In Figure 1.1, the direct and indirect barriers to market access for prosumers in electricity markets and local electricity markets can be observed [25].

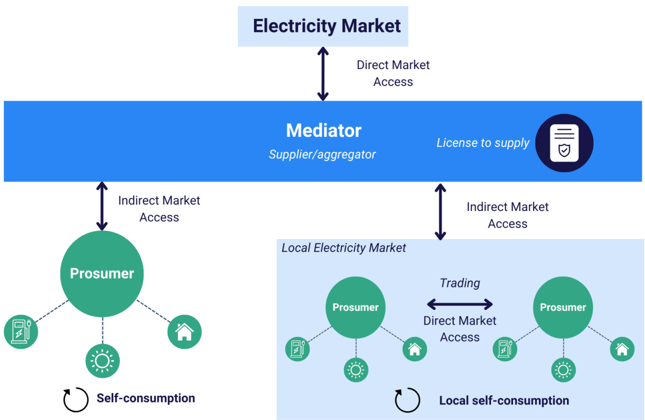

Figure 1.1: Direct and indirect market access for prosumers to electricity markets and local electricity markets (LEMs) [25]

The drivers such as the shift towards a more decentralised energy system, an increase in local energy consumption and the European directives steer towards an increased amount of local participation from prosumers in the distribution grid. Local participation could help Distribution System Operators (DSO's) with alleviating congestion issues in the distribution grid in the shape of a local market. This local market could also be characterised as a transactive energy system, in which market-based interactions in combination with energy management in the distribution grid allow for a participative energy transition [29]. Transactive energy systems that operate in distribution grids are referred to as Local Electricity Markets (LEMs),[83] and are defined in this thesis as:

> 'Local Electricity Markets allow for the trading of energy volumes by decentral market participants within the distribution grid'.

Consequently, through a LEM smaller, decentralized energy producers can participate in electricity markets, by enabling the trading of electricity between decentralised market actors, which can be characterised as an example of direct market access. However, there is still a central party (LEM coordinator) necessary for the integration of the LEM with the wholesale market and operation of the marketplace, such that there is still an element of indirect market access for decentralised actors in a LEM. By defining a LEM locally, regional self-consumption is promoted through the local trading of electricity, which can potentially relieve the distribution system [25]. A LEM provides a number of benefits for both stakeholders and the overall electricity system [118]. An increased amount of renewable energy usage can be achieved using a LEM, as market participants are enabled to sell excess renewable energy to the grid or other market participants thereby reducing the reliance on non-renewable energy resources. Furthermore, grid stability can be improved as multiple distributed energy sources allow for a consistent supply of energy as well as an enhanced amount of energy balancing between supply and demand, thereby reducing energy waste and improving the efficiency of the grid [26]. From a social perspective, energy independence can be improved through LEMs through an enhanced amount of regional self-consumption, thereby reducing the reliance on external energy sources for the LEM participants as well as allowing for transparency and accountability through real-time monitoring and tracking of energy transactions in the local market structures [26].

The effective implementation of LEM's depends on social, technical, economic and environmental factors. In addition, to allow the active participation of smaller decentralized parties in electricity markets, different technical and business models should be deployed. In the academic literature, significant progress has been made regarding the necessary building blocks for Local Electricity Markets [118]. Besides progress in the academic field, there are also examples of practical implementations of Local Electricity Markets.

Network companies can set up online platforms for the facilitation of electricity trading. An example is the ENTRNCE platform, developed by Alliander's new business department, to anticipate onto the future energy system. Alliander is a 'Dutch Network Company', which also contains Distribution System Operator Liander. ENTRNCE is an online platform that implements an electricity exchange, thereby enabling producers and consumers to directly trade electricity with each other. Energy communities are using the platform to supply locally generated electricity to its members, and by using the platform energy communities (or other actors) are not subject to the administrative and financial barriers related to supplying energy to its members (being balance responsible) [41]. Relating this to Figure 1.1, the ENTRNCE platform takes on the role of an intermediary such that prosumers, energy communities and other market participants have access to electricity markets and peer-to-peer trading between the market participants, thereby facilitating LEM structures. As a result, the market participants have access to different energy markets (such as EPEX Spot) and transactions can be facilitated between producers and consumers, regardless of their location or BRP connection or supplier.

1.2 Problem definition

As the result of the four driving forces of the energy transition, decentralised actors, that traditionally have been situated on the receiving end of the vertically-integrated electricity value chain, have become more active participants in the electricity system. Distributed energy resources such as household PV or community-owned renewable energy projects allow for a more proactive and flexible participation in the system through for example consumption management, energy storage and production. The active consumers, or prosumers, have a growing desire to participate in energy communities and energy trading activities [55]. As a result, there is a need to reorganize the existing electricity market infrastructure such that decentralized management and cooperative principles allow for the involvement of decentralised actors into electricity trading. Electrical power systems are evolving towards an increased amount of decentralised management, however, wholesale electricity markets are still based on conventional top-down and hierarchical approaches to pricing and resource allocation, which results in no active prosumer involvement as they remain passive receivers of electrical energy. Through a bottom-up reform of the wholesale electricity markets, prosumers will be empowered to participate in a more active role in which they can for example dynamically influence the electricity market. Through prosumer preference implementation for local and renewable energy, the market will evolve towards a more consumer-centric system [109].

In the paper 'Challenges for large-scale Local Electricity Market implementation reviewed from the stakeholder perspective' [29], it was found that simulations and pilots have proven the potential of local electricity markets (LEMs), however, there are still challenges for the large scale implementation of LEM's. These challenges can be explained by the gap between LEM research and large-scale implementation, as it is essential to incorporate stakeholder perspectives in designing LEM market structures. These perspectives may be overlooked in controlled simulation- or pilot environments as used in LEM research [29]. Relating to this challenge, in the Dutch Klimaatakkoord set a target of end-user involvement in the energy transition is embodied in the target for at least fifty percent of local ownership of renewable energy projects on land by the year 2030. Through 'local ownership, can for example be facilitated through ownership of renewable energy projects by energy cooperation's that represent the local community [103].

The new actors that will participate in the local electricity markets will allow for the creation of a consumer-centric market in which they can manage their energy production and consumption through the local exchange of electricity. Through a local electricity market, an increased amount of renewable energy resources can be integrated into the distribution grid, more energy will be consumed locally, the overall network stability is improved and auxiliary services can be provided to the overall electricity system. [55].

Local pricing in a local electricity market can result in more transparency, a fairer reimbursement for local energy producers, and smoother market- and network operations. Through the introduction of local electricity markets, an alternative market organisation will be introduced that is more consumer-centric such that energy can be more efficiently managed at a community level. The decentralised actors can trade energy securely at a reasonable price, close to real-time with the objective to address the mutual problems (supply and demand) [118, 55]. In addition, as concluded in [48], the willingness of prosumers to participate in a LEM is significantly determined by the community trading price in the local market arrangement. Dab, A. et al. (2023), identified the following benefits of local pricing in local energy trading [26][p.19]:

- Empowering consumers: Local energy trading gives consumers control over their energy usage and costs, allowing them to make informed decisions and potentially save money on their energy bills.
- Offering transparency and accountability: Local energy trading mechanism allows for real-time monitoring and tracking of energy transactions, ensuring transparency and accountability in the energy market.
- Reducing the cost of energy: By enabling direct transactions between energy suppliers and consumers, local energy trading can reduce the cost of energy by removing intermediaries and overhead costs.

- Increasing renewable energy usage: Local energy trading allows for the sale of excess renewable energy generated from sources like solar panels, promoting its adoption and reducing reliance on non-renewable sources.

The goal of the thesis to is identify suitable price formation mechanisms for local electricity markets. ENTRNCE is interested in implementing price formation in its local electricity market platform, in which currently the prices from the wholesale market are followed in the transaction processes. ENTRNCE would like to implement a price formation mechanism into the local electricity exchange that adequately represents the fundamental aspects of local electricity markets, that differ from the fundamentals of the pricing mechanisms used in wholesale electricity markets.

1.3 Research Question

The formulated research question in accordance with the problem description can be defined as follows:

> **What is a suitable mechanism for price formation in a Local Electricity Market?**

The research question will be addressed using sub-questions. The sub-questions for the thesis will each consider a different element of the research:

1. *What are potential price formation mechanisms for Wholesale and Local Electricity Markets?*
2. *What are suitable price formation mechanisms from a stakeholder perspective?*
3. *How do the price formation mechanisms perform in a case study?*

The scope of the thesis can be set in accordance with:

- The concept of 'suitable' is defined on the basis of the input from the stakeholders;
- The concept of price formation refers to the mechanism in which prices in a market are discovered [18];
- The temporal scope of the subject is the day-ahead market, which closes on 12:00 on the day before the physical delivery of electricity;
- The scope of the thesis is focused on the wholesale day-ahead market, the balancing and retail market are therefore out of the scope of the thesis;
- The ENTRNCE platform that will form the base for the study is the Local Energy Exchange. Currently, price formation in this platform is based on following the spot prices in the day-ahead wholesale market.

Thesis structure

The research design for this thesis includes a literature review, Multi Criteria Mapping (MCM) and a simulation using an agent-based simulation environment in Python (LEMLAB). The literature review will be applied to evaluate sub-question 1, which will be answered in Chapter 2 discussing Electricity Markets: Reform and Local Electricity Markets. Next, Chapter 3, discusses the methods applied in the thesis, being the MCM, literature review and simulations. The MCM will be conducted using an innovative online software environment developed by the University of Sussex, that provides structured, reproducible and transparent information on the different perceptions of stakeholders on a certain topic [87]. Through the MCM, the stakeholders will define and weigh criteria for the different options for pricing mechanisms in a local electricity market, thereby answering sub-question 2. In Chapter 4, the results of the Multi-Criteria-Mapping will be discussed in order to conclude which pricing formation mechanisms are the most 'suitable' with respect to the different stakeholder perspectives. In Chapter 5, the performance of the price formation mechanisms will be validated using simulations of a case study, thereby answering sub-question 3. Lastly, the thesis will be concluded with a discussion and conclusion.

The contribution to the academic literature of the thesis can be described as follows:

- Application of MCM methodology to the field of electricity markets;
- Providing a new classification of price formation mechanisms applied in local electricity markets;
- Application of participative and non-participative framework for price formation mechanisms to the field of electricity markets.
- Analysis of a case study in which a fundamental new cooperative price formation is applied: cost-price + (from Local4Local)

In Figure 1.2, the structure of the chapters with reference to the sub-questions as composed for the thesis can be observed. Concluding, The thesis makes a novel contribution to the literature by applying the following:

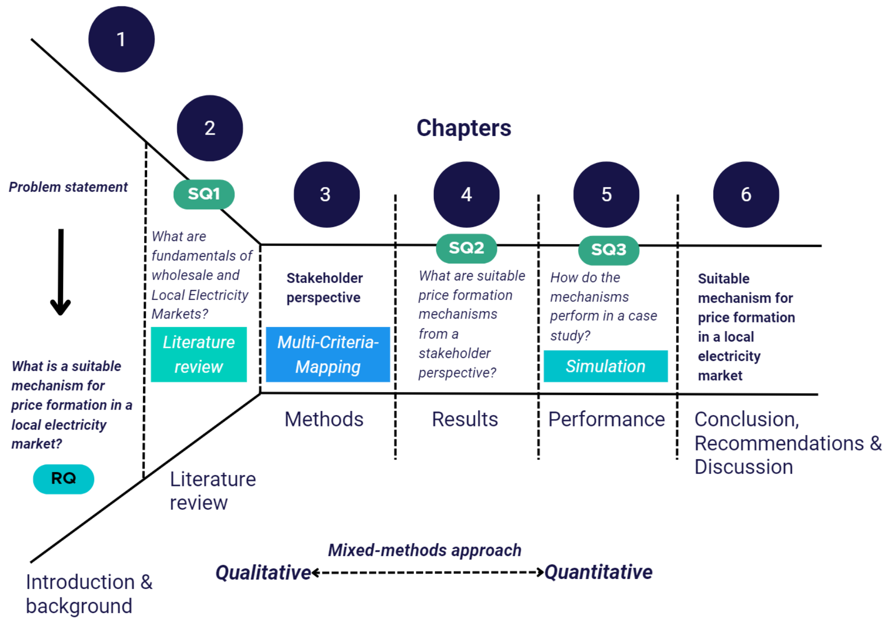

Figure 1.2: The structure of the thesis related to the chapters and methods.

Chapter 2

Electricity Markets: Reform and Local Electricity Markets

2.1 Introduction

Traditionally, the electricity industry was set up in a vertically integrated monopoly structure. Due to the large investment costs, the electricity systems were considered a natural monopoly. In a natural monopoly, a single supplier is able to satisfy the needs of the market at a reduced cost as compared to two or more suppliers [47]. The natural monopoly structure within electricity markets led to single firms running the vertically integrated system (generation-transmission-distribution) without competition until the 1990s [86].

As a result of increasing political and ideological dissatisfaction of the centralised structure of the electricity industry, liberalisation initiatives were implemented into the market by various governmental institutions. European countries reckoned that competition within electricity markets would result in higher economic efficiency, reduced prices for consumers and an increased amount of investment in generators [86]. To increase competitiveness in the electricity industry, barriers to entry in generation and supply chains were addressed and vertically integrated structures have been unbundled [81]. The restructuring and liberalisation of the EU energy sector is the result of the implementation of European directives and regulations that were introduced in 1996, 2003, 2009 and 2019. Through the directives, the European Union worked towards a harmonised and liberalised EU internal energy market (IEM). In the internal energy market, a more customer-centred, competitive, non-discriminatory, and flexible market will be created that is based on market-based supply prices for electricity [86, 45]. The four directives and regulations will be elaborated on in the following sections.

2.1.1 The First Electricity Directive

In a liberalised market, the electricity good is the outcome of a combination of services and tasks performed by different actors in the market. Consequently, a well-functioning market is a crucial factor in the process of liberalising a market. Within the European Union (EU) liberalisation can be characterized as a top-down process, guided by directives and regulations from both the European Council, Commission and Parliament [81].

Historically, electricity supply was characterised as a 'service of general economic interest.' Therefore, the supply of electricity was excepted from the EU treaties concerning competition (specifically the EU Treaties of Maastricht (1993) and Rome (1957)). The consideration of electricity as a service was ended when the European Court of Justice rules electricity as a good on the basis of several occasions, after which the unbundling of activities in the electricity sector was initiated. In 1996, through Directive 96/92/EC, the concept of electricity was treated as two separate legal entities: the transport of electricity (service) and the commodity electricity (good) [81].

The European Commission defines liberalisation as:

> 'Liberalisation aims at increasing efficiency, harmonising and reducing electricity prices, improving public services, cutting reserve production capacities, making a better use of resources, giving customers the right to choose their supplier and providing customers with a better service.' [24][p.1]

The main components of the First Electricity Directive can be described as follows [24]:

- Separate accounts must be kept for transmission, distribution and other electricity related activities in integrated companies. Thereby, misconduct in competition, cross-subsidising and discrimination should be prevented;

- The generation component of the electricity value chain should be accessible to competition. Through tendering or authorisation procedures, new entrants should be able to participate in the generation;

- The transmission and distribution system will remain monopoly structures. A Transmission System Operator (TSO) will be responsible for the operation, maintenance and development of the transmission system. Summarily, the Distribution System Operator (DSO) will be an independent actor that operates and manages the distribution system in its designated geographical area;

- Within the supply element of the electricity value chain, eligible consumers are allowed to switch electricity suppliers. The definition of an eligible consumer may be decided by the EU Member States;

- An independent and competent authority must be established that is responsible for settling disputes that are related to contractual agreements and negotiations.

Following the concept of subsidiarity, the EU Member States should adopt the framework as described by Directive 96/92/EC and should thereby further implement the principles in accordance with the specific situation in the EU Member States. However, after the implementation of the directive, a well-functioning liberalised market was not fully achieved. Issues related to market power in the production of electricity, tariff's and network access were therefore addressed in Directive 2003/54/EC of 26 June 2003. Consequently, Directive 96/92/EC was repealed [24].

2.1.2 The Second Electricity Act

The new directive, 'The Second Electricity Directive 2003/54/EC', introduced new features into the electricity market. From 2007, consumers and non-households should also be free to choose their own energy supplier. The TSO and DSO should be unbundled from a management and legal perspective from supply, generation and trading. An authorisation procedure will be necessary to participate in the generation segment of the market. Next to that, the tasks of the regulator will be broadened: additional responsibility concerning overseeing competition and transparency, the supervision of network tariffs and setting rules on the capacity of interconnections [24].

The Second Electricity Directive led to several advances in the liberalisation of the energy market, however, a number of shortcomings could still be identified: there was an absence of transparency, too little liquidity in the markets and integration between the markets of EU Member States and insufficient unbundling [31].

2.1.3 The Third Energy Package

In response to the issues related to the Second Electricity Directive, the Third Energy Package was introduced in 2009. The core elements of the package were related to the further unbundling of the energy supply and distribution chain, an increased level of transparency in retail electricity markets, increased independence and strength for regulators and other features. Following the Third Package, the regulatory authorities should be independent of industry parties and governmental actors. Lastly, the Agency for the Cooperation of Energy Regulators (ACER) was established [31]. Through the ACER, national regulatory agencies can cooperate at the European level. Thereby, ACER will be responsible for the cooperation between the regulatory agencies between EU Member States, monitoring the progress of the internal energy market and investigate market abuse activities. ACER is responsible for the development of a more integrated and competitive internal energy market with more choice for consumers, the facilitation of free movement of energy cross-border to increase the security of supply and monitor a transparent energy market in which consumers pay a fair price for electricity [42]. In conclusion, through the different elements of the Third Energy Package, the European internal energy market was further liberalised [45]

2.1.4 The Fourth Energy Package

In June 2019, the Fourth Energy Package (Clean Energy For All Europeans) was introduced. One of the core elements of the package was consumer empowerment: 'Consumers need to be at the centre of a renewed EU energy system: improved rules will give them more flexibility and better protection, but also allow them to take their own decisions on how to produce, store, sell or share their own energy' [44][p.12]. Through the Fourth Energy Package, consumers are able to actively participate in the energy transition and citizens can join energy communities in which they are able to 'pool their energy, and benefit from incentives for renewable energy production' [44][p.13]. Consumers should be able to install smart meters at no additional cost, compare the different offers of energy suppliers, switch suppliers without additional charges within three weeks and request a dynamic electricity pricing contract. Lastly, under the Fourth Energy Package, consumers will be able to participate as active consumers in the market. Active consumers will be able to sell self-generated electricity (under no discriminatory or technical requirements) to other participants in the market [45]. New rules for the design of the electricity market were introduced which allowed for the implementation of renewable energy, strengthening the security of supply, improved energy efficiency and governance. The regulation regarding the further development of the internal electricity market sets out improved principles and rules related to competitiveness, and cross-border trade, allowing consumers to be active market participants and following the commitments of the Paris Agreement. Concretely, energy suppliers will be free to determine the price at which they supply energy to consumers. Market-based price competition between energy suppliers and strict protection of vulnerable consumers will be ensured by the EU Member States [44].

2.2 Structure of the Dutch electricity market

As a result of the European energy directives, the Dutch electricity sector was subject to liberalisation, privatisation and unbundling. Throughout the 1980s and 2000, the energy sector in the Netherlands was significantly restructured. In response to the First European Electricity Directive, the Dutch government formulated the Elektriciteitswet which was implemented in 1998. The Elektriciteitswet was set out to facilitate the implementation of market principles in the Dutch electricity sector [30].

One of the core elements of the European directives for the liberalisation of the energy market was unbundling, in which the market functions that were traditionally divided within a single integrated company are provided by independent actors. In the Netherlands, the ownership unbundling approach was implemented. Through ownership unbundling, the commercial operations were split from the network operations in the vertically integrated energy companies. Consequently, the generation, trading and supply companies were subject to privatisation and the networks remained under public control. A level playing field was created in which there were no incentives for network access discrimination and cross-subsidies across the different activities within the electricity value chain. Furthermore, the regulatory body would be able to operate more efficiently and transparently, and transparency within the market would improve [112, 120].

The regulatory changes shaped the electricity sector into the modern electricity market in the Netherlands. In the following subsections, the processes that led to the development of the different market roles in the Dutch electricity sector will be further illustrated.

Energy producers

Before the reform of the Dutch electricity market, a total of four power-generating companies dominated the market: UNA, EPZ, EZH and EPON. The four companies formed the centralised market in the Netherlands and cooperated through an organisation named the 'Samenwerkende Elektriciteits-Productiebedrijven' or SEP [94]. The SEP owned and operated the high voltage (220 - 380 kV) transmission grid and had a monopoly position in energy imports until 1998. In October 1998, TenneT was established, after which the centralised market was no longer coordinated by SEP [56].

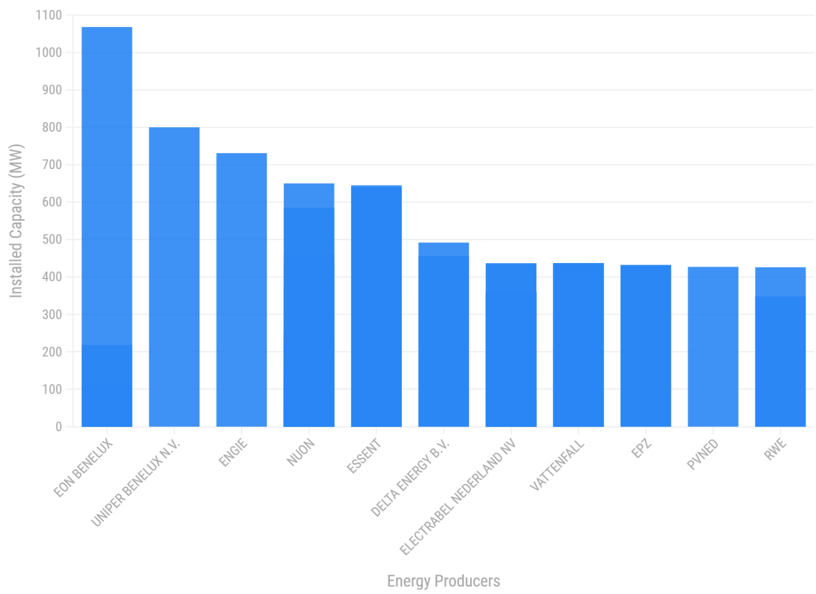

Figure 2.1: Total installed capacity (MW) of energy producers in the Netherlands, 2018 [38]

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As a result of the market reform, the shares of the four central producing power companies were partly acquired by foreign entities. In the year 2000, 21% of the shares of the main generators were owned by Essent/Delta (NL), 18 % by Electrabel (Belgium), 15% Reliant Energy (US), 11% E.On Benelux (Germany), 2% Nuon (NL) and lastly 33% by auto-generators or Combined-Heat-Power (CHP) plants [30]. Consequently, a large proportion of the centrally power-producing companies in the Netherlands were owned by foreign shareholders. To prevent the event of foreign ownership in distribution and transmission networks as well, the Dutch government adopted the Wet Onafhankelijk Netbeheer (WON) (Splitsingswet or separation act) on the 14th of November in 2006. Through the WON, the regional integrated energy companies should be separated into a commercial part that produces, trades and supplies energy and a network company. After the separation, the two entities are no longer allowed to have the same shareholders anymore. The owners (municipalities and provinces) of the vertically integrated energy companies had to sell the commercial component of the integrated company. In addition, the ownership of the 110 and 150 kV grids was transferred to the national transmission grid operator [30]. A total of eight energy companies were subject to the separation, being Nuon, Eneco, Essent, Delta Energies, NRE, Rendo, CONET and Westland in 2008 [66]. Currently, the electricity is still generated by the large-scale energy producers that were subject to separation: Essent, Vattenvall, ENGIE, Eneco, E.On, Electrabel and Delta [120]. In Figure 2.1, the installed capacity of the largest energy producers in the Netherlands can be observed for the year 2018 with a total installed capacity of 19.188 MW [38].

Transmission System Operator

In November 2001 TenneT was purchased by the Dutch State, along with the transmission system assets, such that the state-owned 100% of the shares of TenneT Holding B.V. Since 2008, TenneT has managed not only the national high-voltage grid but also the high-voltage grid from regional network operators [30]. TenneT is the Transmission System Operator (TSO) in the Netherlands and is responsible for the operation of the transmission system (electricity networks with a voltage level equal to or higher than 110kV) and interconnections with neighbouring countries (for example to Norway, Denmark and Germany). TenneT ensures the ability of the Dutch transmission system to meet long-term reasonable demands, through performing maintenance and further development of the electricity transmission system. Within the control area (in this case The Netherlands), TenneT is responsible for providing balancing services, contracting sufficient reserve capacity, black start capability (from a power outage) and ensuring power quality. In addition, the tariffs and conditions for the connection, transmission and system services are regulated by the ACM regulatory agency [69, 120].

Distribution System Operators

On the first of January 2011, the separation of the integrated energy companies had to be completed. In accordance with the Wet Onafhankelijk Netbeheer, the distribution networks should be operated by an independent network manager [120]. Nuon and Essent were separated into Vattenval and RWE for the commercial entity and the network operators into Liander N.V. (part of Alliander NV) and Enexis B.V. (part of Enexis Holding NV). The other 6 vertically integrated energy companies have appointed the following network companies: Stedin Netbeheer, Delta Netwerkbedrijf. (Enduris), Cogas Infra en Beheer, Westland Infra Netbeheer, Rendo Netbeheer and Endinet [120]. In 2022, there are six DSO's in the Netherlands: Delta Netwerkbedrijf (Enduris) was merged with Stedin Netbeheer (2022) and Endnet with Enexis B.V. in 2016 [92].

The six Distribution System Operators are responsible for the operation of the distribution networks (with a voltage level lower than 110 kV) within a given geographical area (as depicted in Figure 2.2), the connection of consumers to the grid and to resolve disturbances in the distribution grid. The tariffs and conditions for the connection and distribution services for small consumers are regulated by the ACM [120].

Energy suppliers

Besides the disintegration of the vertically integrated energy companies, the freedom of choice for energy suppliers was also facilitated as the result of the implementation of market principles in the energy market. From 1998, the market for large energy consumers (on-site demand > 2 MW, equal to 33% of electricity sales) was opened, in 2002 for medium-sized consumers (demand around 50 kW equal to 29%) was opened and in 2004 for small consumers (the remaining 38%) [94]. Consequently, the liberalisation of the Dutch electricity market was completed in 2004, which was earlier than was demanded in The Second European Electricity Directive. Energy suppliers

Figure 2.2: Geographical overview of the Distribution System Operators in the Netherlands in 2022 [92]

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are responsible for purchasing energy from energy producers on the wholesale market (as described in section 2.2) and engaging in transactions with small and large consumers (retail market). In the Netherlands, there are two types of energy suppliers: energy suppliers that solely supply energy to large consumers and energy suppliers that also have a license (on the basis of art. 95a Electricity Act) from the Autoriteit Consument & Markt (ACM) to supply small consumers (consumers that have a maximum grid connection of 3*80A). Licence holders are responsible for providing consumers with electricity in a reliable manner against 'reasonable' tariffs and conditions [16].

After the completion of the liberalisation in 2004, a large number of new entrants entered the retail market as an energy supplier. In 2021, a total of 61 energy suppliers held a permit under which they were allowed to supply energy to small consumers (in 2004, 9 energy suppliers were active in this market). Furthermore, between 2019 and 2021, more than 53% of small consumers switched from the energy supplier [3]. The largest energy suppliers in the Netherlands are, however, still Vattenval, Essent and Eneco and Delta[16, 120].

Balance Responsible Parties

After the liberalisation of the electricity market, the market became responsible for maintaining the balance between the supply and demand of electricity. The supply of electricity should be controlled such that it matches the demand very closely as a result of the fact that electricity cannot be stored. As described in section 2.2, the TSO is responsible for maintaining the balance between supply and demand and uses production and demand forecasts submitted by market players to anticipate potential imbalances in the grid [69]. Energy suppliers automatically choose a Balance Responsible Party for smaller connections, including households and small to medium enterprises (SMEs). Through being balance responsible, an entity is (financially) responsible for its imbalance in the electricity market. Therefore, the entity should be in balance (the total sum of energy exchanged should be equal to zero) on a 15-minute basis in reference to other entities that are balancing-responsible. The market parties that are responsible for balancing are Balancing Responsible Parties (BRPs) [16]. Consequently, all network connections have a corresponding BRP and all BRP's represent all connections within a specific area [71].

Balancing Responsible Parties are legally obliged to submit energy-program's (E-program) to TenneT. In an E-program, a BRP indicates the expected production, consumption and external trade in a portfolio in a granularity of 15 minutes [71]. The E-program should be submitted a day before the program is schedules, after which TenneT can approve the program. The transactions in the E-programs of different BRP's should be in accordance, thereby the balance of supply and demand of electricity is ensured. The BRP's are expected to act in accordance with the E-programs [16]. If the E-program is not in line with the realised generation or consumption and an imbalance occurs, the BRP will be held financially responsible. Consequently, the BRP will have to settle the difference through the imbalance price through which TenneT had to compensate the imbalance [71]. Only a small number of the entities that are balancing responsible have the full responsibility to be BRP's that submit E-programs to TenneT. All BRP's are included in the BRP-register from TenneT, in which in 2022 around 50 market parties are listed [16].

Metering companies

The metering company is responsible for placing, maintaining and reading out the electricity meters installed at consumers and the sub-sequential transmission of the data towards the DSO. An energy supplier can appoint a metering company (on the basis of art. 95a,b Electricity Act) or, alternatively, a DSO can appoint the metering company (which can be part of the DSO). Metering companies should be certified by TenneT, and a total of 10 metering companies are active in the Netherlands. Typically, small consumers had an analogue traditional meter installed in their homes. In contrast, smart meters, are able to communicate the measurement data on a 15-minute basis to the DSO. Small consumers can opt for 'smart-meter-allocation', which them to be able to pay the spot-market price for electricity on an hourly basis (on the basis of a dynamic pricing contract) [16].

Consumers

In the liberalised electricity market, two types of consumers can be distinguished: large consumers (a larger connection than 3x80A) and small consumers (3x80A). In the liberalised Dutch electricity sector, the protection of small consumers is considered essential: consumers are protected against unreasonable conditions and rates and are largely unburdened. The protection of consumers in the energy sector thereby goes further than the regular consumer protection law in the Netherlands. As the result of protection through unburdening, small consumers are not balance responsible as energy companies bare the responsibility of BRP for small consumers, thereby, small consumers can be characterised as 'passive' consumers [16]. Small consumers with a connection smaller than 100 kW are therefore represented by 'standard profiles' in which their typical consumption is depicted. The energy supplier uses the profiles to determine the E-program for the small consumers.

Large consumers, which can be characterised as 'active' consumers, are balance responsible. They can either take on this responsibility themselves or delegate it to another BRP. Additionally, large consumers have the freedom to choose a different Balance Responsible Party (BRP) and energy supplier. The consumer purchases energy from an energy supplier of their choice in the retail market, however, they are not free to choose their metering company or network operator. The costs of the caused unbalances are socialised when a discrepancy occurs [16].

Prosumers

Renewable energy sources (RES) such as residential PV allow for the active participation of consumers in the energy transition. Prosumers can be defined as actors that actively participate in the energy system, for example by producing and consuming RES, offering flexibility or storage services or participation in an energy community. Different types of entities can be prosumers, such as citizens, companies and public institutions, as long as energy production is not their core commercial activity. Different types of prosumers can be identified: individual households, collective prosumers in one building, Small-to-medium enterprises (SMEs) and public institutions, energy communities and cooperatives [37].

Regulatory Agency

In the Netherlands, the Ministry of Economic Affairs is responsible for the energy policy with the core responsibility of ensuring an affordable, reliable and clean supply of energy. The enforcement of the 1998 Elektriciteitswet was the responsibility of the Office for Energy Regulation (DTe), which is part of the Netherlands Competition Authority (NMa) [94]. Until the first of April 2013, the NMa was responsible for the enforcement of competition law in the Netherlands. When NMa, Consumer Authority and Independent Post and Telecommunications Authority merged in 2013, the Authoriteit Consument & Markt was established. The Energy Department within ACM is responsible for the following tasks [120]:

- Setting conditions and tariff structures for both the transmission and distribution networks;
- Granting licences to energy suppliers for supplying energy to small consumers. The ACM will check upon the reliability and conditions of the supplied energy, if the supplier does not supply energy in accordance with the requirements of the ACM, the license can be withdrawn;
- Monitoring misconduct from actors in dominant positions in the energy sector and imposing sanctions if necessary and supervising compliance with the Elektriciteitswet and European regulations.

The Competition Department within the ACM is responsible for both the regulation and enforcement of competition law. The small consumer market is regulated by the Consumer Department within the ACM, and the different consumer protection laws must be in accordance with the Dutch Competition Act.

In Figure 2.3, a schematic overview of the structure of the activities and actors in the energy sector in the Netherlands is depicted. On the left side, the electricity value chain is visualised, which consists of the following activities: generation, transmission, distribution, metering and supply towards the end-consumer. On the right side, the actors involved in the activities are noted: the energy producers, TSO's, DSO's, energy suppliers, and end-consumer. The light blue colour indicates the activities and actors that can operate in a liberalised market. The dark blue shaded elements indicate the activities and actors that operate in a regulated market with characteristics of a natural monopoly [93].

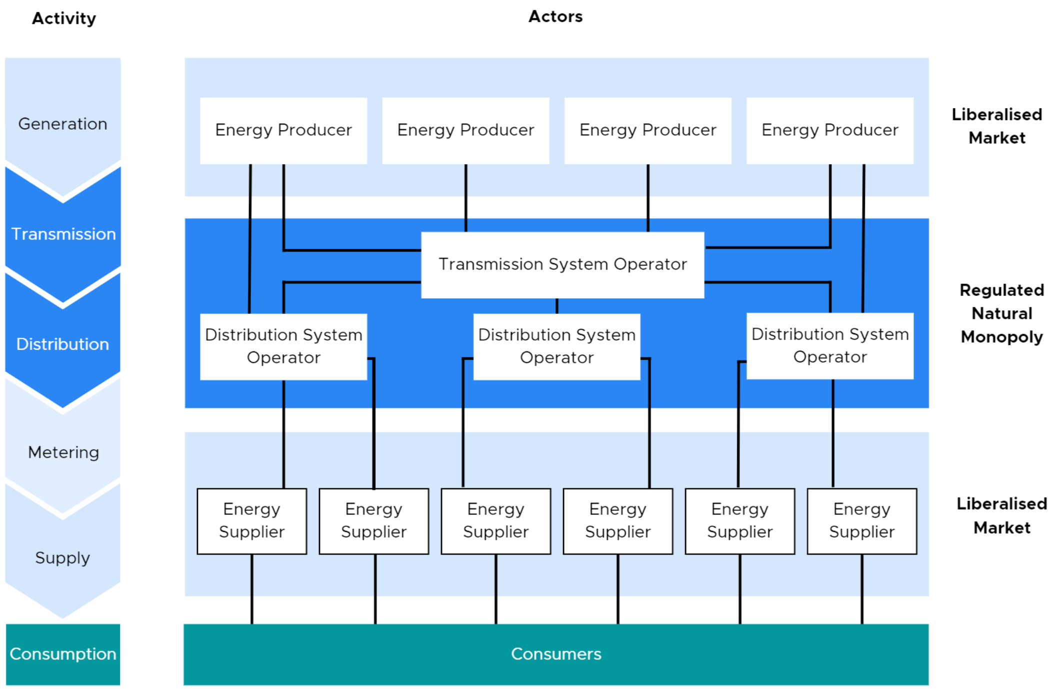

Figure 2.3: Structure of the energy sector in the Netherlands after completion of the liberalisation. Based on [93]

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2.3 Financial organisation of the electricity market

The electricity market is a mechanism through which electricity producers and consumers interact in order to trade electricity at a specific volume and price. As described in chapter 2, the electricity value chain consists of the four subsequent elements: generation, transmission, distribution and consumption. Through the electricity market, electricity is sold to consumers, either through the wholesale market or retail market. The trading of electricity differs from other goods which is the result of its unique characteristics. An important difference is that electricity cannot be stored (over long periods of time); therefore, supply and demand must be in constant balance [67].

2.3.1 Internal European Energy Market

The European legislative packages described in section 2.1 shaped the integration of the European electricity markets. On the first of January 1993, the 12 Member States established the internal energy market. The first step was set towards a European single market for electricity; however, the process in the following years turned out to be problematic and complex (for example, due to the absence of national markets). The national markets within the Member States were slowly opened up as the result of the Second, Third and Fourth (Clean Energy for All) electricity directives and packages. The packages concerned creating the necessary institutions (ACER and ENTSO-E) and conditions that ensured the functioning of electricity markets. The detailed rules for the internal European energy market have been established as the result of cooperation between ACER, ENTSO-E and other relevant actors in the sector and led to the creation of EU network codes and guidelines. The rules ultimately impact the level of freedom that Member States have in designing their national electricity markets, however, no specific rules for the market design are set. Consequently, the market design within the Member States is implicit [80].

In the Second Energy Package, a regulation was introduced that demanded a market-based allocation for cross-border transmission rights in Europe. The first form of market-based allocation were explicit auctions, in which TSOs auction the cross-border transmission rights to the highest bidders. Explicit auctions ultimately became the dominant model for trading cross-border transmission rights in Europe, which varied from a day-ahead basis to a year-ahead basis and did not require significant changes to national electricity markets. However, explicit auctions resulted in coordination issues for traders, as they had difficulties with reference to the prediction of hourly prices which resulted in inefficiencies. After the dominance of explicit auctions, market coupling (or implicit auctions) emerged as the preferred allocation method for cross-border transmission rights. The trading of cross-border transmission rights through implicit auctions was organised by power exchanges. The power exchanges integrated clearing of the day-ahead auctions of the cross-border transmission rights [80].

2.3.2 Wholesale market

In the wholesale electricity markets, the trading of electricity can be characterised on the basis of the different time scales and platforms on which power is traded and delivered. Electricity is either traded on power exchanges or on over-the-counter (OTC) markets, as can be observed in Figure 2.4. On power exchanges, trades on the timescale of days to years for the delivery of electricity are conducted through futures and generally have contract durations between one day and a year [53]. The majority of power trades are conducted on the OTC financial markets (forwards) in which the trades are non-standardised, bilateral, and non-anonymous [86]. The spot market can be further subdivided into the day-ahead market for trading electricity the next day and the intraday market in which trades for the next hour can be conducted. Therefore, short-term events in the electricity market can be addressed in the intraday market which operates on the basis of sub-hourly intervals [67].

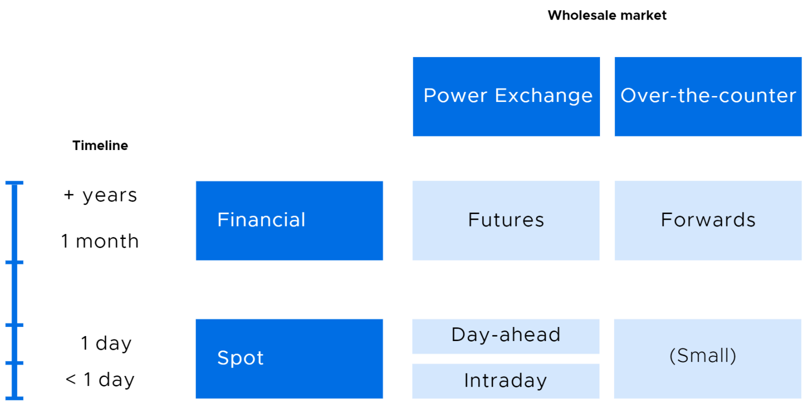

Figure 2.4: The different types of market platforms and categories in wholesale electricity markets [54]

On the spot market, the fundamentals of the electricity market are well reflected, since the clearing prices reflect the marginal operating costs of the power plants and the marginal price consumers are willing to pay for electricity [53]. The important decisions for power plant operation are therefore derived from the day-ahead market [67]. In addition, the price of electricity on the exchange markets is often used as a reference price for the OTC market, thereby resulting in a similar electricity price in the different types of wholesale markets [86]. However, due to the demand for tailor-made contracts and products by market participants, OTC markets will continue to be larger in size as compared to day-ahead and intraday markets [42].

Table 2.1: The historical trading volumes on European Electricity Exchanges EEX & EPEX in TWh [68].

Year	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**
Futures	1.570	2.537	3.920	2.822	3.347	3.973	4.736
Day-ahead	427	507	468	464	485	502	504
Intraday	47	59	62	71	82	92	111

In Table 2.1, the historical trading volumes on European Electricity Exchanges EEX & EPEX in TWh are depicted. It can be observed that in the futures market, more volume is traded as compared to the physical markets. This can be explained by the fact that the futures contracts serve mainly as hedging products and are executed several years into the future [68] as will be elaborated on in section 2.3.4.

2.3.3 Spot market

Day ahead

The day ahead market is a component of the spot market, in which market participants can buy or sell electricity before the physical delivery of electricity on the next day. In Europe, the day-ahead markets are set up as centralised double-sided auctions on power exchanges in which the supply and demand of electricity are matched with reference to the submitted bids [112]. Market participants have until 12:00 on the day before delivery to submit their bids to the exchange (such as EPEX spot) for each of the 24 hours. The bids can range from a -500 to 3000 €/MWh with a traded volume from 0.10 MWh [15]. In the market clearing process, the constraints for the physical transmission and dispatch of electricity are respected. The different wholesale markets in Europe are interconnected through Single Day Ahead Coupling (SDAC) [4]. In SDAC, the cross-border capacity is allocated such that social welfare is maximised, which is achieved through optimising the value to consumers, suppliers, and any fees for using interconnectors. The final value is calculated by adding all these components together. Technically, the bids of the market actors in combination with the constraints of the transmission network, serve as input for the algorithm that solves the market coupling problem. The algorithm is named EUPHEMIA (EU + Pan-European Hybrid Electricity Market Integration Algorithm), and it quickly finds a good initial solution for the market coupling and then tries to improve and increase overall welfare. It can be used in any type of market and can handle any number of orders or network constraints [91]. The output of the algorithm are the market clearing price and flows per interconnection, within a maximum of 17 minutes (on average 3.2 minutes). EUPHEMIA is responsible for the SDAC of a large proportion of the EU, with a total trading volume of 1.530 TWh in which 8.9B Euros of financial profit was booked in 2020 [4].

Intraday

After the day ahead market is cleared, the market participants can adjust their consumption and production schedules close to real-time on the intraday market. The participants are able to adjust their spot positions until 5 minutes before the physical completion of the trade, however, adjusting positions is in general more expensive as compared to the day ahead market [112]. The uncertainties related to renewable energy production (as renewable energy sources are typically more weather dependent), power plant failures or adjusted consumption profiles can thereby, for example, be covered in the intraday market. Through Single Intraday Coupling (SIDC) the European intraday markets are coupled, in which a continuous trading (pay-as-bid) mechanism is employed. Through this mechanism, market participants can enter offers and bids into the order book at any time, and a transaction will be performed when the sell order is lower than the buy order. Consequently, only the two bilateral parties involved are affected by the trade. Cross-border trades can be matched when the necessary transmission capacity is available, all on a 15/30/60 minute basis [4].

2.3.4 Financial market

Forwards and futures

As described in subsection 2.3.1, before the liberalisation of the electricity market, long-term contracts were in place between generators and consumers in order to allocate transmission rights and trade electricity. As a result of the implementation of power exchanges in Europe, electricity trading became more transparent and more actors were able to participate in wholesale markets [80]. Generally, in electricity markets, consumers seek to reduce the risk of being exposed to volatile electricity prices and producers are interested in achieving a stable return on investment on the power generators and covering the marginal costs of production. The opposite risk profile of the two parties is applied in the financial market, in which futures (on a power exchange), forwards and Contracts for Differences (CfDs) can be traded (see Figure 2.4). The parties 'hedge' their risk by engaging in the practice of buying electricity at various intervals of time in order to even out the possibility of price fluctuations. Through hedging, revenue streams for generators can be ensured and the impact of extreme price movements can be limited. Consequently, power exchanges and OTC markets co-exist, with varying traded volumes over Europe. Hedging the risks of trading electricity can be achieved through the financial markets, in which no physical product is traded, or bilateral contracts (OTC). In the OTC market, parties are able to negotiate contracts (electricity forwards) in accordance with their specific demands, such as contract duration and price aspects. Standardised contracts can be traded on exchanges (futures), which is a legally binding contract for the supply of electricity at an agreed-upon price. The futures contracts are traded on a transparent and anonymous basis and typically have low commission charges. Other hedging products are Electricity Swaps, CfDs, Electricity Price Area Differentials (EPADs), options and spreads. In Europe, electricity futures can be traded on the European Energy Exchange (EEX). Forwards markets allow for 'price discovery', in which they are able to provide an indication of where the future prices for electricity may move to, which helps with forecasting future electricity prices. In addition, reliable forward prices allow for investment in generation and transmission technologies when high-volume trades in the future will be conducted in the futures market. However, the forward market is based on the real-time (spot) wholesale market, which leads to the value of electricity being derived by the assets in the physical market, making the forwards market a 'derivatives market' [34].

2.3.5 Power Exchanges

There was a gradual implementation of power exchanges in Europe, starting with the Statnett-Marked AS in Norway in 1993. In 1996, Sweden joined the first power exchange and Nord Pool ASA was established; later, Finland and Denmark also joined Nordpool. In the Netherlands, the Amsterdam Power Exchange (APX) was established in 1999 and in 2002 the European Power Exchange (EEX) was established in Germany. Different member states followed the trend and established power exchanges. In 2010, the Belgian power exchange Belpex joined the APX after which the APX was integrated into the EPEX SPOT (which was formed as the result of the merger of the German and French power exchanges) in 2015 [80].

Power exchanges are market infrastructures that could be set up by system operators, financial market institutions, market parties, or other private actors. Through trading platforms, anonymous trades can be facilitated between market parties. As the prices and volumes of the transactions are published on the power exchanges, the transparency of the trades are enhanced [80]. Consequently, on an exchange, buyers and sellers can find each other for the transaction of services or products, in which fair and transparent transactions are ensured. A power exchange thereby is a digital platform where market parties can submit bids and offers to sell or buy energy products or services. The power exchange provides a reliable, robust, and transparent mechanism for the formation of prices. The power exchanges thereby provide a competitive spot market for trading on an intraday or day-ahead basis. A power exchange can provide the following services to the participants of the platform [108, 42]:

- An online platform for electricity trading, where buyers and sellers can submit bids and offers for energy products or services;
- It facilitates the process of market clearing and trade settlement;
- It provides financial services such as billing and accounting, helping market participants manage their financial transactions;
- Providing necessary information to buyers and sellers, helping them make informed decisions about their trades;
- It helps manage financial risk, protecting market participants against unexpected losses;
- It maintains a reliable electricity price index, providing a benchmark for prices in the market;
- It increases transparency, which offers more possibilities and higher security for investors;
- It facilitates more efficient trading activities due to the reduced work involved in closing deals over the trading platform compared to bilateral trading.

The working principle of a power exchange can be described as follows. The power sellers submit their sell offers to the power exchange within pre-defined time intervals. Similarly, power buyers submit their buying offers (bids) to the power exchange within the same intervals. Specifically, the engaged parties submit hourly or half-hourly volume-price offers and bids. Next, the power exchange processes all the submitted sell and buy offers after which the market is cleared: a supply-demand equilibrium is found at a certain price (MCP). The volume of the traded power at the equilibrium point is termed the market clearing volume (MCV). After finding the equilibrium point, a power flow algorithm is run to identify potential congestion or other issues related to the power flow. The power exchange facilitates the financial settlement of the trades which are proportional to the traded volumes after which information of the trades is communicated to the trading parties. This information is related to the (un)cleared volume, MCP, congestion status, and dispatch schedules. For network operators, the power exchange shares information related to dispatch schedules, transmission losses, and cleared power demand. In Figure 2.5, the steps involved in clearing the market in a power exchange can be observed [108].

A number of benefits of trading power through a power exchange can be identified. A fair and transparent Market Clearing Price (MCP) for the engaged market parties can be ensured, the optimal buying and selling parties can be found on the platform, the power exchange acts as a facilitator of the trade, helping to ensure that the trade is completed smoothly and efficiently, the power exchange takes steps to ensure that the loss of energy during transmission is minimised and that it is distributed fairly among all market participants, and it provides price signals to enhance competition on the power exchange. The performance of a power exchange can be evaluated using several criteria, such as the total number of participants' liquidity in the market, Equal treatment for all market participants and anonymity for all trades and the amount of traded volume [108].

Consequently, a large number of participants in a power exchange indicates a stronger market whilst an exchange with a smaller number of participants may resemble a less strong market with little competition [108]. An open and liberalised electricity market is important for the establishment of a reliable electricity price index in the bidding zone. The liquidity of the market is also a measure of the performance of the power exchange, as it reflects the resilience of the market to price fluctuations which can be the result of an increase in the volume of offers and bids. Liquidity of the market is thereby a measure of the bids and offers distribution. In a market

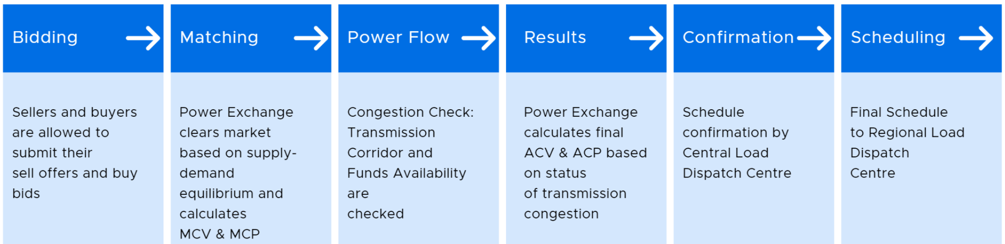

Figure 2.5: The steps involved in clearing the market in a power exchange [108][p.4].

with low liquidity (for example with only one electricity supplier), the price may be subject to overbidding and manipulation. A power exchange can enhance liquidity through market coupling with neighbouring countries and increasing the number of active players on the market. In OTC trades, the parties trade electricity directly whilst on a power exchange the trading parties are matched in an anonymous and nondiscriminatory manner. Consequently, all trades should be executed through transparent and unbiased trading with a transparent price formation process, which creates a secure business environment for all stakeholders. The power exchange acts as a middle entity between the trading parties and thereby should facilitate robust clearing and settlement of the trades in order to reduce the risk of insolvency or delayed payment [108, 42].

In Figure 2.6, the clearing of the market in a power exchange is schematically visualised. It can be observed that producers and consumers submit bids to the market which are collected in the order book. The input for the market clearing algorithm is the order book and the cross-zonal capacities after which the market can be cleared, resulting in the market clearing price and volume.

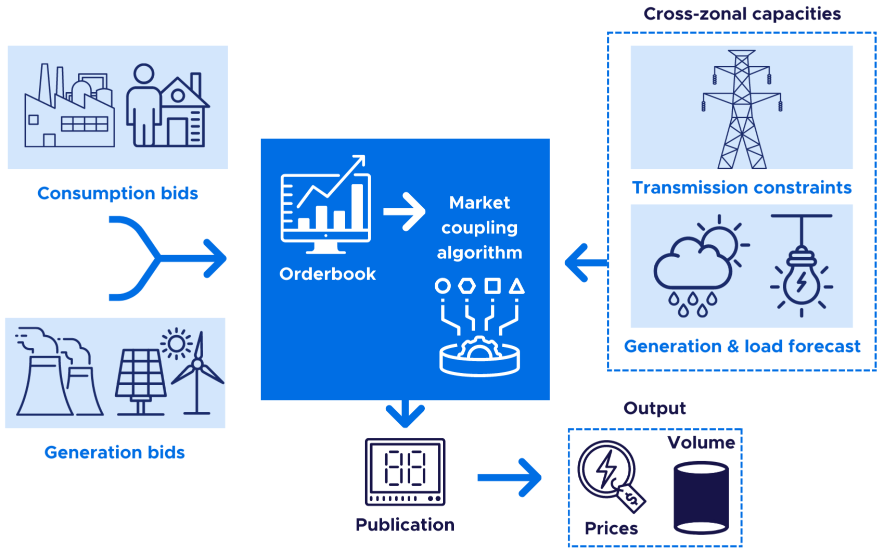

Figure 2.6: The working principles of market clearing. Bids are collected into the order book, after which the transmission constraints are Incorporated and the market is cleared. The output is the MCP and MCV.

2.4 Marginal Pricing and the Merit Order

2.4.1 Marginal Pricing

As described in subsection 2.3.5, suppliers and buyers submit bids to the power exchange in which they express their willingness to pay and their 'willingness to sell electricity.' Most power exchanges accept 'simple bids', in which the market participants submit hourly or sub-hourly offers and bids (sell or buy) to the power exchange. The bids contain information concerning the execution time, volume specification and price per MWh (limit price). The European power exchanges operate using the 'pay-as-clear' principle, in which suppliers receive the same MCP for the produced electricity also if their submitted bids were lower than the MCP (producer surplus). The buying parties also pay the MCP, although their bids may have been higher than the MCP (the orders are 'in-the-money', resulting in consumer surplus). Alternatively, when buyers submit a bid lower than the MCP or sellers a bid higher than the MCP, the bids are rejected (orders are out-of-the-money) [108].

Electricity producers submit bids at their marginal cost (MC) of operation. The marginal cost can be defined as [13, p.211]: 'the cost of producing one additional unit of electricity (MWh)', thereby consisting largely of fuel and CO2-costs [21]. The electricity producers have invested capital expenditure into their generators and are therefore willing to sell their electricity on the wholesale market in order to recover the sunk costs. Producers will bid in the wholesale markets with the amount of electricity they are willing to supply at a certain marginal cost, after which the power exchange constructs a bid ladder. In the bid ladder, the lowest bid (the lowest MC) is listed first with the amount of electricity that they are willing to supply. Next, the second bid is then added to the bid ladder with the second-lowest MC, thereby lining up the merit order [21]. After the merit order has been constructed for a market, the demand can be determined through which the clearing volume can be set: the demand volume that should be accommodated by the producers. The last price of the marginal electricity producer that can meet demand (the marginal plant) sets the MCP, which will be uniformly paid to all selling parties active on the market [13]. In Figure 2.7, the merit order is visualised in which the electricity producers submit bids to produce at their marginal costs of operation, after which an equilibrium point is found in which supply meets demand. The area between the MCP and marginal costs of operation are the profits for the producing power plants.

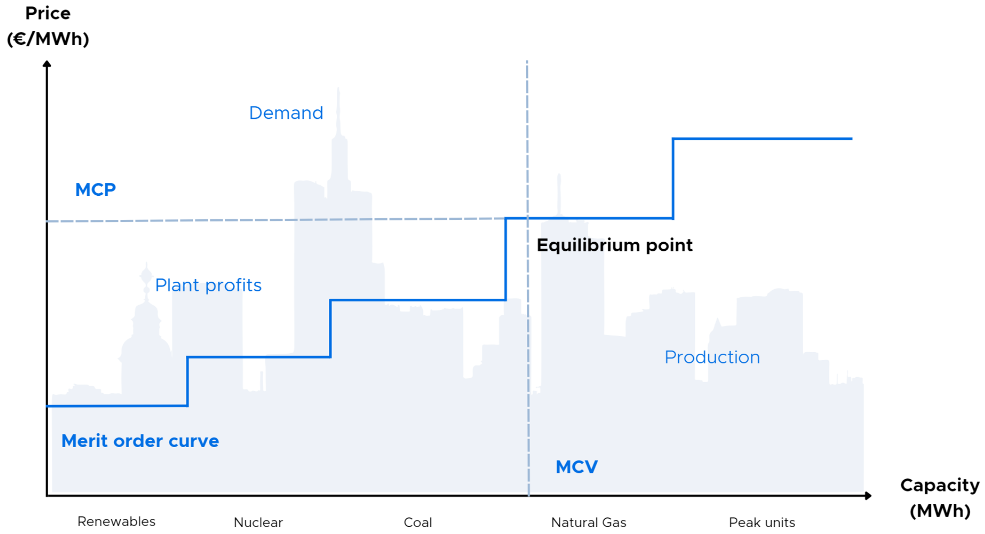

Figure 2.7: Marginal pricing in the wholesale electricity market. Demand meets supply at the equilibrium point after which the MCP and MCP are determined. The area under the MCP and the marginal cost of operation are the profits for the power plant (own illustration).

2.4.2 The Merit Order Effect

As a result of the principle of marginal pricing, all producers that submit bids to the power exchange are ranked in ascending order on the basis of their marginal costs of producing electricity. Energy sources with a low production cost, will therefore first be listed in the merit order. Renewable energy resources such as wind and solar typically have low (or close to zero) marginal costs because they do not need to pay for fuel in order to operate. After renewables, nuclear energy, lignite, hard coal, gas and fuel oil electricity producers are lined up in the merit order [21]. Fossil fuel generators (based on coal or gas) alternatively have higher operational expenditures due to their fuel resources which need to be accounted for, thereby placing them later in the merit order. When an increasing amount of low marginal cost, renewable energy resources bid into the market, the equilibrium point (where demand meets supply) will shift towards the left in the merit order resulting in a lower wholesale market price. This phenomenon is referred to as the Merit Order Effect, in which the MCP is suppressed by the introduction of renewable energy into the electrical system [67]. In Figure 2.8, the merit order effect can be observed; when more energy sources are introduced in the merit order with a low marginal cost, the MCP will be driven down. It is however possible that, due to high CO2 costs, gas will be cheaper then coal-based generators.

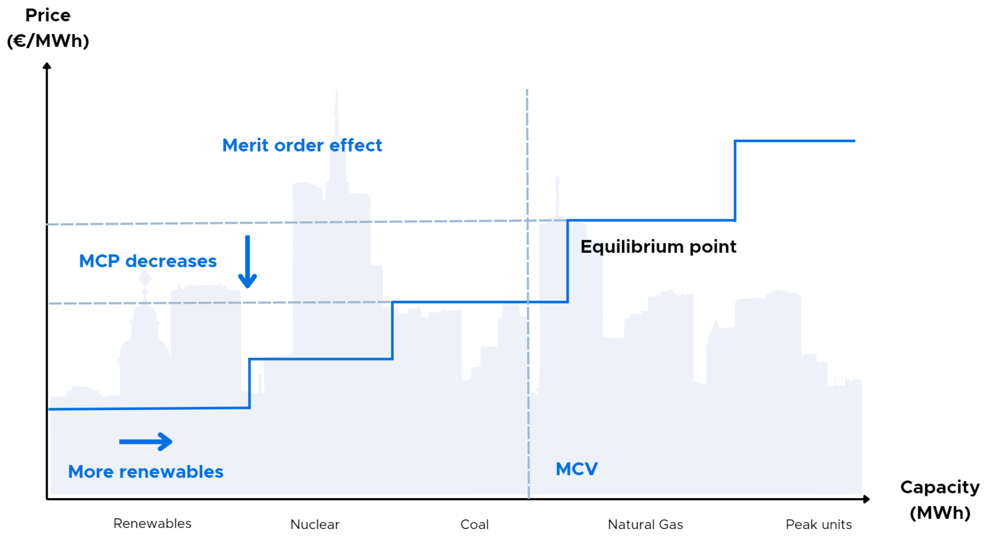

Figure 2.8: The marginal clearing price in the merit order, with the merit order effect depicted when renewables are introduced into the market (own illustration).

2.5 Conclusion: Electricity Market Reform

Traditionally, wholesale electricity markets were designed in a vertically integrated manner, in which a single firm was responsible for the generation, transmission and supply processes without competition until the late 1990's [86]. However, as a result of political and ideological dissatisfaction with the centralised structure, a number of liberalisation initiatives were introduced by the European Union with the objective to increase competitiveness in the market, higher economic efficiency, reducing prices, lower entry barriers in supply chains and unbundling of vertically integrated companies [81]. Four legislative packages were introduced in 1996, 2003, 2009 and 2019 which constructed the internal European energy market which evolved to be more consumer-centered, competitive and non-discriminatory [86, 45]. The First Electricity Directive was introduced in 1996 and initiated the unbundling and liberalisation of the European electricity sector, and introduced TSO and DSO unbundling and regulatory authority for electricity markets, among others [24]. The Second Electricity Act was introduced in 2003 and introduced new aspects in the electricity market, such as freedom of choice for energy suppliers, further unbundling for TSO's and DSO's from a management and legal perspective and additional tasks for regulatory authorities [24]. There were still shortcomings in the electricity market after the introduction of the Second Electricity Act, related to transparency, market integration and insufficient unbundling. To address the shortcomings, the Third Energy Package was introduced in 2009. The Third package was concerned with further unbundling of the supply and generation chains, more transparency in the retail market and enhanced independence and strength for regulators. In addition, a new entity was introduced: ACER, which is responsible for the cooperation between regulatory agencies between the EU member states [31].

The Fourth Energy Package was introduced in 2019 and is also referred to as the Clean Energy For All Europeans package. Consumer empowerment is a key aspect of the package, as the package underlines that consumers need to be at the centre of a renewed European energy system, in which they can make their own decisions on how to produce, share and trade their own energy. In the Clean Energy for All package, consumers are envisioned to actively participate in the energy transition, through for example joining energy communities [44]. Active consumers, also referred to as prosumers, will be able to sell their self-generated renewable energy to other participants in the market. Next to that, the package introduced new rules into the market for increased implementation of renewable energy, strengthening the security of supply and improved governance and efficiency [45].

The legislative packages introduced by the European Union also impacted the organisation of the electricity market in the Netherlands, which was significantly changed from the 1980s on-wards. Before the reform of the electricity market in the Netherlands, a total of four power-generating companies dominated the market (SEP). Until 1998, when the Elektriciteitswet was introduced, the SEP was subject to different monopolistic privileges such as the rights to energy imports [94]. After the reform, the shares of the four central power-generating companies were acquired by foreign entities with the result that a large proportion of the energy producers in the Netherlands were subject to foreign ownership. To prevent the foreign ownership of the distribution networks in the Netherlands as well, the Wet Onafhankelijk Netbeheer was introduced in 2006 which required the separation of the integrated energy companies into a commercial part that produces, trades and supplies energy and a network company [30]. Currently, the large commercial energy producers in the Netherlands are Essent, vattenvall, Eneco, E.On, Electrabel and Delta [120] and the six Distribution System Operators are Liander, Enexis, Stedin, Coteq, Rendo and Westland Infra [92].

In 1998, the ownership responsibility of the national high voltage transmission grid was transferred to TenneT from SEP and in 2001 TenneT was purchased by the Dutch State [56, 30]. TenneT is the Transmission System Operator (TSO) in the Netherlands and is responsible for the operation of the transmission system and interconnections with other countries in combination with providing balancing services, reserve capacity, black start capability (from a power outage) and ensuring power quality among other responsibilities [69, 120]. A core responsibility of TenneT is maintaining the balance between supply and demand, and by using E-programs, TenneT is able to anticipate potential imbalances in the grid. Market parties that are responsible for submitting E-programs to TenneT are Balance Responsible Parties (BRPs), and all network connections have a corresponding BRP such that all BRP's represent all connections within a grid area. When an imbalance occurs with reference to the submitted E-program, the BRP will be held financially accountable and the imbalance will be settled in accordance with the imbalance price. In 2022, a total of 50 market parties are listed in the BRP-register from TenneT [71, 16].

The Authoriteit Consument & Markt is responsible for the regulatory activities and enforcement of competition in the Dutch electricity sector, which include setting conditions and tariff structures for both the transmission and distribution networks and granting licences to energy suppliers for supplying energy to small consumers [120]. The energy suppliers purchase energy from energy producers, engage in transactions with small or large consumers, and licensed energy suppliers are responsible for providing consumers with electricity in a reliable manner against 'reasonable' tariffs and conditions [16]. The largest energy suppliers in the Netherlands are Vattenval, Essent and Eneco and Delta and a total of 61 suppliers held a license to supply small consumers in 2021 [16, 120]. There are both small (up to a 3x80A connection) and large consumers, and small consumers are not balance responsible as energy companies bare the responsibility of BRP for small consumers, however, large consumers are balance responsible [16]. Distributed energy resources (DERs) such as household solar PV allow for the active participation of consumers in the energy system, and thereby consumers could become a prosumer. Different types of entities can be prosumers, such as citizens, companies and public institutions, as long as energy production is not their core commercial activity [37].

The electricity market is a mechanism through which energy producers and consumers interact in order to trade electricity at a specific volume and price and is shaped by the European legislative packages to ultimately construct the Internal European Energy Market [67]. The different electricity markets in the European member states were opened up and different institutions were established, such as ACER and ENTSO-E to coordinate the European electricity markets. In the wholesale electricity market, electricity can be traded on different timescales and platforms

[80]. Electricity can be either traded over-the-counter (OTC) or through power exchanges with centralised clearing. The majority of electricity is traded OTC, typically for timescales into the future. On the spot market, electricity can be traded for the next day (day-ahead) or on the intraday market in which it trades for the next hour can be facilitated [67]. In general, the fundamentals of the electricity market are well-reflected on the spot market as the clearing price reflects the willingness to pay for consumers and marginal operation cost for producers, and OTC markets typically follow the spot price as reference [53, 86]. The day-ahead market is set up as a centralised double-sided auction, in which both consumers and producers submit bids and offers after which the market is cleared and suppliers and buyers pay and receive the same clearing price (pay-as-clear). On the intraday market, the market participants can adjust their consumption and production schedules close to real-time, however, this is typically more expensive as compared to the day-ahead market. The bids and offers are continuously matched on a pay-as-bid basis, which facilitates continuous trading [112].

2.6 Towards a distributed electricity market

As described by the International Energy Agency (IEA), the introduction of Distributed Energy Resources (DER) creates new opportunities and challenges for the power system [57]. DERs refer to power generation technologies connected to medium voltage (MV) or low voltage (LV) distribution systems, as compared to the more traditional configuration in which power sources are connected to the high voltage (HV) transmission system. Thereby, DERs can include generation technologies such as solar PV, wind turbines, Combined Heat and Power (CHP) units and fuel cells next to storage technologies such as flywheels and batteries [5]. Between 2019 and 2021, a total of 167 GW of distributed solar PV was installed globally, which is a larger installed peak power output than the combined peak consumption of both Britain and France [57]. In the Netherlands, the installed capacity of solar PV was equal to 14.4 GW at the end of 2021, of which 8.6 GW large-scale PV (installations with a larger power output than 15 kWp) and 5.8 GW small-scale PV (installations with a smaller power output than 15 kWp). In 2021, a total of 9.3% was generated using solar PV, which is equal to an annual generation of 11.3 TWh [105]. As described in the section 1.1, in 2030, a total of 35 TWh of renewable energy production on land should be achieved through both solar PV (large scale) and wind. It is expected that in 2023 already, 29.1 TWh of renewable energy production on land will be realised through both solar PV and wind [105]. As for wind on land, in 2023, an annual production of 18.5 TWh is expected to be realised [104]. As can be observed in Figure 2.9, through the realised production of wind and solar on land as expected in 2023, the target from the Klimaatakkoord of production of 35TWh will already readily be achieved [105].

Distributed solar PV allows for the supply of affordable electricity for the consumers that own the installations [57]. As set in the Dutch Klimaatakkoord, in 2030 50% of the land-based renewable energy production assets should be in the ownership of the local region. As a result, citizens must be able to directly benefit from 50% of the solar PV and wind projects on land, for example, through partial ownership of a renewable energy project of land or local reinvestment of the projects in neighbourhood initiatives. In 2021, a total of 1.5% of the installed solar PV capacity was owned by local cooperatives. Next to that, a total of 96% of the installed capacity of small-scale solar PV is installed on the roofs of residential households as 20% of the households in the Netherlands own small-scale solar PV [105]. In 2020, a total of 6% of the wind on land installed capacity was in the ownership of public cooperatives and 11% in shared ownership between public and commercial entities. Public ownership can, for example, be facilitated through energy cooperatives, in which residents and local companies cooperate on the local energy transition. In 2019, there were a total of 582 energy cooperatives in the Netherlands, of which around 80% are focused on solar PV projects and 24% on wind projects [52]. Concluding, the growing amount of DER in the Netherlands and the policy goal of local ownership are both forces that drive the energy transition at the local level in the Dutch context. The energy cooperatives are active in 80% of

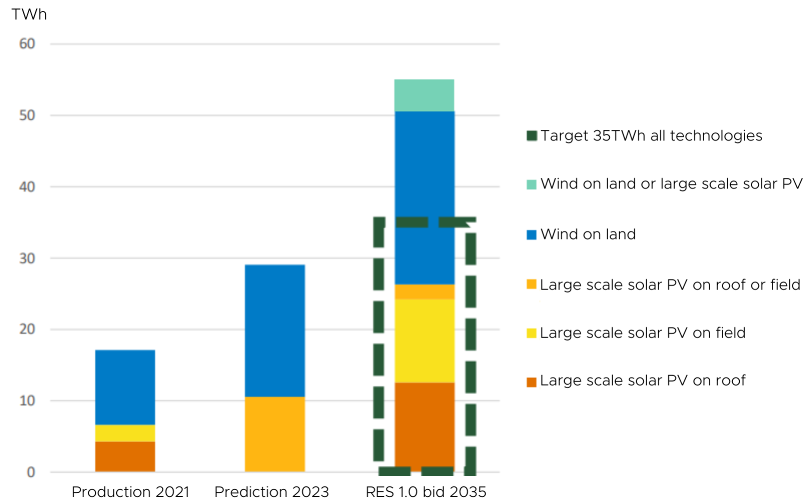

Figure 2.9: Expected realisation renewable on land and target 2030 (TWh) [105].

the municipalities in the Netherlands, which are typically connected to the social environment as local residents are active in their own living environment [52].

In subsection 2.1.4, the Clean Energy Package was described in which consumer empowerment was a core subject. Consumers can become active participants in the energy transition, for example, through joining community energy initiatives [44]. However, to ensure that the community initiative plays a sustainable role in the energy system of the future, additional value should be created for the participants in the energy community. Value creation can, for example, be realised through trading locally generated energy. Through local trading, prosumers can actively participate in the transition towards renewables and will have the means to optimise self-consumption in the community. Local energy trading can be facilitated in a Local Electricity Market (LEM), which is a platform that allows for the trading of locally generated energy between end-consumers within a socially and geographically close community [106, 86]. In the academic literature, LEMs have been a proposed solution for the integration of DERs into the future electrical system and serve the general purpose of incentivising prosumers, energy producers and consumers to engage in the exchange of electricity in a competitive local market in order to balance the local demand and supply of electricity [18]. As there is not yet a uniformal definition for LEMs in the academic literature, a holistic definition for Local Electricity Markets as defined in this thesis is:

> 'Local Electricity Markets allow for the trading of energy volumes by decentral market participants within the distribution grid'.

For the basic functioning of a LEM, buyers (consumers or prosumers), sellers (producers or prosumers), a DSO for the connection to the physical grid and a platform provider to facilitate the operation of the LEM is necessary. Other actors that could participate in a LEM are retailers, aggregators and a BRP (to allow trading when not all connections are under the same BRP) that provides the license for trading energy between the parties [86, 124]. The design of the LEM is the outcome of the objectives and characteristics of the participants, which are connected to each other using the bi-directional electricity and information flows. The design of a LEM should ultimately serve the goal of the sustainable and efficient provision of electricity to end consumers [113]. Through the empowerment of local communities, the local economy is strengthened as profits could be locally re-invested. Through local energy consumption, community members can become less dependent on large energy suppliers as smaller actors can participate in the exchange of electricity [86].

2.7 Market design for Local Electricity Markets

Local Electricity Markets allow for the trading of locally generated electricity. Local electricity trading allows for the transfer of electricity from grid elements with a surplus of electricity to elements with a deficit of electricity, thereby, LEMs allow for the integration of prosumers and consumers with DERs into the energy system. Designing a market structure in which local electricity trading can be facilitated is an application of market design, in which different objectives must be considered in order to identify which market design reflects the demands of all involved stakeholders the best [61]. As can be derived from the definition for LEMs in the previous section, the concept of 'local' refers to a 'close social or geographical proximity' of the actors engaging in the exchange of electricity [86]. The term local is also relevant for local energy communities, and in a recommendation for the European Commission it was noted that there are four ways to define proximity that fosters inclusiveness and public acceptance in this context [7][p.22]:

- **Network-based**: Define locality using the topology of the electrical grid, for example using sub-stations;
- **Administrative**: Administrative restrictions may ease bureaucratic and regulatory processes such as permitting and registration. Also, an administrative or political region such as a municipality, commune, or district may be a good proxy of a community (in the broad sense of the word);
- **Distance based**: Conceptual simplicity for energy community members and stakeholders. However, uniform implementations of distance-based restrictions throughout a Member State may miss regional characteristics and implicitly discriminate regions or technologies;
- **Ad-hoc**: Define locality on an ad-hoc basis, depending on the specific application of the project.

Next to that, the term 'market' can be defined as [123][p.6]:

> A market is a set of humanly devised rules that structure the interaction and exchange of information by self-interested participants in order to carry out exchange transactions at a relatively low cost.

Through market engineering, a market is re-structured or set up such that an efficient and effective exchange of transactions can be facilitated with the ultimate goal to 'make markets work' [123]. When designing a market, the rules for the participants that engage in trading must be specified, thereby including the rules concerning information that should be provided by the market mechanism (for example bids and offers structures), rules for the matching of supply and demand, the pricing mechanism and the settlement mechanism [126]. Reflecting market design to LEMs, the market structure of local electricity markets can be classified in three different structures based on the level of decentralisation and the degree of DER involvement. Three market structures for LEMs are a fully decentralised market (peer-to-peer market), hybrid market and centralised market (community-based), and the key difference between the market structures is the fact that for the hybrid- and centralised markets third parties are necessary to organise the trades, whilst this is not the case in fully decentralised markets [89]. The definitions in the literature for the three distinct market archetypes vary, however, in general, the academic literature is in the consensus of the operating principles for the three structures.

- **Decentralised**: The decentralised, full P2P market structure is designed on the basis of the facilitation of direct, transparent trades between two peers without the intervention of a third party (such as a mediator) [89]. In a P2P market structure, all peers cooperate in a decentralised manner with regards to commons-based producing, trading or distributing a good or service, and thereby differ from the centralised market structures that can be found in the more traditional economic sectors [109].

- **Centralised**: In the centralised, community-based market, the trading of electricity is organised using a mediator (third party) that: receives data from the communities, organises the trades and balances supply and demand in the market[89]. A community can be defined as a group of peers that share common interests and goals. The community-based market is more structured as compared to the full P2P market, as the mediator manages the trading activity within the community and facilitates trades between the community and the wholesale market [109].

- **Hybrid**: The hybrid market model is a combination of the decentralised (full P2P) and the centralised (community-based market) market archetypes. Peers can choose to trade directly with other peers (decentralised) or engage in an exchange with the mediator (centralised). Peers can be grouped as different communities and be linked together, which results in a more scalable system and a reduced transaction cost [89].

The decentralised market allows for aligning energy exchange with the specific preferences of the prosumers (relating to energy type, source and cost) in a transparent manner. However, this market model is less scalable as compared to the other two models, as the result of the different negotiation processes that may result in computational burdens. In addition, due to the decentral nature of the market model (an absence of centralised control), the system behaviour is more difficult to predict for system operators. The central market structure is more scalable and structured, allowing for the provision of services to the network operator. Next to that, the social aspect of communities is enhanced as community members are involved and empowered through the exchange of a common good, electricity. The hybrid market combines the strengths of the two market models, in which both the decentral and centralised markets can co-exist and interact with each other [109]. In Figure 2.10, the three different market structures can be observed. The dots are the different actors engaging in the exchange of electricity and the arrows indicate the flows of information and power. In Table 2.2, a comparison of potentials and challenges of the decentral (full P2P) and central (community-based) LEM structures can be observed [127].

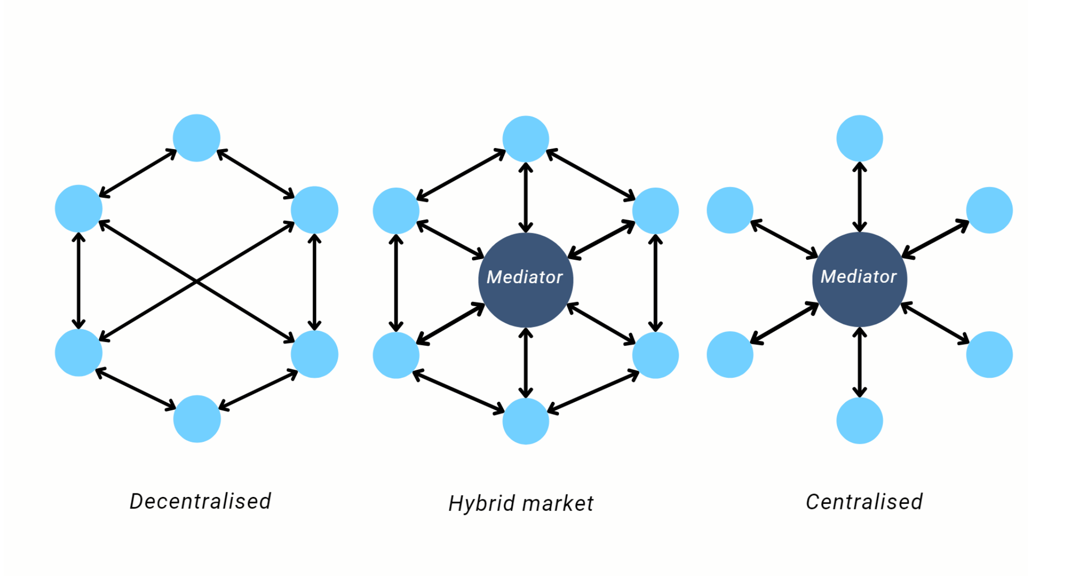

Figure 2.10: The different possible market structures for LEMs: decentralised, hybrid market and centralised market [89].

Table 2.2: Comparison of potentials and challenges of the decentral (full P2P) and central (community-based) LEM structures [127]

LEM structure	Main potentials	Main challenges
Decentralised	Decentralization	Scalability
	Democratization	Convergence rate
	Autonomy	System behavior prediction problem
	Transparency	High information and communication infrastructure costs
	Customer-centricity	Safety and high quality energy delivery issue
Centralised	More community involvement	Aggregation of all community members data
	Social cooperation	Optimization of large amounts of data
	More predictable system behavior	Large members' influence (market power)
	Additional services for utility grid (peak shaving)	
	Customer-centricity	

2.7.1 Internal market structure

Within the market structure of the LEMs, an internal market structure can be identified that is responsible for the actual matching of the trades and the financial transactions. Only the actors that participate in the LEM should be allowed access to the internal market structure, which should be tailored to the number and type of actors that participate in the LEM. As a result, the components of the micro market structure should be designed in a stakeholder-centric manner. The three different components of the internal market structure are the market mechanism, pricing mechanism and information system [86]:

- **Information system**: The information system is necessary to connect all the different market participants in the LEM to a platform. Through the information system, the information and communication flow within the market mechanism and the other components of the LEM is facilitated such that the flow is efficient, reliable and consistent [86, 84].

- **Market mechanism**: The objective of the market mechanism is to provide an efficient allocation of the traded goods (electricity in this case) between all the different active market participants [86]. The market mechanism thereby consists of the allocation and payment rules, bidding language and format (if applicable) whilst taking market constraints into account (minimum and maximum allocation of energy for example) and is implemented by the information system [84].

- **Pricing mechanism**: The pricing mechanism is integrated in the market mechanism, and serves to determine the financial remuneration for the market participants. It is responsible for determining the allocation of financial resources between the active market participants in the LEM [86]. The result of the interaction between the market mechanism and the pricing mechanism is price formation, through which the market prices are discovered for the traded good [18]. Price formation is the outcome of the way a market is designed, which results in a price for the traded good, in this case, electricity [28].

In Figure 2.11, the interaction between the internal market structure and the energy infrastructure can be observed. From the energy infrastructure in the LEM, information is submitted to the information system, which is used to perform the transactions within the market mechanism after which the market can be cleared. The market clearing price is set using the pricing mechanism after which the pricing information is communicated to the market participants, using the information system [84, 65]

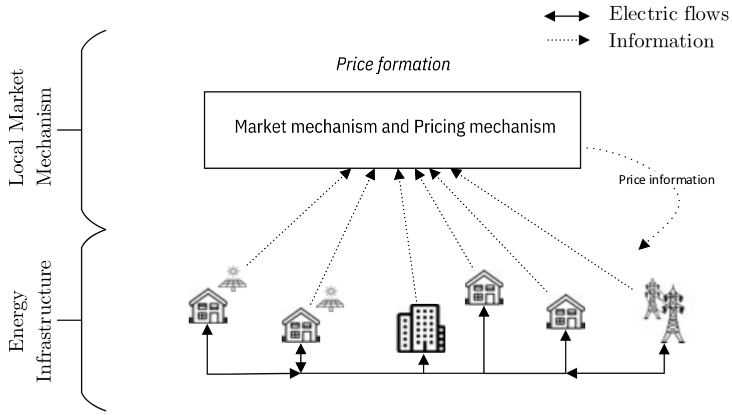

Figure 2.11: Price formation in a LEM through interaction between the micro market structure and energy infrastructure [65].

In Figure 2.12, the physical and virtual layers are visualised, representing how a LEM is embedded between the wholesale market and the physical distribution network. Based on the definition of 'locality', a LEM could be defined within the physical distribution grid, for example on the basis of sub-stations Different market structures could be applied in the LEM, as represented in Figure 2.10, and these market structures are present within the virtual LEM layer. Trading is facilitated within through the internal market structure, and when a deficit or surplus in trading volume occurs (the demand can for example not be met), the LEM engages in trading with the wholesale market (for example EPEX spot) to allocate the necessary volumes.

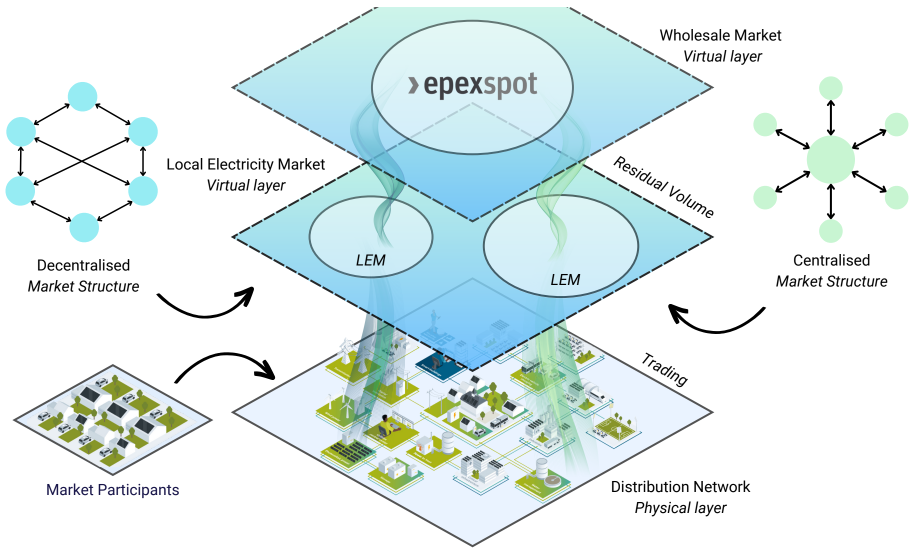

Figure 2.12: Schematical representation of the embedding of a LEM between the physical distribution network and virtual wholesale market layer.

2.7.2 Participative and non-participative price formation

Price formation was traditionally a process in which a seller sets a price for a good or service (posted price or fixed price) and buyers accept this price and proceed to purchase the good or service [27]. Alternatively, participative pricing mechanisms allow for (individually) differentiated pricing as the result of the interaction between a buyer and a seller. Participative pricing mechanisms are those in which consumers participate in setting a final price for a product, such as an auction. In participative pricing, the heterogeneous valuations of a consumer for a product or service are incorporated, which leads to increased efficiency of the interaction and the possibility of serving buyers who would otherwise be positioned outside of the market [64]. Through the participation of buyers in participative price formation, buyers perceive a higher degree of fairness and satisfaction with the price as compared to non-participatory price formation [100]. Kim, J. et al (2009) identify two types of participative pricing mechanisms based on the type of interaction between the buyers and the sellers: 'one-to-one' in which one seller and one buyer interact and 'horizontal interaction' in which several sellers and/or buyers interact. Prominent examples of participative pricing mechanisms with horizontal interaction are auctions and exchanges, whilst an example of one-to-one mechanisms are negotiations in which the buyer and seller interact to determine a price [64].

2.7.3 Identification of price formation mechanisms in literature

The academic literature in general converges with regard to the types of price formation mechanisms in local electricity markets. In a literature review performed by Capper, T. et al (2022), a total of 139 papers were systematically reviewed in order to identify the different types of price formation processes in local electricity markets. The paper concluded that 'five main categories of price formation mechanism were employed and tested: single auction, double auction, system-determined mechanisms, negotiation-based mechanisms, and equilibrium-based mechanisms' [18][p.5]. Mello, J. de Lorenzo, C. Campos, F. et al. (2023) state that [18] 'provides the most comprehensive review on LEM to date', however, 'it needs to detail the reviewed price mechanisms, missing the opportunity to set a standard nomenclature and mathematical formulation.' [82][p.3] which was a novel contribution from the paper to the literature. In a similar study, performed by Doumen, S. Boff, D. Widergren, S. et al. (n.d.) [28], a literature review was performed of the completed and ongoing Transactive Energy Field deployments. Transactive Energy can be defined as an energy management approach in which the control of local systems with market-based interaction allows for an increased amount of bottom-up coordination of distributed energy sources. The study focuses mainly on transactive energy projects in Europe and North America, and a total of 24 field applications were subject to the research. The study identified the following approaches to price formation in transactive energy projects: bilateral trade (peer-to-peer), bilateral trade (brokerage), double auction market, order book and iterative consensus [28]. In a similar study, performed by Wang, N. Verzijlbergh, R. Heijnen, P. et al. (2020) [122] a total of three types of mechanisms were identified: cost-sharing mechanisms, auction-based mechanisms and bilateral contracts. The study reviewed a total of 49 papers. Lastly, Cramer, W. Vasconcelos, M. Heringer, F. et al. (2019) also distinguish three LEM price formation archetypes: auction-based designs, bilateral negotiations and price formation by a central coordinator with no active user participation [25]. Concluding, in general there is a consensus in academic literature with regard to the different price formation mechanisms, which will set the foundation for the further classification of the mechanisms in this thesis.

A crucial criterion for scoping the further classification of price formation mechanisms is their operational feasibility in the day-ahead market. In this market type, all trading is conducted before the settlement period (ex ante, or before the fact). In these markets, market participants aim to stick as closely to their traded positions as possible during the settlement period. Capper et al. (2022) identify three types of mechanisms that can are commonly applied in these markets, namely single auctions, double auctions and bilateral negotiations [18]. This observation is in line with the different types of market clearing processes applied in wholesale markets, which typically consist of over-the-counter (OTC) transactions (bilateral negotiations) and central clearing on power exchanges using auctions.

Classification of price formation mechanisms

The literature review conducted by Capper, T. et al (2022) [18] was extended for the purpose of this study with further subcategories for the five identified categories by Capper, T. et al (2022). The single auction and double auction were classified under the auction mechanisms and the bilateral negotiations under the negotiation-based mechanisms. Furthermore, the system-determined mechanisms were further specified under the subsequent subcategories: Fixed and pre-determined mechanisms, Optimisation and game theory-based mechanisms (from equilibrium-based mechanism) and demand-based mechanisms.

Doumen et al. (n.d.), distinguish two types of bilateral trading: Peer-to-peer (P2P) and brokerage (central) and the order book mechanism can be characterised as a mechanism in which buyers and sellers have insight into specific orders at specific delivery periods after which they can engage in bilateral trading. Consequently, the mechanism will be classified under negotiation-based mechanisms. The iterative consensus mechanism can be applied to both auction-based mechanisms and negotiation-based mechanisms as market participants iteratively correct their transactions closer to the settlement period as new trading information can be used to allow for the correction of the trades [28]. The cost-sharing mechanism identified by Wang et al. (2020), is a mechanism that is often applied 'ex-post', or after the fact, which is the result of the fact that the energy balance or meter data is necessary to allocate the costs over the different end-consumers using, for example, balancing criteria. In these mechanisms, the benefits of electricity trading are for example distributed over energy community members on the day after settlement [33]. As a result of the ex-post price formation process in cost-sharing mechanisms, the mechanisms will not be incorporated in the classification that is established for mechanisms suitable for day-ahead markets. System-determined mechanisms, as identified by Capper et al. (2022), can be applied in ex-ante markets such as fixed pricing mechanisms and will therefore be included in the classification. In Figure 2.13, a visual representation of the distribution of different price formation mechanisms in the academic literature identified by Capper, T. et al. (2022) can be observed after further specification. The figure only includes specified mechanisms, 19 papers (14%) did not specify a mechanism.

The extended literature review of the price formation mechanisms identified by Capper et al. (2022), Doumen et al. (n.d.) and Wang et al. (2020) can be classified as follows using the framework by Kim, J. et al. (2009):

Participative pricing mechanisms:

- Auctions
  - Single Auction
  - Double Auction
- Negotiation-based mechanisms
  - Bilateral trade (peer-to-peer)
  - Bilateral trade (centralised)

Non-participative pricing mechanisms:

- System-determined mechanisms
  - Fixed and predetermined mechanisms
  - Optimisation and Game Theory

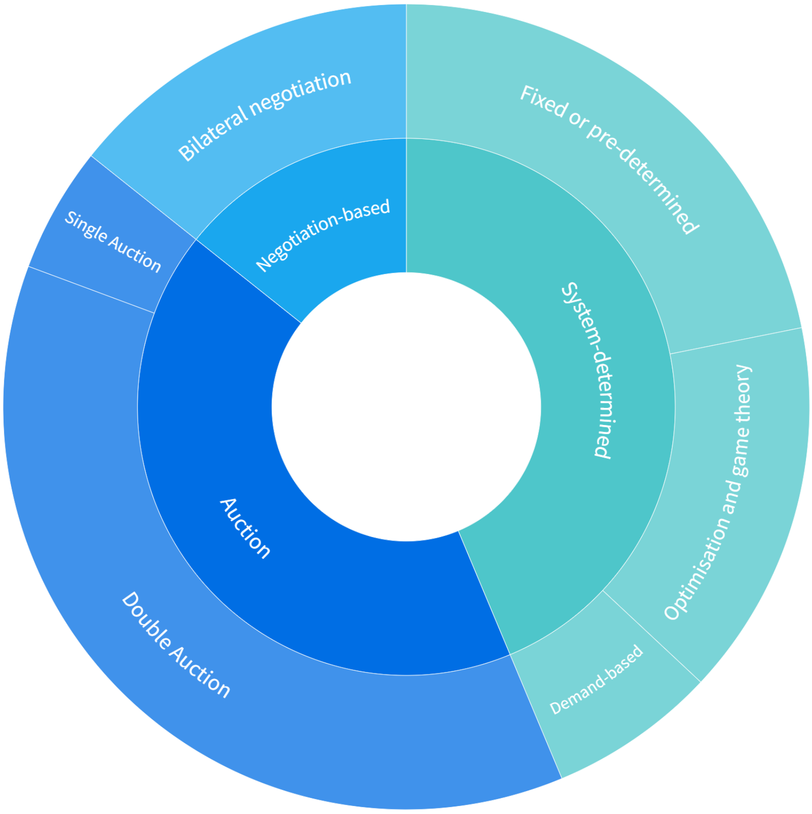

Figure 2.13: Visual representation of the distribution of different price formation mechanisms in academic literature [18].

– Demand based

In double-sided auctions, several buyers and sellers interact and participate in setting the price through horizontal interaction. In single-sided auctions, either the buyers or the sellers set the price. In both single and double auctions, multiple buyers and/or sellers participate in the price formation process. In negotiation-based mechanisms, a one-to-one interaction takes place between the buyer and the seller to determine the price, such that both sides participate in the price formation process. In contrast, system-determined mechanisms are non-participative as the price is based on a mathematical formula or through market forces without direct interaction between buyers and sellers. In Figure 2.14, the price formation matrix can be observed with four different quadrants based on the interaction between the buyers and sellers and the side that sets the price.

2.7.4 Challenges for price formation in LEMs

In a study conducted by Dab, A. et al. (2023) a literature review of the benefits, opportunities and challenges for price formation mechanisms for peer-to-peer energy trading were identified [26]. In Table 2.3, the challenges for the implementation of P2P energy trading pricing mechanisms [26][p.20] can be observed.

In a study conducted by Ableitner, L. Tiefenbeck, V. Meeuw, A. et al. (2020) the behaviour of market participants in a peer-to-peer electricity market was researched on the basis of the evaluation of two different price formation mechanisms: one based on active participation and a non-participative mechanism. The first mechanism emphasises 'agency' through an active role

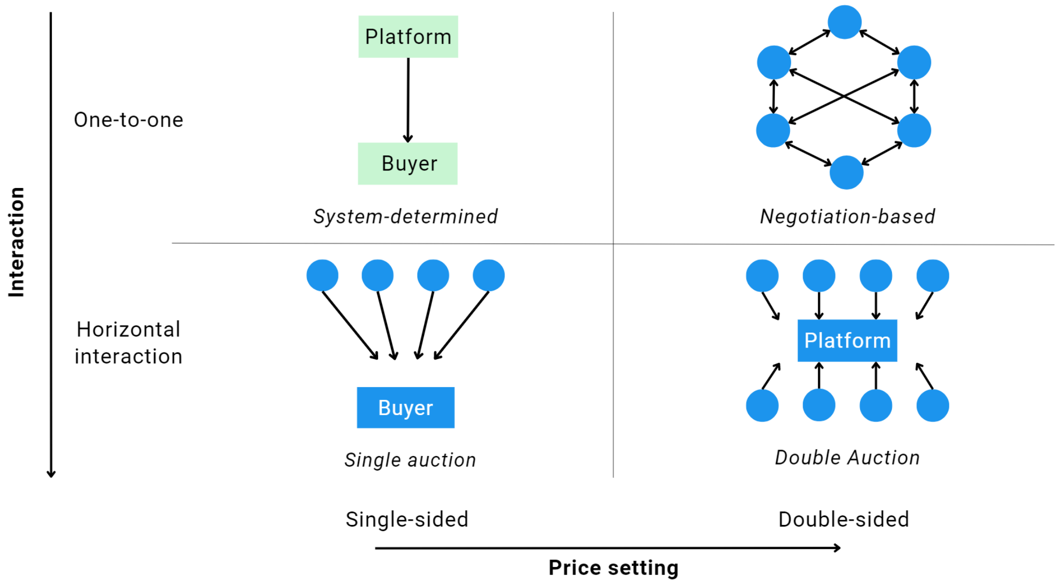

Figure 2.14: Visual representation of a classification of the four categories of mechanisms with reference to their participative (blue) or non-participative (green) nature.

in price formation, whilst the non-participative mechanism is characterised by the convenience of automation as prices are determined by a central authority. The active inclusion of market participants into price formation allows for more autonomy in the market, however, it also demands more time and cognitive resources which is connected to the extensive effort accompanied by participative price formation. The non-participative, uniform price was based on the supply-demand ratio and balanced between the retail price and feed-in tariff. The participative pricing mechanism is implemented through a double auction mechanism (as described in section 2.8) to which the market participants submit bids and offers. The study showed that 30% of the market participants preferred participative pricing as this group in the case study 'values the gamification character, the idea of a free market, and the fact that they don't have to trust a third party in determining prices for their surplus (respective of locally purchased) electricity.' [2][p.10]. Alternatively, 35% of the case study group preferred non-participative price formation as 'they seem to value automated prices for reasons of convenience and simplicity' [2][p.10] (11% where non-respondents and 24% non-users). The authors recommended that future local electricity markets should consist of a combination of automated smart agents that place bids for market participants based on indicated preferences whilst providing an option for active user participation in price formation [2].

Table 2.3: Challenges for the implementation of LEM price formation mechanisms [26][p.20]

Challenge	Description
Price discovery	In LEMs, participants need to agree on the price of energy being traded. However, it can be difficult to establish a fair market price that takes into account the variability of energy supply and demand, as well as the cost of energy generation and distribution.
Scalability	As the number of participants in LEM trading increases, the complexity of the system can grow exponentially. This can lead to issues with scalability, including slow transaction times and high transaction fees.
Interoperability	LEM trading requires a high degree of interoperability between different energy systems, including different types of energy storage, renewable energy sources, and smart grid technologies. Achieving this level of interoperability can be challenging, particularly in systems that have been designed independently by different vendors.
Data privacy and security	LEM trading involves the sharing of sensitive information, such as energy consumption data, between participants. Ensuring the privacy and security of this data is critical to prevent fraud and other malicious activities.
Regulatory compliance	LEM trading may be subject to a range of regulations, such as energy market rules and tax laws. Participants in P2P energy trading must ensure that they comply with all applicable regulations to avoid legal and financial penalties

2.8 Auction based mechanisms

The auction process is a market mechanism that can be defined as: 'a well-specified negotiation mechanism mediated by an intermediary that can be considered as an automated set of rules' [89][p.10]. Auctions are commonly applied trading mechanisms in which market participants submit offers and bids for the buying or selling of a good or service and are known as one of the oldest forms of trading and were already applied at 500 B.C. in Babylon. In general, auctions are used for three reasons [121][p.111]:

1. Speed of sale;
2. Information revelation of buyers' valuation;
3. Prevention of dishonest dealing between the sellers and buyers.

The defining feature of auctions is the fact that both buyers and sellers can communicate through bids and offers, in which bids represent the willingness to pay, reflecting both utility and preferences. Offers represent a willingness to accept, thereby representing the underlying costs [18]. A central market operator collects the bids and offers, after which the supply and demand price-quantity orders are matched and the market is cleared at the equilibrium point between supply and demand [28]. In general, two types of pricing mechanisms can be identified for auctions: uniform pricing (pay-as-clear) and discriminatory (pay-as-bid) pricing. In uniform pricing, the market clearing price is the equilibrium price that all producers receive and all consumers pay. In pay-as-bid pricing, all winning producers are remunerated at their bidding prices, and this mechanism is also referred to as discriminatory pricing as all producers receive a different price [114]. There are different types of auctions, as can be observed in Figure 2.15, and they can be classified on the basis of participants and the trading horizon [95].

2.8.1 Participants based

Auctions with one seller and multiple buyers, or, one buyer and multiple sellers can be classified as single auctions. Specifically, single auctions with one seller and multiple buyers are referred to as Forwarding auctions, and single auctions with one buyer and multiple sellers as Reverse auctions.

Auctions that involve multiple sellers and multiple buyers can be classified as double auctions [89], which operate in a two-sided market in which both sellers and buyers can participate in the price formation process. Two-sided auctions can further be classified on the basis of the matching process. In a Continuous Double Auction (CDA), the bids and offers are continuously matched in the order book (open auction). Alternatively, Periodic Double Auctions (PDA) operate on the basis of predefined intervals (for example 15 minutes or hourly) to match bids and offers. Periodic Double Auctions can be considered as allocationally efficient mechanisms and are applied in stock exchanges and electricity markets [124]. For reference, the day-ahead auction is a periodic double auction that clears the electricity market on a 60-minute basis.

2.8.2 Horizon based

The auctions can further be categorized on the basis of the bidding horizon: in an open auction, multiple rounds of bids can be submitted to the auction. In open auctions, bidders can monitor the submitted bids and modify their bids if desired. A disadvantage of open auctions is the complexity and long duration of the bidding process. The bids in a single-sided, open auction can be sorted in ascending order such that the highest bidder wins the auction (English auction). In the English auction (ascending bid auction), bidders are in competition with each other to submit the highest bid until no additional bid is submitted. Alternatively, in the Dutch auction, the participants engage in 'reverse bidding' in which the auction starts with a high price which gradually decreases as participants submit lower bids. In the Dutch Auction (descending bid auction), buyers are aware of the leading bid value and in this process, the auctioneer assigns a value to the auctionable good and the negotiation process can be settled quickly when the bidders accept the lowest bid. In a sealed-bid auction, the auction process is static such that the bid is 'sealed' and cannot be adapted after submission. In a sealed-bid auction, the bids are not visible to other participants, and the highest bid is the winning bid. A similar approach is the second price sealed bid auction (Vickrey auction), in which the winning bidder pays the second highest bid price [95, 89]. In Figure 2.15, a classification of the different types of auctions can be observed [95].

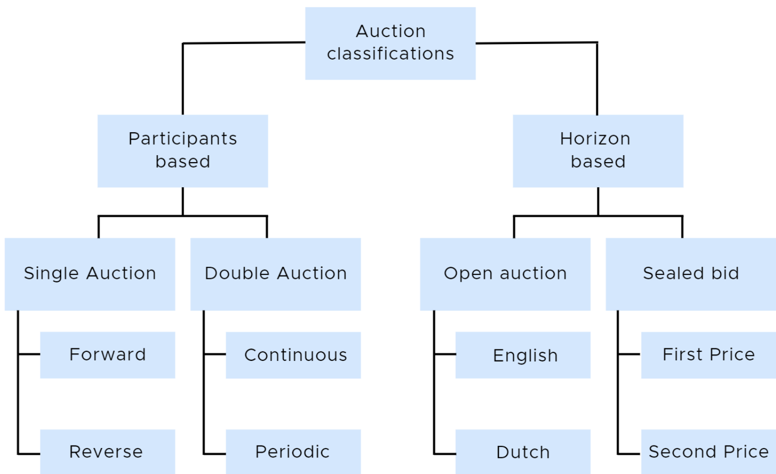

Figure 2.15: Classification of the different types of auctions [95].

2.8.3 Application in LEMs

Auctions are applied in different academic papers for trading energy between buyers and sellers in local electricity markets [124]. In the literature review performed by Capper, T. et al (2022) [18], it was found that single auctions could be applied in LEMs through for example consumers bidding in a community to purchase excess available renewable energy (English auction) from a network operator [75]. The double auction is also widely applied in LEM literature and research, in many forms and generally yields highly efficient outcomes through considerable learning between the market participants [18]. Zade, M. et al. (2022) consider periodic double auctions (PDAs) to be the most suitable type of double auction for LEMs, as continuous double auctions encourage high-frequency trading such that non-professional participants might not be able to capture an equal amount of welfare. As a result, the goal of PDA's is to maximize the social welfare of participants, which is defined as 'the sum of the bidders' utility minus the sum of the producer's cost' [124][p.2]. A second objective function that is used in LEM literature is maximising trading volume, which can be a suitable objective in community-based markets in which not all private values of the individual actors might be known to compute the social welfare [6].

A key aspect of auctions is the bidding format, which describes which kind of information a participant needs to exchange with the trading platform in order to engage in a trade. A typical bid in a conventional electricity market consists of a buy or an ask price with a quantity (for example in MWh) and a user identification number. Zade, M. et al. (2022) [124] expand the conventional bidding format with incorporation of user preferences for energy quality and a willingness to pay a premium (WTPP) for energy of a certain quality. Energy quality refers in this paper to local, green-local and na (non-allocated as in the source of energy is not specified), such that a consumer can indicate a preference for electricity from a certain region and from a specific generation type (renewable for example). Through the WTPP, the buyers can express their preference for a specific energy quality such that the auction mechanism can ensure satisfaction for this allocation. The bids are collected in an order book, after which a periodic double auction is conducted and all bids are matched if the buy price is equal to or above the ask price. The energy quality preferences are matched in an iterative manner in the modified double auction mechanism, such that the heterogeneous user preferences are satisfied. The paper found that the proposed clearing algorithm can increase the usage of local, renewable energy sources and coordinates the increasing amount of DERs in local electricity markets [124]. A potential problem, however, with the submission of bids are the threats to the privacy of the users in the local electricity market. The bids and offers reveal a significant amount of private information, related to the lifestyle of the market participant. As bids always include the required amount of electricity for a market participant, the consumption profile can, for example, be derived which can expose further sensitive private information [1]. Auction-based mechanisms operate on the basis of information from the market participants related to their energy consumption patterns, which might not always be available in real transaction environments. Overall, small users with a small power capacity might not be willing to participate in such complicated bidding procedures and can expect it as intimidating [128]. Lastly, auctions have proven to be a well scalable clearing mechanism as compared to computationally intensive optimisation methods such as Locational Marginal Pricing (LMP) or optimal power flow (OPF) methods [10].

2.8.4 Multi-agent systems

Another double auction-based mechanism based on the matching of supply and demand is The Powermatcher concept (developed by Dutch research institute TNO) which is a Multi-Agent-System (MAS). This concept is concerned with optimally matching supply and demand in electricity networks with an increased share of distributed energy resources (DERs). The concept optimally matches the operation of the DERs in order to match production and consumption, by representing each device in the market by a control agent, which optimises the operation of the device in an economically optimal manner. The agents are organised in a logical tree, in which the leaves are the number of logical device agents that represents a DER and a concentrator agent that represents a cluster of device agents (which can be applied for the purpose of scalability). Optionally, an objective agent can be implemented that represents the business logic behind the cluster of device agents such as for example setting the goal of balancing supply and demand within the cluster itself. The root of the logical tree is formed by the auctioneer agent that establishes price formation on the basis of establishing an equilibrium price using a double auction. The device agents communicate bids and offers to the central auctioneer agent, after which it receives price information from the auctioneer agent. The device agent uses the price information in combination with its last bid in order to set the amount of power that the agent either produces or consumes. The PowerMatcher concept has been validated in different field studies and simulations, and has proved an increased match between production and consumption whilst offering a scalable solution in which privacy is maintained [70]. However, in a field-study of the PowerMatcher concept with 22 households in the PowerMatching city, users in general where satisfied with the level of living comfort provided by the PowerMatcher concept however they did not see sufficient control and energy feedback through which they where able to actively support the balancing of supply and demand using the PowerMatcher concept. As stated in the study: 'several end-users appeared to miss the insight and controls that could support them in reaching their household's energy-related goals, such as to save energy and to maximize consumption of locally produced solar energy' and 'there was little incentive to become a more active participant in the smart grid'. [46][p.5]. The study concluded that active end-user participation in the balancing of supply and demand might be beneficial for the PowerMatcher concept, in which end-users are now represented by automated software agents.

In Figure 2.16, the structure of the logical tree can be observed.

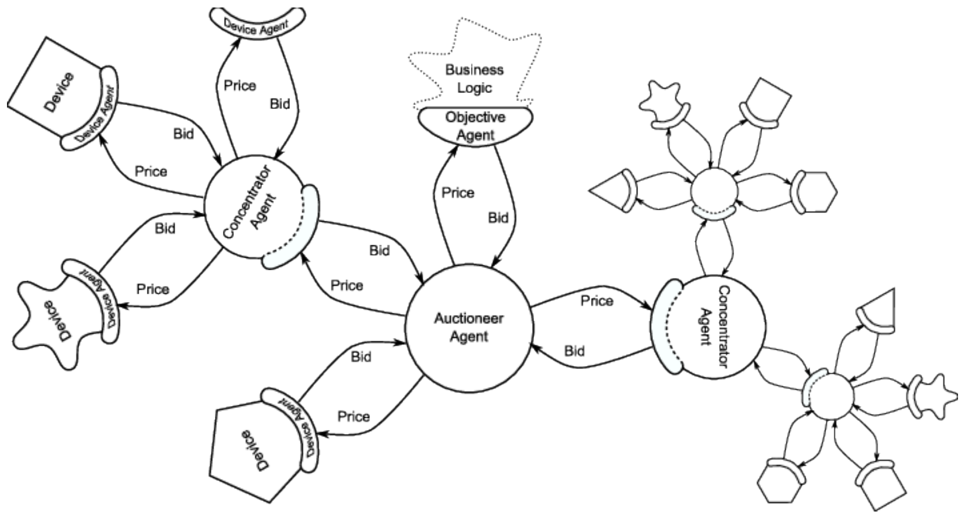

Figure 2.16: Logical tree structure in the PowerMatcher concept with four types of agents [70]

2.9 Negotiation-based mechanisms

The auction based price formation mechanisms as described in section 2.8 generally involve a centralised platform in which buyers and sellers can find each other in order to participate in the bidding process. A more decentralised approach to price formation can be facilitated through negotiation based mechanisms, which allow for peer-to-peer transactions that are less structured as compared to the auction mechanism. As a result, negotiation based mechanisms allow for the decentralised peer-to-peer transactions without a central market operator [18]. Alternatively, in centralised negation based markets, the market operator takes an intermediary position, in which the supervising, facilitating and administrative tasks are executed for the bilateral trades [122]. As the result of negotiations in a P2P market, the market participants create mutually agreed upon trading contracts: bilateral contracts. A bilateral contract can be defined as 'an agreement between two parties (buyer and seller) to exchange electric energy, generation capacity rights or related products for a specified period of time, as well as at an agreed price' [109][p.368]. Doumen et al. (n.d.) identify two types of bilateral trading mechanisms: a decentralised P2P structure and a centralised P2P structure.

2.9.1 Bilateral trade (decentralised)

The bilateral negotiation mechanism based on one-to-one interaction between two peers results in mutually agreed upon contracts consisting of both price and quantity specifications [61]. Bilateral P2P mechanisms operate on an iterative basis, in which the peers are typically represented by autonomous agents. In this process, the automated agents organically reach a joint decision in which the conflicted interests are respected [19]. Chakraborty S. et al (2020) developed an automated P2P negotiation approach in which bilateral energy contracts are settled as energy loans between peers [19]. In the mechanism, the peers are represented by autonomous agents and engage in the bilateral negotiations after selecting a random peer to negotiate with. In this one-to-one mechanism, the peers negotiate the contract details and heterogeneous preferences (such as sustainability) in order to agree upon a bilateral energy contract. The mechanism converges to an optimal solution for the bilateral trades, such that the social welfare and fairness is optimised. Fairness in this case is measured by the concept of Nash social welfare, in which the peers select the best strategy with respect to the strategy from the other peers in the market. As a result, the peers will not be able to improve their own outcome when their strategy changes, thereby the Nash social welfare is a measure for the fairness for the individual peers [19].

Mengelkamp, E. Staudt, P. Garttner, J. et al. (2017) [85] implement a decentralised peer-to-peer market design that operates on the basis of random and anonymous pairwise meetings between two peers. No central authority is needed in this design and prosumers and consumers engage in individual trading with each other. The peers are matched in a randomised order on a pay-as-bid basis in an iterative manner until all peers are matched or all energy is procured. The matching quantity of electricity is equal to the minimum amount of the buyers ask and sellers bid amount and the pricing rules follow the principles as defined in the pay-as-bid auctions. Each transaction results in individual prices and competitive advantage is minimised as the result of randomisation in matching. The paper concluded that this market design in combination with intelligent bidding agents (that learned from transactions in the past) can reach the highest amount of locally traded energy compared to a double auction, however a double auction found the lowest feasible market price [85].

Through bilateral P2P negotiation based mechanisms, a true decentralised local electricity market can be achieved. However, as this approach allows for different degrees of freedom, the bilateral negotiations can lead to individual price arrangements. These prices can significantly differ from the market based equilibrium prices, which are for example the outcome of auction based mechanisms. As a result, social welfare maximisation and the overall matching of orders cannot be guaranteed in P2P bilateral trade mechanisms [25]. An advantage of decentralised markets is that they protect the privacy and autonomy of the market participants and are relatively scalable [126].

2.9.2 Bilateral trade (centralised)

The second type of bilateral trading for P2P is a centralised structure in which a central market operator operates the trading platform, for example a distribution system operator. An example of such a centralised bilateral platform is described by Liu, Y. et al (2019). The central party does solely operate the platform and does not take an active role in facilitating the trades. On the platform, the peers can register and post trading offers, consisting of price and quantity specifications. The offers are posted on the platform, such that the market participants can browse the offers and send a bilateral contract if it would like to engage in a trade. After approval of the contract from the second peer, the DSO can approve the trade (taking system constraints into account) and remove it from the platform [76]. In bilateral clearing, the buying and selling offers are cleared when the bilateral aspects are in accordance with each other, leading to each individual bilateral transaction having a unique price relating to the involved bids. In bilateral markets, no single market price exists, however an average can be computed [82]

Through bilateral contract trading, market participants can engage in Multi-class Electricity Trading (MET), in which the heterogeneity of electricity sources can be incorporated. In MET, electricity is not differentiated on a physical basis but rather on environmental, social and economical aspects. A market participant can for example give a discount for buyers in low income communities or indicate a preference for locally generated green electricity in the contract [76]. As this mechanism relies on active participation from the participants, this could be a non-trivial process associated with high opportunity costs. Altough automated software agents can release some burden of the market participants, user intervention is hard to completely avoid [76].

2.10 System-determined mechanisms

The nature of electrical power systems, based on physical coordination and maintaining the balance between supply and demand, has led to system-determined price formation mechanisms. In this type of non-participatory price formation, market participants do not submit bids and offers as price formation is determined by a market operator that establishes prices on the basis of a pre-set or pre-agreed on formula or mechanism. The platform operator in this context could be a local retailer, DSO or community manager that takes over all the tasks in the LEM in order to maximise an objective function and establish equilibrium prices. Market participants for example give access to individual information regarding their assets and behavioural flexibility such that the individual schedules can be defined centrally [25]. The market participants are paid or charged on the basis of the quantity of electricity they feed in or out of the grid, at a fixed or dynamic price, as a result, there will be no trading to determine a volume and price equilibrium [18], such that the market participants have no direct access to the market (non-participative mechanism). Under system-determined mechanisms, price formation is the result of mathematical formulations which make the pricing process more straight forward, time-efficient, and understandable for the end-consumer as compared to negotiation-based mechanisms and auctions [12]. In addition, participative pricing mechanisms such as auctions are high demanding structures, and their participative nature might be intimidating for some market participants, leading to a discouragement for LEM participation [33]. In Figure 2.17, a visual representation of the operation of a system-determined mechanism, in which a central LEM coordinator optimises social welfare can be observed. In this configuration, a single optimisation problem is solved and the central coordinator has all the necessary information to maximise social welfare and the allocation of resources. The determination of the respective shares of self-consumption, local exchange, backup retrieval, and feed-in at the individual level is centrally determined, and the prosumers are allocated binding schedules [25].

The system-determined mechanisms will be further classified into Fixed and predetermined mechanisms, Optimisation and Game Theory based mechanisms and Demand based mechanisms. In Figure 2.18, a visual representation of the distribution of system determined mechanisms applied in LEMs in academic literature can be observed [18].

2.10.1 Fixed and pre-determined mechanisms

Under fixed and pre-determined mechanisms, the prices for electricity are set up to a limit or per unit (kWh or MWh) [18]. As described in Figure 2.6, the number of energy communities is growing in the Netherlands. As energy communities are not profit-driven organisations (often cooperatives), they seek to supply the members of the energy community with electricity at the

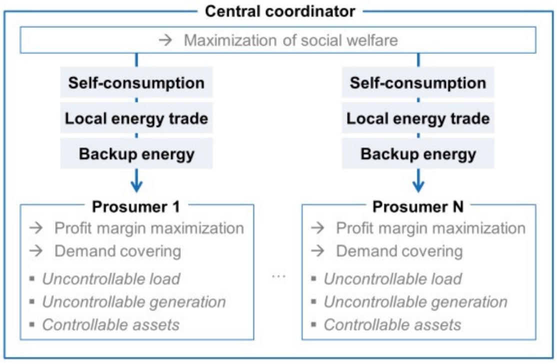

Figure 2.17: Visual representation of the operation of a system-determined mechanism, in which a central LEM coordinator optimises social welfare [25].

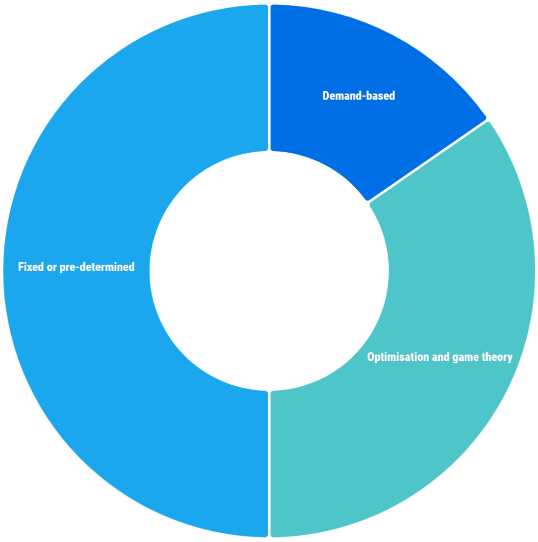

Figure 2.18: Visual representation of the distribution of system determined mechanisms applied in LEMs in academic literature [18].

cost-price. This is the full charged price of the costs plus the required investments and reserves of generating, purchasing, distributing, storing, sharing and supplying renewable energy, settled with the income from flexibility markets and the sale of surpluses of renewable electricity. The cost price plus ensures that there are economically sound business cases for energy communities. The costs include, among other things, financing costs including interest, personnel costs, material costs and research costs. The plus includes, among other things, reserves for future investments, the absorption of risks and investments in social goals. As a result, energy communities are able to supply their members with low-cost, local renewable energy for a stable price. The Local4local consortium applies cost-price plus pricing for seven energy communities in the Netherlands and aims to implement the module for more energy communities in the future. Practically, cost price plus pricing will be implemented through a calculation module for energy communities through which they can compute the specific cost plus price for their renewable energy project after which cooperative energy suppliers will supply the members of the energy community with electricity at the cost plus price [77]. As a result, the price formation mechanism can be characterised as a fixed and pre-determined price (determined by the energy cooperation), in which there is no direct interaction with the consumer (non-participative) and the price is determined on the basis of a pre-defined formula, being the cost price calculation module.

An advantage of fixed and pre-determined mechanisms is that the prices are predictable and they are not prone to manipulation by market participants, however, it does not account for the implementation of efficiency improvements and overpaying or underpaying for electricity is plausible as the mechanism does not accurately represent real-time market conditions or system constraints [58].

2.10.2 Optimisation and Game Theory

An optimisation method that can be applied in LEMs is Distribution Locational Marginal Pricing (DLMP), similar to traditional Locational Marginal Pricing (LMP), in which the clearing prices are settled at the different individual distribution nodes [128]. In the United States, Locational Marginal Prices (LMPs) are used to account for the variation of electricity costs over the grid as the result of distances and transmission capacities between loads and generation. As a result, LMP is an effective optimisation method to provide effective locational price signals in distributed markets by using it as a tool for DSOs and TSOs to coordinate local trades [36]. Through DLMP, the grid operations can be improved with regard to congestion management whilst facilitating loss reduction, among others. Through a mathematical optimisation model operated by, for example, the DSO constraints related to line loading, voltage drop and loss reductions can be implemented. The DLMP model can be utilised to reflect the operational state of the grid in price signals, resulting in an incentive for rational users to adapt their consumption pattern [128]. The price computed by the DLMP represents the marginal costs of supply, which allows the mechanisms to be allocationally efficient as it represents the accurate state of the grid in the price formation process. A disadvantage, however, of DLMP is scalability as with an increasing amount of DERs; the model becomes increasingly complex as the number of iterations required to converge the optimisation increases with the amount number of DERs [88].

Game theory is applied when there is strategic behaviour from the market participants in the local electricity market. Game theory is a valuable tool to simulate the actions of market agents and analyze various mechanisms that can optimise market participants' individual and collective benefits [82]. A predominant concept to identify an equilibrium is the Nash equilibrium (where no market participant is further willing to adapt his position further) or the Shapley method (in which the 'fairest' equilibrium point is found in the market with respect to the strategic goals of the market participants), which are often regarded in the literature as the best approach to allocating the benefits in LEMs [117].

In game theory, a central LEM coordinator takes over all the tasks within the LEM to establish an equilibrium. Active prosumer engagement cannot be achieved in this mechanism (hence it is classified as a non-participative mechanism) as the market participants do not directly engage in trading activities with other market participants. The central coordinator could, for example, gather information from the market through access to the individual monitoring and metering systems of the DERs and the prosumers and consequently establish a market equilibrium using this information or through submitting bids and offers [25]. Generally, two types of game theory can be distinguished: cooperative and non-cooperative. In cooperative game theory, market participants cooperate with each other to obtain maximal collective profits or social welfare distribution. In contrast, in non-cooperative games, the market participants compete with each other for individual benefits. As a result, non-cooperative games are applied in P2P energy trading in which prosumers try to minimise their operating costs or maximise individual benefit through trading with other prosumers [20] (as described in subsection 2.9.1).

In cooperative game theory, market participants can form coalitions (for example, energy communities) and make binding agreements on how to distribute the benefits fairly and equitably. Different cost-allocation mechanisms can be applied in cooperative energy trading, such as the application of the Shapley value [18]. The Shapely value is a unique value that allocates the profit in a cooperative game based on the weighted average of the marginal contribution of a market participant to the cooperation (a group, collective or system) in a fair manner [20], which can, for example, be facilitated by a platform operator. An example of the application of the Shapley value in LEMs is performed by Lee, W. Xiang, L. Schober, R. et al. (2014) in which the benefits of a LEM are distributed based on the contribution of the different market participants to the LEM [73].

The different optimisation and game theory-based mechanisms that a central operator can apply to facilitate system-determined pricing in a local electricity market can impact the end consumers differently. Non-cooperative game theory may result in a stable equilibrium in the market. However, it tends to favour market participants with more market power. Cooperative game-theory methods maximise social welfare and establish benefits for all market participants but face scalability issues due to the computational effort required to converge the model [49]. In general, the practical deployment of game theory is complex as the result of human behaviour and other unpredictable variables (such as uncertain DER production). Next to that, in terms of scalability, when large amounts of data are used, the performance of game theory is heavily dependent on the capability of the communication infrastructure. When large amounts of renewable energy resources are implemented into a system, accompanied by human decision factors (related to personal interests and emotions), game theory-based models will face implementation issues. Therefore, the assumption of rational behaviour in game theory-based mechanisms is not guaranteed in real-world scenarios [8].

2.10.3 Demand-based

A dynamic pricing scheme can achieve decentralised market participation from prosumers. In this mechanism, prosumers do not reveal their individual properties to the central market operator (non-participative) and are exposed to pre-determined time variable prices that reflect the actual system cost. The goal of this mechanism is that market participants adjust their demand patterns and activate their flexible resources (implicit flexibility) such that they can reduce their payments. As in this mechanism, the individual properties of the market participants are not communicated to the central operator (as is the case in non-participative mechanisms), and the preferences of the prosumers are captured in the form of constraints in the mechanism such that the market clearing objective is a generation cost minimisation problem (as compared to a social welfare optimisation problem in auctions) [98].

As described by Capper, T. et al. (2022) [18], system-determined mechanisms also consist of time-of-use prices and other dynamic mechanisms for the demand side. These mechanisms are examples of real-time pricing mechanisms that fluctuate over time, such as time-of-use pricing, critical peak rate and real-time rate. They are determined by the system operators to influence the energy consumption behaviour of consumers (an example of demand response). In the time-of-use rate, the price for electricity varies overtime periods (daily, weekly or monthly). It reflects the basic production costs of electricity to decrease consumer demand. In the critical peak rate, the consumers are subject to dynamic pricing that reflects the actual electricity production costs during critical peaks. This mechanism is usually offered on a day-ahead basis and has the goal of improving the reliability of the power system as it reflects the current state of the system. In real-time rate pricing, consumers pay the price for the actual, real-time market rates based on hourly or day-ahead scheduling, and these rates will vary due to power supply fluctuations [60].

In the GridFlex Heeten LEM pilot, a pricing scheme is proposed that incentivises self-consumption through a reduction of the transport costs for the network operator as proposed by Rajasekhar et al. (2019) [99]. The transport costs within the community depend on the total power consumption, which increases with the power demand on the transformer connection for the community. As a result, each inhabitant in the group pays the same price for the connection, but the price depends on the aggregated behaviour of the energy community. Three levels of demand are identified related to the power range of the transformer (low, medium, high), leading to three different prices (on a 15min basis). The price follows a quadratic function as the result of the demand on the transformer, which is known to support the reduction of demand peaks. The mechanisms are designed so that the prices for the end consumer are still reasonable with the ultimate goal of reducing transport losses and addressing congestion in the grid [102].

Dynamic mechanisms such as time-of-use and demand-based functions are mechanisms that function based on one-way communications from the system operator and thereby encourage load-shifting behaviour based on changes in electricity pricing. However, there is no negotiation on the total quantity of load to be shifted, such that the system operator is subject to estimating the consumers' response with no further information on the actual change in consumed quantity. An advantage of these mechanisms is the simplicity and user-friendliness of one-way communication, whilst a drawback is the lack of efficient mechanisms for balancing supply and demand in the market [74].

2.11 Conclusion: Design of LEMs

Local Electricity Markets (LEMs) have been proposed as a solution for the integration of the growing amount of Distributed Energy Sources (DERs), whilst facilitating the trading of locally generated electricity between end-consumers in a socially and geographically close community [106, 86]. In general, three market designs for LEMs based on decentralisation and the degree of DER involvement can be distinguished: a fully decentral in which direct trading between peers is facilitated in a fully decentralised manner, a centralised market in which a community manager organised the trades between LEM participants and a hybrid structure that combines both elements from the decentralised structure and the centralised market. In general, the fully decentralised market is less scalable as compared to the other structures. In the centralised market, the social aspect is enhanced as community members cooperate to exchange a common good, being electricity and the hybrid market combines the strength of both models [109].

In the internal market structure within the LEM, the actual matching of the trades and transactions is facilitated. The internal market structure consists of an information system, market mechanism and pricing mechanism [86]. The information system is responsible for the information flow and communication between the different market participants. The market mechanism facilitates an efficient allocation of the traded goods and encompasses the payment rules, bidding format and market constraints [84]. The pricing mechanism determines the financial remuneration for both the buyers and the sellers in the market and allocates the financial resources between the active market participants. The result of the interaction between the market mechanism and the pricing mechanism is price formation, which is the outcome of the way a market is designed and results in a price for the traded good [18, 28].

Two types of price formation mechanisms were distinguished: participative mechanisms and non-participative mechanisms. In participative mechanisms, consumers are involved in setting the final price in a transaction. As a result, in participative pricing, the heterogeneous valuation of consumers for a good can be incorporated into the price formation process [64]. The academic literature converges with regards to the different price formation mechanisms that can be applied in local electricity markets, and the mechanisms were classified using the framework from Kim, J. et al (2009) into participative mechanisms: auctions and negotiation-based mechanisms and the non-participative, system-determined mechanisms.

Auctions have been widely applied in LEM literature, as they generally yield efficient outcomes for market participants. Auctions can be characterised as well-specified negotiation mechanisms that are mediated by an intermediary [89]. In general, auctions are applied for different reasons, such as their speed of sale, information revelation of the buyers' valuation for a good (disclosing willingness to pay in a bid, or underlying costs in an offer) and the prevention of dishonest dealing as the result of the well-specified trading rules [121, 18]. Buyers and sellers submit bids and offers, after which the supply and demand price-quantity orders are matched and the market is cleared in either a uniform or pay-as-bid manner [114, 28]. Different types of auctions can be distinguished, based on the participants or bidding horizon in the auction such as a single, double, open or sealed-bid auction with further differentiation. An auction can optimise social welfare or maximise trading volume and through adaption of the bidding format, heterogeneous preferences of users can be incorporated [124, 6]. A potential problem however is related to privacy concerns [1], and their demanding structure which might be intimidating to some market participants and can ultimately lead to discouragement for LEM participation [33]

A second type of participative price formation mechanism is a negotiation-based mechanism, which is based on a one-to-one (P2P) interaction between market participants that results in a mutually agreed upon bilateral contract consisting of both price and quantity specifications [61]. This is a more decentralised approach as compared to auction-based mechanisms, as no central platform is necessary for the organisation of the trades [18]. In this mechanism, market participants can express their heterogeneous valuations for electricity (related to the energy source for example) in order to facilitate the trading of locally generated renewable electricity. The bilateral contract agreements result in individual price arrangements, which significantly differ from market-based equilibrium prices such that social welfare maximisation and the overall matching of all orders cannot be guaranteed in this mechanism. An advantage of this decentralised mechanism is that the privacy and autonomy of the market participants are ensured [126], however, the mechanism inherently requires user participation which can be a non-trivial process associated with high opportunity costs [76].

System-determined mechanisms are a form of non-participative mechanisms in which the market operator establishes prices on the basis of mathematical formulas or mechanisms. The market operator can for example be a DSO, local retailer or community manager. The market participants are charged or paid on the basis of the quantity of electricity they feed in or out of the grid, for either a fixed or dynamic price. In this mechanism, there is no active trading and the market participants do not submit bids and offers [18]. System-determined mechanisms typically allow for a conceptually simplistic and time-efficient mechanism that is relatively understandable for the end-consumer as compared to the more demanding mechanisms such as auctions and negotiation-based mechanisms. In general, the system-determined mechanisms can be further classified in Fixed and predetermined mechanisms, Optimisation and Game-theory based mechanisms and demand-based mechanisms based on their nature of operation [18].

Examples of Fixed and predetermined mechanisms are cost+ pricing, in which the price for electricity is determined on the basis of the costs of exploiting renewable energy assets with a markup for operating the assets, as applied in the Local4Local initiative [77]. In these mechanisms, the end-user pays up to a limit or per unit and the mechanism is relatively simplistic and well-understandable for the end consumer.

Optimisation and Game theory-based mechanisms are also system-determined mechanisms that can be applied when there is strategic behaviour from the market participants, and in general, two types of game theory can be identified: cooperative and non-cooperative game theory. In cooperative game theory, market participants cooperate in order to find an equilibrium that maximises the collective benefits or social welfare distribution. Non-cooperative game theory alternatively facilitates competitive behaviour between market participants that seek to optimise their own benefits [20]. Game theory can result in a maximisation of social welfare, but is subject to scalability issues when large amounts of data and uncertain human-decision factors are incorporated, which affects real-world scenario's in which not all human behaviour is rational and an increasing amount of DERs are implemented with uncertain behaviour (related to production for example). Next to that, not all necessary information necessary for the operation of optimization and game theory-based mechanisms might be available in real-world applications, contrary to auctions in which market participants engage in information revelation through the necessary submission of bids and offers.

Demand-based mechanisms are for example time-of-use pricing, critical peak rate pricing, real-time rate [60] or mechanisms based on a demand function [102]. The dynamic mechanisms aim to achieve load-shifting behaviour and operate on the basis of one-way communication. As a result, there is no active negotiation with the market participants with reference to the price formation process, and no information is submitted to the central operator in the form of bids such that the operator has to estimate the response of consumers to the dynamic prices. As a result, demand-based system-determined mechanisms are relatively simplistic to implement but are no efficient mechanism to balance supply and demand in the market as compared to market-based mechanisms [74].

In Table 2.4, a comparison of the advantages and disadvantages of the different price formation mechanisms identified in the literature review can be observed.

Table 2.4: Comparison of the advantages and disadvantages of the price formation mechanisms

Price formation mechanism	**Advantages**	**Disadvantages**
Negotiation-based		
	+ Decentralised + Privacy, autonomy + Cost-reflective + Heterogeneous valuation + Scalable	- No social welfare max. - Intimidating - Non-trivial - No single market price
Auction-based		
	+ Structured + Speed + Prevention of dishonest dealing + Information revelation + Cost-reflective + Max social welfare + Heterogeneous valuation + Scalable + Highly efficient outcomes	- Intimidating - Privacy exposure through bidding - Less autonomy
System-determined		
Fixed and pre-determined	+ Time-efficient + Conceptual Simplicity + Privacy + Scalable + Prone to manipulation	- Not participative - No detailed information for central operator - No efficient supply-demand balancing - Homogeneous preferences assumption - Low transparency
Optimisation and game theory	+Privacy + Maximise collective profits + Reflect system cost + No intimidating process (no bidding) + Optimise for social welfare/ + Optimise for Fairness + Efficient supply-demand balancing	- Low transparency - Scalability is limited - Not participative (representation by software agents) - No information revelation - Computational cost - Strategic behaviour - Assumption of rational human behaviour - Conceptually complex
Demand-based	+ Time-efficient + Conceptual Simplicity + Reflect system-cost + Steer demand (improve reliability) + Privacy + Scalable	- Not participative - No detailed information for central operator - No efficient supply-demand balancing - Homogeneous preferences assumption - Low transparency

Chapter 3

Methodology

In the paper 'Challenges for large-scale Local Electricity Market implementation reviewed from the stakeholder perspective' [29], it was found that simulations and pilots have proven the potential of local electricity markets (LEMs). However, there are still challenges for the large-scale implementation of LEMs. These challenges can be explained by the gap between LEM research and large-scale implementation, as it is essential to incorporate stakeholder perspectives in designing LEM market structures. These perspectives may be overlooked in controlled simulation- or pilot environments as used in LEM research [29]. In this thesis, stakeholder involvement will play a crucial role in identifying the definition of 'suitable' in the context of price formation mechanisms in a LEM. The methodology for stakeholder involvement is Multi Criteria Mapping, through which different stakeholder perspectives can be mapped. After completing the Multi Criteria Mapping process, the mechanisms will be assessed on their quantitative performance in a real-life case study simulation. Through a mixed methods approach, consisting of both quantitative and qualitative methods, a combination of methods will be applied to answer the research questions.

3.1 Literature review

The literature review is applied to evaluate sub-question 1, answered in Chapter 2, discussing Electricity Markets: Reform and Local Electricity Markets. The literature review is conducted using the academic search engine Scopus. Key articles are identified, and further literature research will be conducted using the citations within these articles. In Appendix A, the keywords used in the literature research are listed. The keywords are derived from the leading research question and sub-question 1, as described in section 1.3.

3.2 Multi Criteria Mapping method

Multi Criteria Mapping is a method developed by Stirling at the University of Sussex [87]. Through Multi-Criteria Mapping, not specifically a 'best' solution is identified. However, different perspectives are mapped for comparing project options and criteria for these options [50]. Thereby, technical, social and economic aspects of a specific option, in this case, price formation mechanisms for LEMs, can be mapped out using the perspectives of relevant stakeholders. MCM was developed with the core purpose of 'opening up' and 'unpacking' diverse concepts and discussions, thereby differentiating itself from methods such as a cost-benefit analysis (CBA) or multi criteria decision analysis (MCDA) in which the debates concerning the best course of action for a specific solution are 'closed down' [111]. As described in [29], to overcome challenges in the large-scale implementation of LEMs, involving stakeholders in the process of designing LEMs is crucial for allowing broader market participation and overall success, such that 'opening up' the discussion of pricing mechanisms for LEMs through MCM allows for a fitting approach to the research goal.

In the MCM, first, a **focal goal** is defined (1), being a 'broadly shared societal aim, function, quality, or value that it is the purpose of the appraised 'options' to address' [22][p.74]. In this thesis, the focal goal can be defined as: *what is the optimal pricing mechanism for local electricity markets?* After setting the focal goal, **core options** should be identified (2) [111]. The options will be identified in the literature review and consist of the different price formation mechanisms that will be evaluated. After identification of the core options, stakeholders will be identified (3) for the interviewing process [111]. The stakeholders should 'appraise' the different options from their different perspectives, relating to the optimal way to achieve the focal goal [23].

In the MCM interview, stakeholders appraise the different core options but are also able to add **discretionary options** to the list of options (4). After appraisal of the options, the different stakeholders create a set of **criteria** for the different core options [111], in which: 'the criteria are the different factors that the interviewee has in mind when they choose between, or compare, the pros and cons of different options' (5). [23][p.32]. After formulation of the criteria, the stakeholders score the relative **performance** of the criteria against the options (6). The performance scoring can be conducted using a scale from 1 to 10, with higher scores resembling a more optimal performance. Stakeholders can also indicate **uncertainty**: during performance scoring, stakeholders submit both an optimistic and a pessimistic score (7), thereby capturing a degree of uncertainty in the scoring. After performance and uncertainty scoring, stakeholders weigh the relative importance (8) of the different criteria [111, 50]. After completion of the interviews, the MCM software computes a 'mapping' (9) of the ranking of the different project options using the weighted sum method, thereby producing a visual representation of the criteria and their weighting such that the stakeholder can approve of the procedure [111]. In Figure 3.1, the procedure for the multi criteria mapping is visualised [101][p.584].

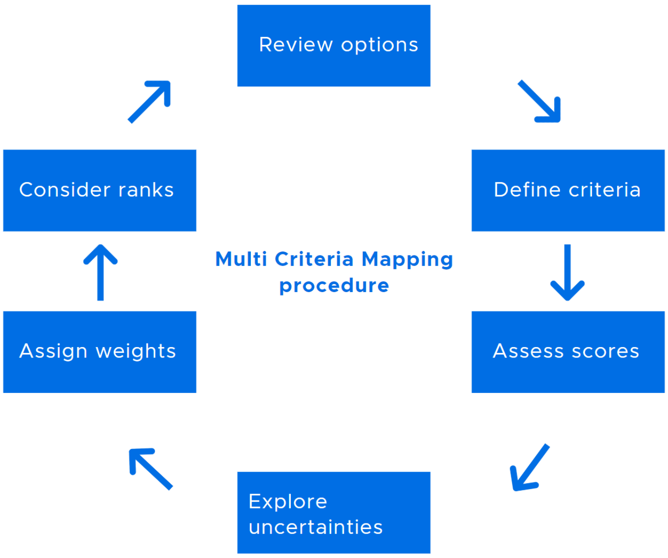

Figure 3.1: The methodological procedure of multi criteria mapping [101][p.584]

3.2.1 Stakeholders

For the MCM interviews, a number of stakeholders were identified for an interview. The goal of the stakeholder selection process was to establish a diverse and complete group of actors that can provide different insights and feedback on price formation in Local Electricity Markets. The stakeholders were identified based on their working sector and the basis of their expertise related to the thesis subject. The goal of the stakeholder selection process was to obtain pluralistic views to get as robust and valid an assessment as possible, and therefore actors from different disciplines were approached. After the selection of the stakeholders, the stakeholders were contacted and informed about the research.

The stakeholders were invited for a voluntary interview, which was organised online using Microsoft Teams or at a physical location. The interviews typically lasted between 60 and 120 minutes and, on average, 90 minutes. The stakeholders were grouped based on their perspectives, which is also possible within the MCM software. The following perspectives were defined: public sector, cooperative sector, private sector, network operators, market and academic. In Figure 3.2, the mapping of the stakeholder perspectives and the stakeholders within the perspectives can be observed.

- **Public Sector**: Perspective based on institutions from the public sector that serve the interests of the public with no commercial interest.

- **Cooperative Sector**: Perspective based on institutions from the cooperative sector, such as energy communities, energy cooperations or representative (umbrella) organizations.

- **System Operators**: Perspective based on institutions from the field of system operators, such as network companies, system operators or representative (umbrella) organisations.

- **Market**: Perspective based on market-based institutions.

- **Academic**: This perspective is based on academic institutions and includes researchers from various academic institutions.

Table 3.1: Stakeholders interviewed in the MCM interviews and their perspective

Code	Stakeholder	Perspective
A	Umbrella Organisation for energy cooperatives	Cooperative Sector
B	Dutch Network Company	System Operators
C	Dutch DSO	System Operators
D	Umbrella organisation for Dutch DSO's & System Operators	
E	Public Institution	Public Sector
G	Wholesale Market institution	Market
H	Academic	Academic
I	Energy Cooperative	Cooperative Sector
J	Academic (Economics Department)	Academic
K	Academic (Energy Justice Department)	Academic
L	Market Party	Market

3.2.2 Core options and criteria

The following core options and core criteria were identified for the MCM interview process, which are the concepts that are subject to appraisal by all the different stakeholders. The core options are identified in the literature review and consist of the following price formation mechanisms: auction-based mechanisms, negotiation-based mechanisms and system-determined mechanisms. The core options and their definitions can be observed in Table 3.2.

Figure 3.2: The mapping of the stakeholder perspectives and the stakeholders within the perspectives

Table 3.2: Core options

Core Options	**Description**
Auction-based mechanisms	Well-specified negotiation mechanisms in which market participants submit bids and offers and the market is cleared at the intersection between demand and supply.
Negotiation-based mechanisms	One-to-one interaction between market participants that result in a mutually agreed upon bilateral contract consisting of both price and quantity specifications.
System-determined mechanisms	Mechanism in which a market operator establishes prices on the basis of pre-defined mathematical formulas or mechanisms.

In addition to defining the core options, also core criteria were identified for the appraisal process. Consequently, all stakeholders will evaluate the core options on the core criteria. The core criteria can be observed in Table 3.3.

Table 3.3: Core criteria

Core Criteria	Description
Data privacy and security	How does the mechanism ensure the protection of sensitive data that is necessary to operate the mechanism? Data privacy and security is crucial for the operation and acceptance of the mechanism.
Transparency	Does the mechanism facilitate transparent price formation? Transparency is crucial for the involvement of the market participants in the price formation process, such that, for example, the working principles and underlying formulas are disclosed.
Participation	Does the mechanism allow for the participation of the end-consumer in the price formation process? Through participation, decentral market participants can participate in the establishment of LEM prices through interaction with other market participants.
Fairness	Is the mechanism perceived as fair by the market participants? Fairness is crucial for the uptake of the price formation mechanism in a LEM as it can impact the welfare of the participants and the overall transparency and trust in the market.

3.2.3 MCM Results presentation

The Multi Criteria Mapping process results will be visualised using box plots. The box plot is used to visualise the dispersion and skewness of a data set, using the smallest observation, first quartile (Q1), the median (second quartile (Q2)), third quartile (Q3) and the largest observation. The area between the first and third quartile is noted as the interquartile range (IQR), which is the area that covers 50% of the observations close to the median value and also gives an indication of the spread of the data. The whiskers connect the interquartile range with the largest or smallest values in the dataset that are outside the middle 50% range and indicate the dispersion of the data [79]. In Figure 3.3, the structure of a box plot can be observed [79].

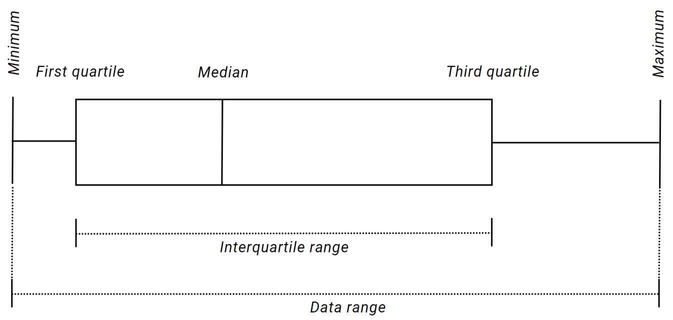

Figure 3.3: the structure of a box plot [79]

3.3 Simulation

The simulation of the price formation mechanisms will be conducted using LEMLAB and PyMarket. LEMLAB is a multi-agent-based, open-source tool for simulating local energy markets, in which different market-clearing algorithms and pricing mechanisms are available. The Python-based tool has been used in different studies related to local energy markets, for example in studying new auction-based clearing algorithms for community-based local energy markets [124]. Python is a cross-platform and open-source programming language, that has experienced an increased rate of popularity over the last years. The first release of the programming language was in 1991 and it can currently be used for a range of applications such as simulations, calculations and scientific computing. Furthermore, the Python programming language has been widely used for the simulation of (local) electricity markets and clearing mechanisms. The LEM was simulated in LEMLAB after which the generated bids and offers were cleared with the three price formation mechanisms in a separate Python notebook. In Chapter 5, the methods as applied in the simulation, set-up of the case study and performance metrics will be further discussed.

Chapter 4

Results

4.1 Multi Criteria Mapping Results

In this section, the results of the MCM interviews will be discussed. The stakeholders are grouped by their perspective, as is elaborated on in Table 3.1. In Appendix B, the individual scoring of the mechanisms on the core and discretionary options and the specific stakeholder are described. This section is based on the aggregated scores, and for further inspection of the individual scores, it is advised to inspect Appendix B. In Appendix C, the definitions for all introduced discretionary criteria are listed. The results will be discussed per perspective, in which, first, the overall scoring will be evaluated, followed by specific scoring of the criteria per mechanism.

4.2 Network Operators

Overall Scoring

The network operator's perspective is based on the perspectives of three stakeholders from this field. namely Stakeholder B, Stakeholder C and Stakeholder D. In Figure 4.1, the results can be observed for the scoring of the core options by the stakeholders from the network operator's perspective. It can be observed that the uncertainty, or level of agreement, varies over the three mechanisms. Generally, the stakeholders scored system-determined mechanisms in a broader range than auctions and negotiation-based mechanisms. This observation can be explained by the fact that system-determined mechanisms encompass a wider range of sub-mechanisms, as indicated by the stakeholders, and are subject to more considerable uncertainty in the scoring process. Consequently, the interquartile range is the largest for system-determined mechanisms (37.03), followed by negotiation-based mechanisms (30.94) and auctions (25.22). The median score of system-determined mechanisms is also the highest (56.26), followed by auctions (50.78) and negotiation-based mechanisms (48.95). System-determined mechanisms also showed a larger spread between the ends of the two whiskers, as the data distribution is wider. Negotiation-based mechanisms follow the system-determined mechanisms in the spread between the two extremes of the whiskers, and auctions have the smallest spread between the minimum and maximum values.

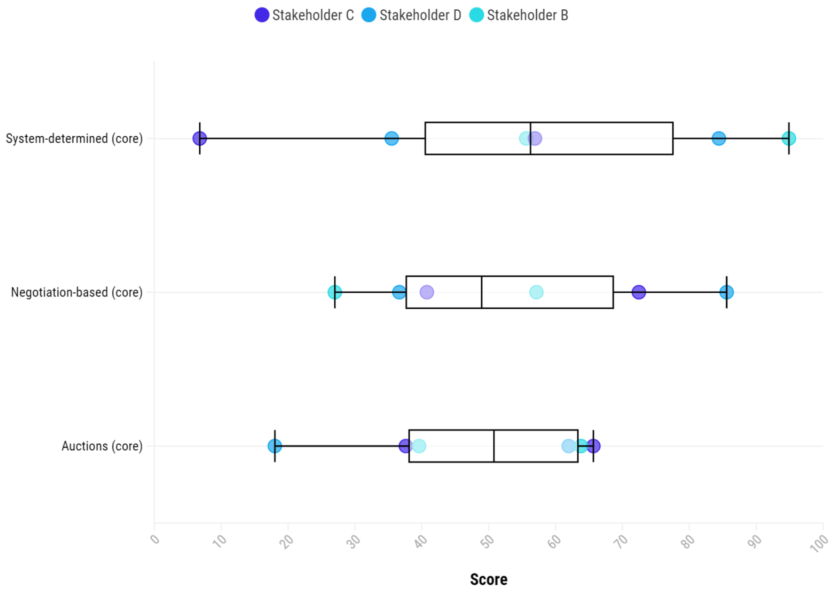

Figure 4.1: MCM Results for Network Operators perspective

Core criteria scoring

In Figure 4.2, the individual average scoring of the core criteria for the three mechanisms can be observed. In general, the stakeholders scored auctions and system-determined mechanisms high on Data Privacy and security, whilst they saw a trade-off in the criterion for negotiation-based mechanisms. The stakeholders also agreed on scoring the Participation criterion for Auctions and Negotiation-based mechanisms. There was more uncertainty in the scoring of Participation for the system-determined mechanisms as the stakeholder from Stakeholder D indicated that system-determined mechanisms allow for more indirect (responsive) participation of the market participants in price formation as compared to the other two mechanisms subsection B.1.2. As for Fairness, Stakeholder D and Stakeholder B scored the mechanisms similarly on the criterion, whilst the stakeholder from Stakeholder C indicated that auctions allow for a relatively fair price formation process as market power could be mitigated, whilst negotiation-based mechanisms are more sensitive to market power abuse due to strong bargaining positions from market participants and Fairness in system-determined mechanisms depends on the implementation of the specific system-determined mechanism. Stakeholder D and Stakeholder B also scored the three mechanisms similarly on Transparency. Stakeholder D indicated that auctions are a relatively transparent mechanism for price formation as the process is well understandable for the market participants. Negotiation-based mechanisms scored lower on Transparency as the stakeholder indicated that the negotiation process is less structured and transparent than an auction. Lastly, system-determined mechanisms scored well on Transparency as the mechanisms or formula used in the mechanism should be published and understandable to allow for a transparent price formation process subsection B.1.2. Stakeholder C also indicated that auctions could allow for transparent price formation; however, in negotiation-based mechanisms, information revelation is crucial in the price formation process as this is crucial for establishing a bilateral contract. The stakeholder indicated that system-determined mechanisms could become a 'black box' when the operating principles of the mechanism are not disclosed, and therefore scored the mechanism low on the criterion subsection B.1.1.

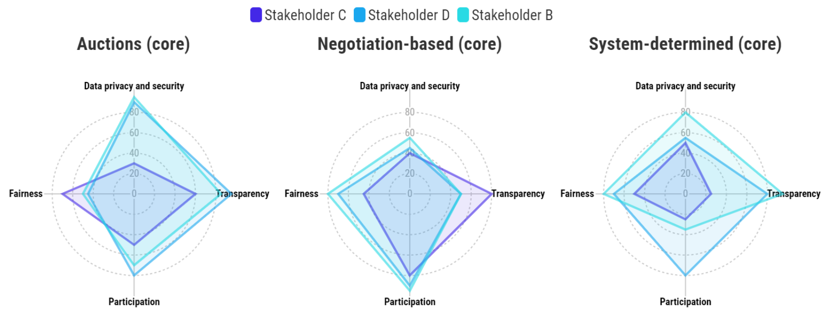

Figure 4.2: Criteria scoring for Network Operators perspective

Core criteria weighting

In Figure 4.3, the weighting of the criteria by the stakeholders from the Network Operators' perspective can be observed. The stakeholders agreed on assigning the lowest weighting to the Data Privacy and Security criterion. Stakeholder D and Stakeholder C weighted the Transparency criterion as second-lowest, whilst Stakeholder B weighted the participation criterion as second lowest. Stakeholder D and Stakeholder C scored participation as the second-most important criterion, while Stakeholder B weighted Transparency as the second-most important criterion. From the Network Operators' perspective, all stakeholders weighted Fairness as the most important criterion.

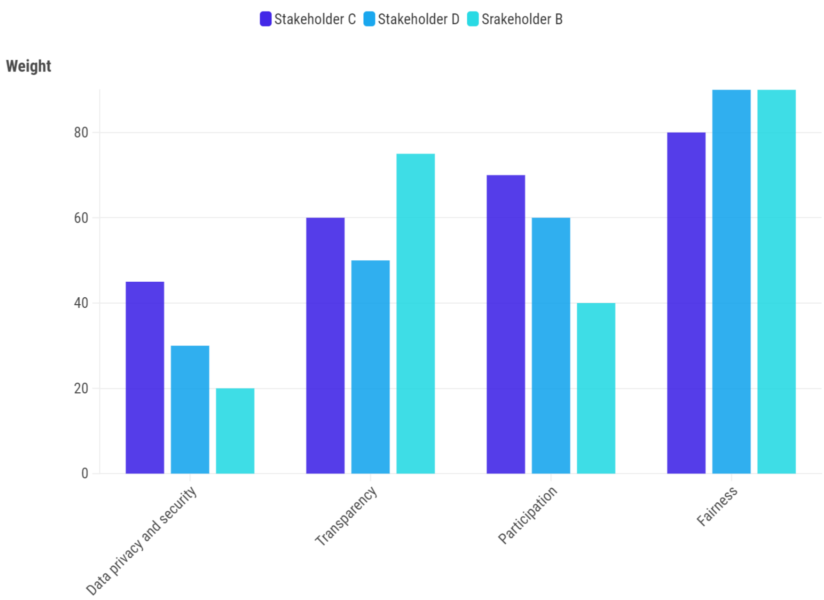

Figure 4.3: Criteria weighting for Network Operators perspective

Discretionary criteria scoring and weighting

In Figure 4.4, the discretionary criteria scoring weighting for the Network Operators' perspective can be observed. The size of the dots represents the criteria weights on a scale from 1 to 100, and the horizontal axis is the average score of the bar on the different mechanisms. The stakeholders introduced five discretionary criteria: Efficiency (matching), Prevention of dishonest behaviour, Decentralisation, Effort and Multidimensionality. The system-determined mechanisms, in general, scored the highest on the introduced criteria, followed by negotiation-based mechanisms and, lastly, auctions. Auctions performed especially poorly on the Prevention of Dishonest Behaviour from the stakeholder's perspective as market participants have more freedom and less control in the price formation process subsection B.1.2. As for the maximum score, the system-determined mechanisms scored well on the Effort criterion. The stakeholder indicated that this mechanism is less effort-intensive as the mechanisms can operate without too much end-user participation by definition subsection B.1.3.

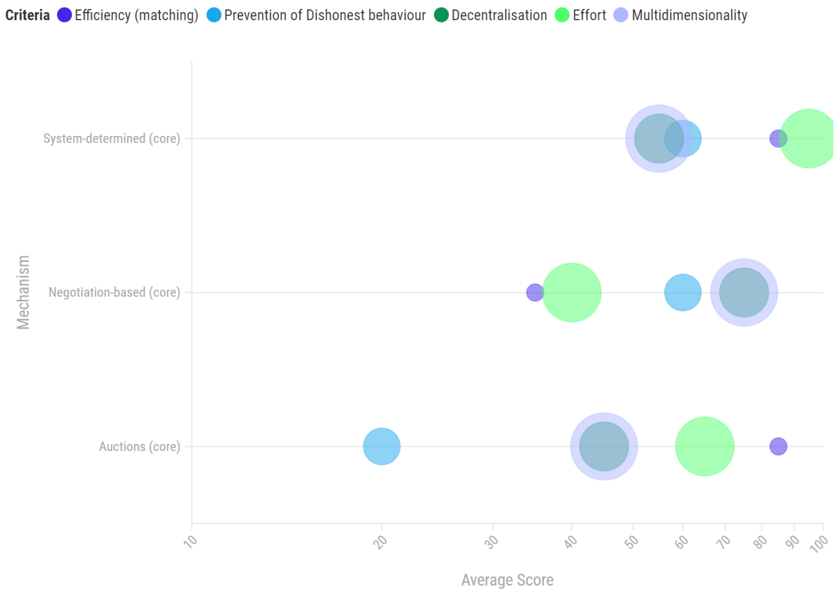

Figure 4.4: Discretionary criteria scoring weighting for Network Operators perspective

4.3 Public Sector

Overall Scoring

The public sector perspective is based on input from a single stakeholder, Stakeholder E. In Figure 4.5, the final scoring results on the core options from the Public Sector perspective can be observed. In general, the interquartile ranges for the different mechanisms are relatively similar for the three mechanisms, with system-determined mechanisms having the lowest dispersion of data (13.42), followed by auctions (15.76) and negotiation-based mechanisms (16.86). The whiskers of the plots show a similar uncertainty in the ranges over the three different plots, as only the data from a single stakeholder is incorporated in the perspective. As for the medians, the auctions score the highest in the perspective (60.29), followed by the system-determined mechanisms (51.38) and negotiation-based mechanisms (33.52).

Core criteria scoring

The criteria as assessed by the stakeholder can be observed in Figure 4.6. Auctions also performed well on the Fairness criterion, as auctions establish price formation in a market based-manner, whilst negotiations do not necessarily always result in fair market outcomes due to for example strong or weak bargaining positions. System-determined mechanisms were assessed as 'fair' as the system could optimise for the fairest price for the end-consumer and no bargaining power could affect the price formation process. The stakeholder saw limitations in the Transparency criterion for auctions, as the mechanism does not operate in a conceptually simplistic manner

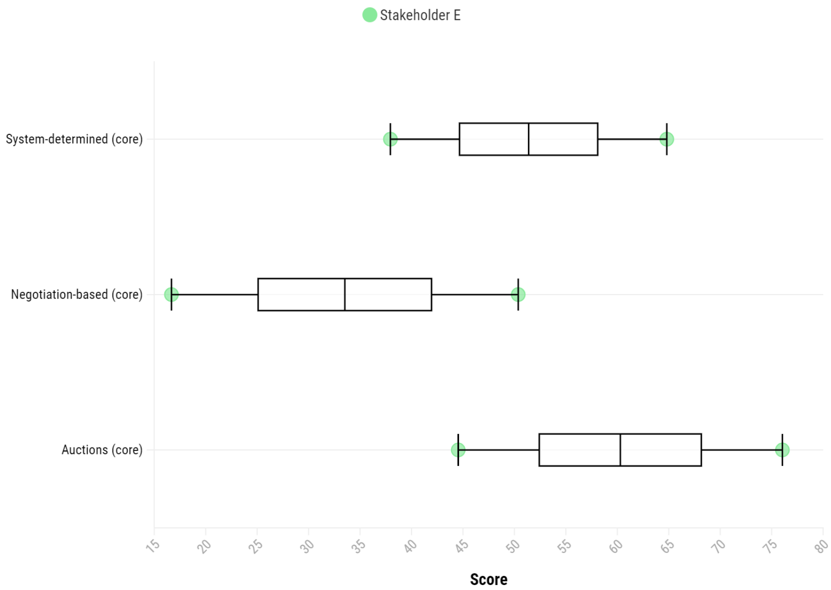

Figure 4.5: MCM Results for Public Sector perspective

for the end-consumer, whilst the negotiation-based mechanism could provide more transparency in the price formation process and into the counter-party, which is not necessarily known in auctions. System-determined mechanisms could provide transparent price formation, as long as the mechanism or formula is disclosed for the end consumer. As for the Participation criterion, the stakeholder saw no practical participation of the end-consumer in the price formation process in auctions as active participation in auctions is more a 'theoretical' concept, and less feasible from a practical perspective. Negotiation-based mechanisms allow for participation in the price formation process from the market participants, for example in the form of bargaining. System-determined mechanisms do not allow for active participation of the market participants in the price formation process by definition and scored lower on the Participation criterion. The last criterion that was subject to evaluation was Data Privacy and Security, the stakeholder envisioned that auctions would operate on the basis of aggregated data, which allows for maintaining data privacy and security. A negotiation-based mechanism requires information revelation of the parties involved in the transaction by definition, however, the information is typically kept between the two transacting parties. System-determined mechanisms allow for price formation on the basis of aggregated, anonymous data and information such that it allows for price formation that respects data privacy and security subsection B.2.1.

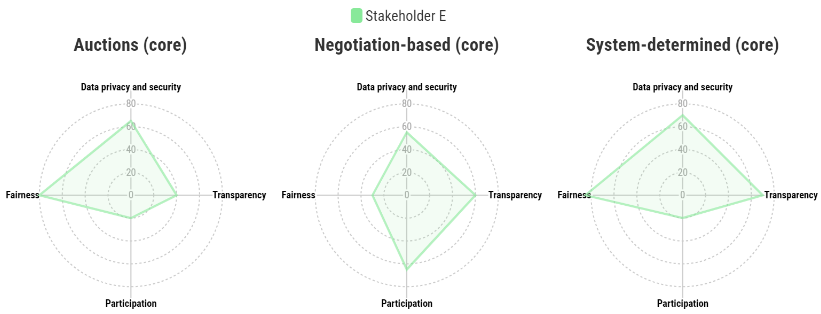

Figure 4.6: Criteria scoring for Public Sector perspective

Core criteria weighting

In Figure 4.7, the weighting of the criteria by the stakeholder from the Public Sector's perspective can be observed. The stakeholder from Stakeholder E weighted Participation as the least important, followed by Transparency. The stakeholder weighted Fairness as the second most important and Data Privacy and Security as the most important criterion.

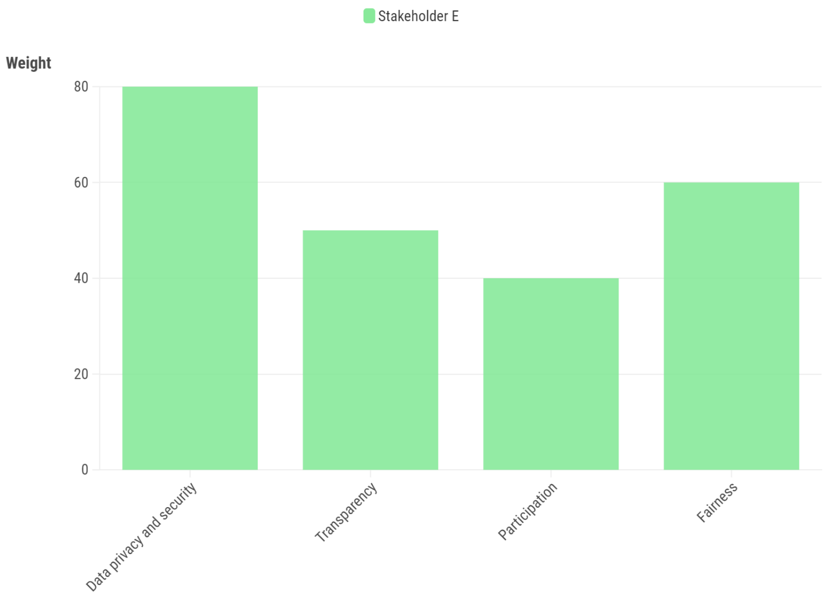

Figure 4.7: Criteria weighting for Public Sector perspective

Discretionary criteria scoring and weighting

Only one discretionary criterion was introduced by the perspective of the public sector, Non-discriminatory: the different market participants should not be discriminated against in the price formation process. In auctions, discrimination between market participants is not possible due to the equal bidding structure in the auction process in which no preference for the matching procedure can be incorporated. The stakeholder mentioned that negotiation-based mechanisms are not in line with the procedure of tenders as market participants can be selected for the bilateral contracts, which is not in accordance with the non-discriminatory characteristics of tendering procedures. System-determined mechanisms do also not meet Non-discriminatory aspects as the mechanism also appoints a single party for setting the price and there is no objective selection process.

4.4 Market

Overall Scoring

The perspective of the market institutions is based on the individual perspectives of two stakeholders such as Stakeholder L (construction-services business) and the wholesale market (Stakeholder G). Both stakeholders evaluated the mechanisms from a market-based perspective, and in Figure 4.8 it can be observed that there are differences in the spread of the data for both stakeholder evaluations. In general, the stakeholder from Stakeholder L assessed the mechanisms with a broader uncertainty as compared to the stakeholder from the Wholesale Market. As a result, the whiskers of the box plots are for the negotiation-based mechanisms and auctions determined by the minimal and maximal scores of the stakeholder from Stakeholder L, whilst the maximum score (right whisker) for the system-determined mechanism is set by the stakeholder from the Wholesale Market. The interquartile range for the system-determined mechanisms is the smallest (23.64), followed by auctions (35.58) and negotiation-based mechanisms (36.72). As a result, the dispersion of the data is the smallest for system-determined mechanisms and the largest for negotiation-based mechanisms. The median is the highest for the system-determined mechanisms (54.30), followed by the auctions (51.61) and negotiation-based mechanisms (49.47).

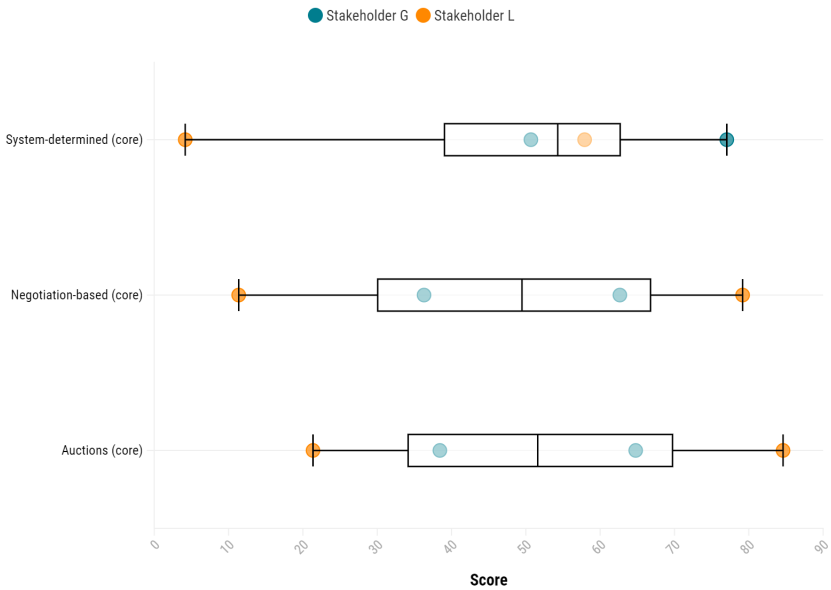

Figure 4.8: MCM Results for Market perspective

Core criteria scoring

The criteria as scored by the stakeholders from the Market perspective can be observed in Figure 4.9. In general, the scoring patterns for the negotiation-based mechanisms and system-determined mechanisms are relatively similar, whilst the magnitude of scoring differs for the system-determined mechanisms. As for the fairness criterion, the stakeholder from the wholesale market indicated that in auctions, the market participants are treated equally and have the same opportunities within the market process and therefore the mechanisms could be perceived as relatively fair. Negotiation-based mechanisms are more sensitive to market power issues as the market size is more relevant in this mechanism, related to negotiation power. The stakeholder indicated that in theory, all market participants should have equal opportunities. The stakeholder scored system-determined mechanisms high against Fairness, as the mechanism is not based on market forces and therefore is not subject to risks related to market power or low liquidity in the market subsection B.4.1. The stakeholder from Stakeholder L assessed the mechanisms on the same basis for Fairness, also adding that negotiation-based mechanisms allow for the freedom by the market participants to influence the price formation process and thereby achieve fair prices from their perspective, however, the mechanism is also more sensitive to market power subsection B.4.2. The stakeholders also scored the mechanisms similarly on Participation. The stakeholder from the Wholesale Market saw issues with participation in auctions due to the complexity of the mechanism. As a result market participants with less expertise face an entry barrier and might therefore not be able to participate on a 'levelled playing field' in the price formation process. In negotiation-based mechanisms, the stakeholder indicated that it is possible to actively participate in the price formation process, as the process is less complex as compared to auctions. As system-determined mechanisms allow for a less complex price formation process according to the stakeholder, participation is accessible because there is no information barrier in this mechanism, as you are a price taker (participation in the market) subsection B.4.1. The stakeholder from Stakeholder L indicated similar concerns for auctions, as he stated that auctions allow for participative price formation as long as there are no entry barriers to placing bids in the auction, for example, households should bid a minimum of 10 kWh in order to engage in trading in the auction (who will set the rules for trading in an auction). As a result, both stakeholders saw entry barriers with regard to participation in auctions. Also for system-determined mechanisms, the stakeholder from Royal BAM group noted that the mechanisms allow for more indirect participation in the price formation process, as market participants are more dependent on the auctions of other market participants for the price setting subsection B.4.2. The stakeholders also agreed on the scoring of the Data Privacy and Security criterion, with the stakeholder from the Wholesale Market indicating that centrally operating mechanisms allow for more secure as compared to negotiation-based mechanisms, whilst the stakeholder from Royal BAM group noted that system-determined mechanisms may require more data to operate, which could make the mechanism more vulnerable. The last criterion that was assessed by the stakeholder was Transparency, in which the scoring differed. The stakeholder from the Wholesale Market noted that auctions are typically not considered as a transparent process by the market participants as the process is difficult to understand for the average market participant. Negotiation-based mechanism are typically no transparent process for price formation, as the process is a 'black box' for the other market participants. The stakeholder scored system-determined mechanisms high on Transparency as the stakeholder indicated that the mechanism is not dependent on market forces and the mechanisms are published for the market participants subsection B.4.1. The stakeholder from Stakeholder L indicated that auctions allow for transparent price formation, for example when the market participants have insight into the trading order book. Negotiation-based mechanisms were scored lower on the transparency criterion by the stakeholder as the price formation process is not transparent for third parties that are not involved in the trading process, these market participants are not able 'to inspect the negotiation room' as indicated by the stakeholder. The stakeholder scored system-determined mechanisms between the auctions and negotiation-based mechanisms as the used mechanism could be experienced as a 'black box' when the mechanism is not published to the market participants, which could hinder Transparency subsection B.4.2. The stakeholders both mentioned that the system-determined mechanism should be published in order to allow the mechanism to be perceived as Transparent.

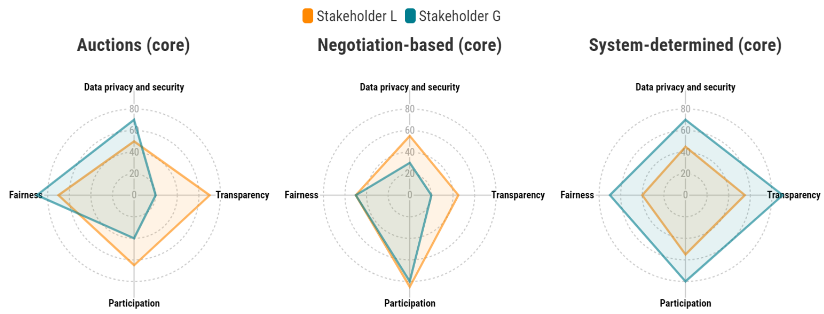

Figure 4.9: Criteria scoring for Market perspective

Core criteria weighting

In Figure 4.10, the weighting of the criteria by the stakeholders from the Market perspective can be observed. Both stakeholders weighted Data Privacy and Security the lowest, followed by Participation and Transparency. The weights for Transparency and Fairness are however the same for the stakeholder from Stakeholder L, whilst the weights for Transparency and Participation are the same for the stakeholder from the Wholesale Market. For the stakeholder from the Wholesale market Fairness is the most important criterion, whilst the same can be stated for the stakeholder from Stakeholder L in combination with the Transparency criterion.

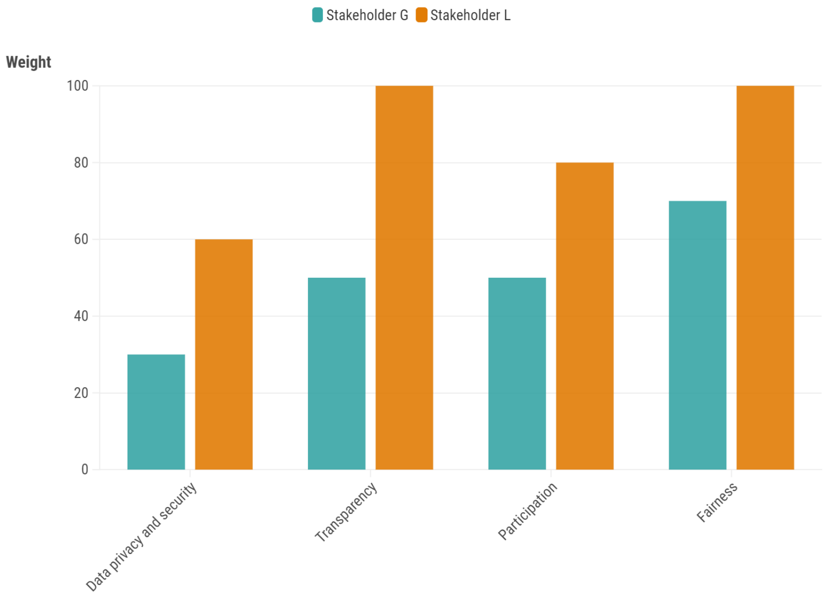

Figure 4.10: Criteria weighting for Market sector perspective

Discretionary criteria scoring and weighting

In Figure 4.4, the discretionary criteria scoring weighting for the Market sector's perspective can be observed. The size of the dots represents the weights of the criteria, on a scale from 1 to 100, and the horizontal axis is the average score of the criterion on the different mechanisms. A total of 4 discretionary criteria were introduced by the stakeholders: Trust, Operation under low liquidity, Complexity and Market Power. It can be observed that there is a large spread in the scoring of the criteria for the system-determined mechanisms and auctions, whilst the negotiation-based mechanisms show a smaller spread. The Trust criterion is scored the lowest for system-determined mechanisms and the highest for both auctions and negotiation-based mechanisms. The stakeholder indicated that under optimal market liquidity conditions, auctions allow for trustworthy price formation. Negotiation-based mechanisms were scored equally by the market participant on the criterion, as in general trustworthy price formation can be established by the mechanism under good market conditions. The stakeholder indicated that under sub-optimal market conditions (low liquidity), the price formation process in market-based mechanisms becomes increasingly untrustworthy. System-determined mechanisms are not operating under market-based conditions and were therefore characterised as less trustworthy by the stakeholder subsection B.4.1. A second noteworthy score can be observed for the Complexity criterion, in which the stakeholder indicated that auctions are typically considered as a complex process in which the underlying economic principles are difficult to understand for the average market participant. Negotiation-based mechanism operate in accordance with the 'normal way of doing business' and are in general perceived as less complex. System-determined mechanisms are not considered as complex from a market participants perspective as indicated by the stakeholder subsection B.4.1.

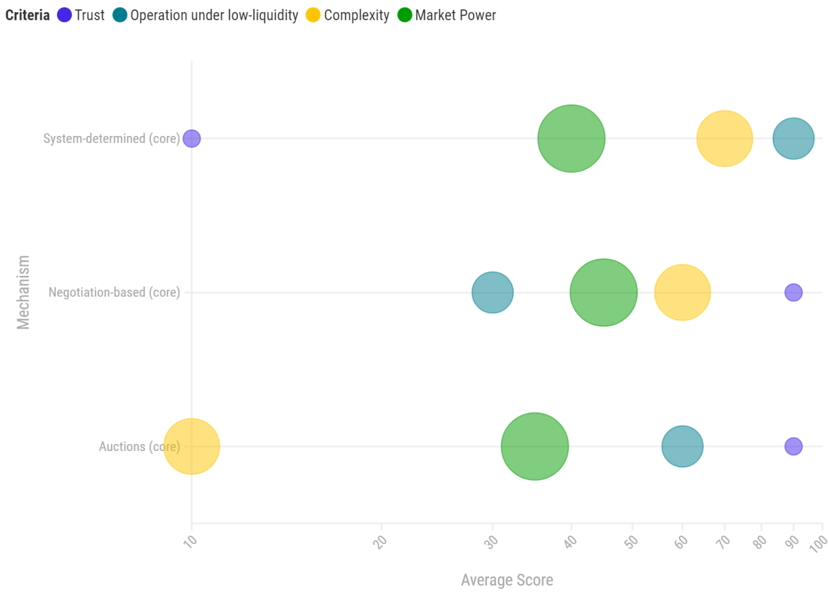

Figure 4.11: Discretionary criteria scoring weighting for Market sector perspective

4.5 Cooperative Sector

Overall Scoring

The perspective of the cooperative sector is based on the two perspectives from Stakeholder A and Stakeholder I. In Figure 4.12, the results of the scoring of the core options by the stakeholders can be observed. The interquartile range is relatively small for auctions (22.02), followed by system-determined mechanisms (44.56) and negotiation-based mechanisms (45.55). As a result, the scoring data is more dispersed in the latter two mechanisms as compared to the auctions. The overall spread between the end's of the two whiskers is the smallest for the negotiation-based mechanisms, followed by the system-determined mechanisms and auctions. The auctions show a large dispersion between the minimum and maximum scoring values, indicating the difference in scoring by Stakeholder A and Stakeholder I on auctions. The median score in the cooperative perspective is the highest for the system-determined mechanisms (68.70), followed by negotiation-based mechanisms (58.98) and system-determined mechanisms (47.89).

Core criteria scoring

In Figure 4.13, the individual average scoring of the core criteria for the three mechanisms can be observed. As was observed in Figure 4.12, there was a large dispersion in the minimum and maximum scoring for both the auctions and system-determined mechanisms. Looking at the individual scoring of the mechanisms on the core criteria, it can be observed that auctions are scored significantly different on all criterions except Data Privacy and Security. As for Data privacy and security, Stakeholder A indicated that cooperations in general have no objections to the submission of data as they operate using the principles of transparency and accountability subsection B.3.1. Similarly, Stakeholder I indicated that the cooperation will engage in the price formation activities on behalf of the cooperation and that the cooperation will ensure that the data collection process will be facilitated in a secure manner subsection B.3.2. The stakeholders also scored the negotiation-based mechanisms and system-determined mechanisms similarly on Fairness and Transparency, however the stakeholders scored auctions differently on both criterions. Stakeholder A indicated that energy is a basic need for individuals and should not be subject to the principles of market forces, which are applied in auctions (establishing an equilibrium on the basis of supply and demand)

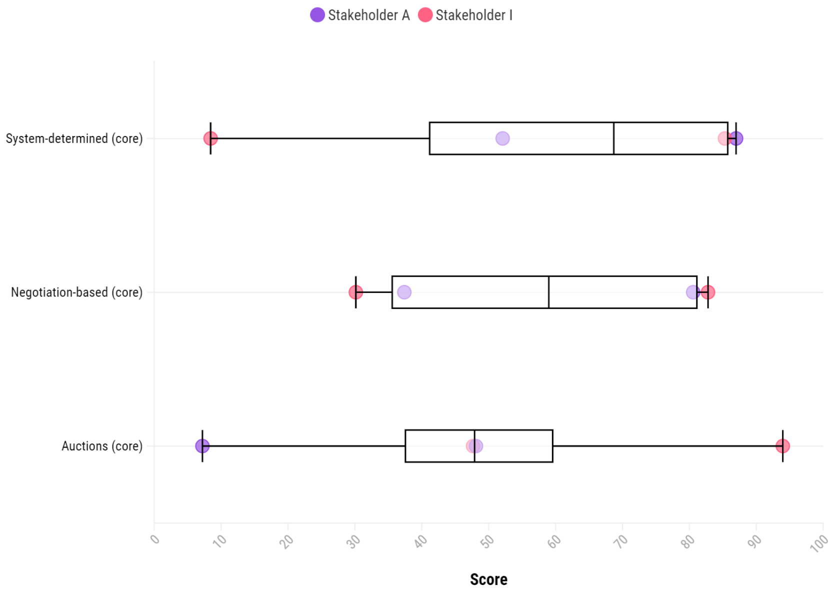

Figure 4.12: MCM Results for the Cooperative Sector's perspective

subsection B.3.1. Stakeholder I, alternatively, indicated that auctions could allow for a fair price formation process when all market participants are able to participate on a leveled playing field in the bidding process subsection B.3.2. As for Transparency, Stakeholder A indicated that auctions do not necessarily allow for transparent price formation due to the conceptually complex process, whilst negotiation-based mechanisms allow for transparent price formation as the market participants have insight in the bilateral negotiation process subsection B.3.1. Stakeholder I Scored negotiation-based mechanisms and system-determined mechanisms similar on Transparency, however, the stakeholder indicated that auctions allow for the transparent formation of prices as long of the order-book is published after the clearing period. However, it is not necessarily transparent how the market participants come to their bids and offers (do they for example use forecasts or not) in the auction process subsection B.3.2. The stakeholders also scored the system-determined mechanisms and auctions differently on the Participation criterion. Stakeholder A indicated that not all market participants have the same capacity to navigate the market, which could lead to fairness issues with regards to market forces. As a result, the stakeholder scored auctions with a large uncertainty on Participation, depending on the capabilities of the different market participants to participate in an auction. Negotiation-based mechanisms inherently allow for participation in the price formation process, whilst system-determined mechanisms typically do not allow for participation in the price formation process subsection B.3.1. Stakeholder I indicated that negotiation-based mechanisms allow for more indirect participation of market participants in the price formation process, as households are for example represented by energy cooperation in the price formation process, thereby scoring slightly lower on this criterion as compared to auctions. System-determined mechanisms typically allow for less participative price formation as a central party established a price on the basis of pre-defined formulas or mechanisms, however, when the cooperation is able to participate in selecting the mechanism, the mechanism could allow for indirect participation (thereby explaining the difference in scoring with Stakeholder A on the criterion). Auctions could allow for a participative price formation process as market participants could actively place bids as form of participation subsection B.3.2.

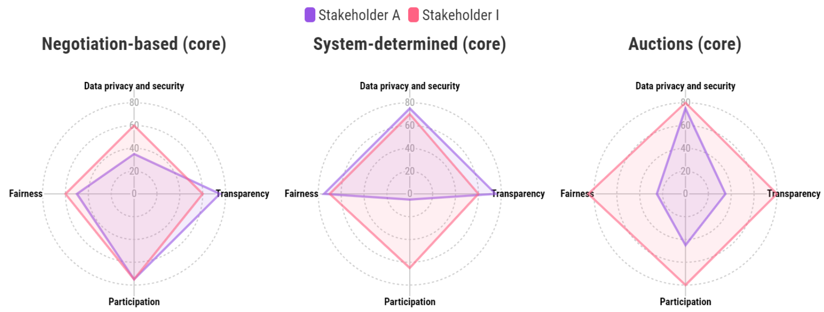

Figure 4.13: Criteria scoring for Cooperative Sector's perspective

Core criteria weighting

In Figure 4.14, the weighting of the criteria by the stakeholders from the Cooperative Sector's perspective can be observed. Both stakeholders weighted Data Privacy and Security the lowest, followed by Transparency for Stakeholder I. Stakeholder A weighted Transparency and Participation as equally important. The most important criterion from the perspective of Stakeholder A was Fairness, whilst Stakeholder I weighted both Fairness and Participation as equally important.

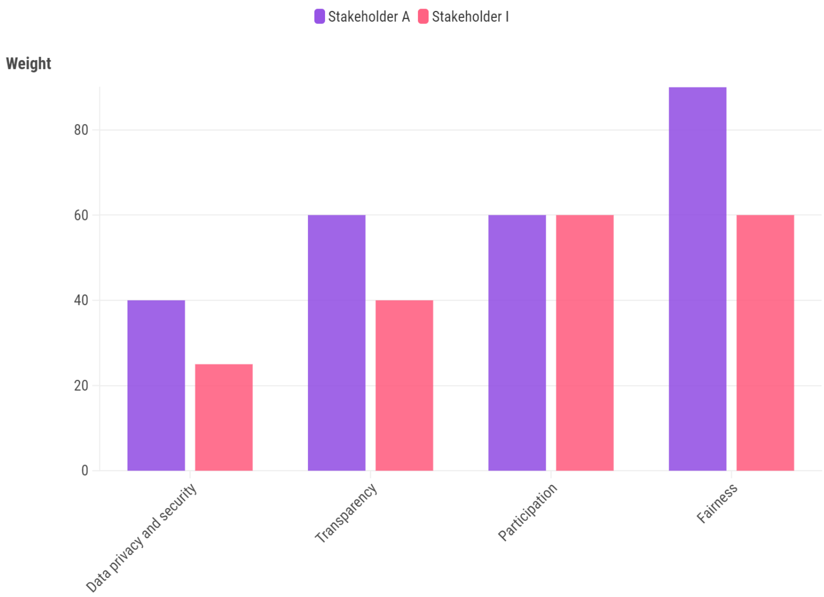

Figure 4.14: Criteria weighting for Cooperative Sector's perspective

Discretionary criteria scoring and weighting

In Figure 4.15, the discretionary criteria scoring weighting for the Cooperative sector's perspective can be observed. The size of the dots represents the weights of the criteria, on a scale from 1 to 100, and the horizontal axis the average score of the criterion on the different mechanisms. A total of 5 discretionary criteria were introduced by the stakeholders: Cost/benefit distribution, Arbitrage, Externalities Pricing, Local reflectivity and Autonomy. The spread in the scoring is the smallest for the system-determined mechanisms, followed by the negotiation-based mechanisms and auctions. Auctions scored the lowest on Cost/benefit distribution and system-determined mechanisms the highest. The stakeholder indicated that auctions allow for the application of market forces in order to establish a price for electricity, however this may not always result in a fair distribution of the costs and benefits among the market participants. In Negotiation-based mechanisms, it is possible to fairly distribute the costs and benefits over the market participants, which can be agreed upon in the negotiation process. However, the stakeholder indicated that the demand side is often in a less power full position as the supply side within the bilateral negotiation, which can lead to an unfair distribution in the costs and benefits. System-determined mechanisms allow for a fair distribution of the costs and benefits as long as the market participants have insight in the pre-defined mechanisms and it operates in a transparent and democratic manner subsection B.3.1. A similar scoring pattern can be observed for the arbitrage criterion, in which Auctions scored relatively low as the market participants operate relatively unsupervised in this mechanism. Negotiation-based mechanisms are subject to better supervision and the prevention of misconduct as in bilateral negotiations the market participants are subject to more control by the counter party. In the centrally organised System-determined mechanisms, it is in general well possible to implement arbitrage measures in the pre-defined mechanism to prevent misconduct in the market subsection B.3.1.

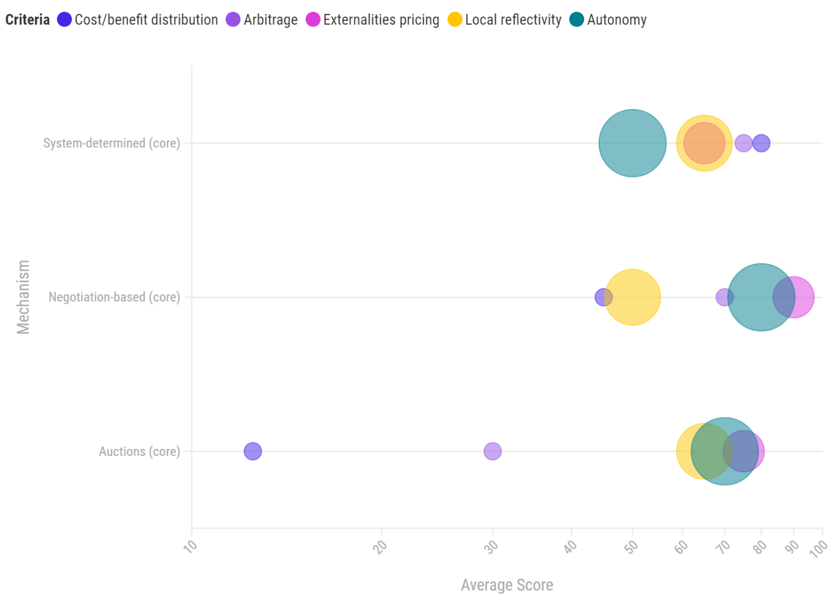

Figure 4.15: Discretionary criteria scoring weighting for Cooperative sector perspective

4.6 Academic

Overall Scoring

The perspective of the Academic sector is based on the individual perspectives of three stakeholders, stakeholder H, J and K. In Figure 4.16, the overall scoring of the stakeholders from the academic perspective can be observed. It can be observed that the median of the auction scores the highest (59.77), followed by the system-determined mechanism (43.48) and the negotiation-based mechanism (38.22). The interquartile range (box-lengths) is also the smallest for the auction (39.41), followed by the system-determined mechanism (45.75) and negotiation-based mechanism (54.87) indicating that the dispersion of the data is the smallest for the auction and largest for the negotiation-based mechanism. Lastly, the overall spread of the scoring (difference between the whiskers) is the smallest for the negotiation-based mechanisms, follwed by the auctions and system-determined mechanisms.

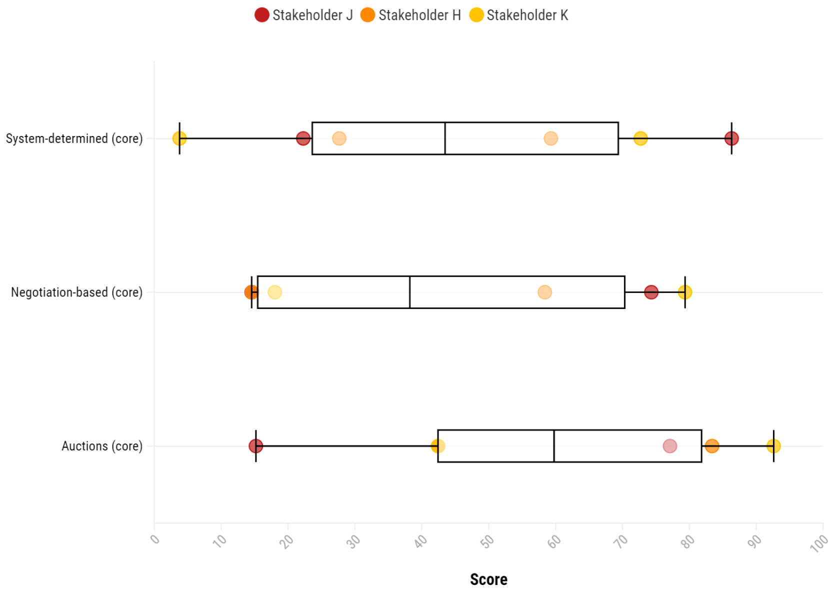

Figure 4.16: MCM Results for Academic perspective

Core criteria scoring

In Figure 4.17, the core criteria scoring for the Academic perspective can be observed. In general, the scoring patterns are relatively similar, especially for auctions. Next to that, the scoring patterns from both stakeholders J and K are also similar for the system-determined mechanisms. The stakeholders agreed less on the participation criterion, in which stakeholder H indicated that auctions allow for a participative market as market actors only have to submit bids in order to participate. In negotiation-based mechanisms more strategy and knowledge is necessary in order to navigate the mechanism, thereby hindering participation. System-determined mechanisms allow for a participative market as there is no participation barrier in the form of bidding, only information should be communicated subsection B.5.2. Stakeholder K indicated that auctions allow for participative price formation as market participants can actively place bids. Negotiation-based mechanisms are more dependent on the structure of the market for participation, for example in a less balanced market there will be less participation as market participants experience market power as deterrence. System-determined mechanisms are a one-sided mechanism and therefore allow for less participation by definition unless market participants are involved in the upfront structuring of the mechanism. In addition, it is possible that 'boards' monitor the operation of the system-determined mechanism during the usage of the mechanism within a LEM subsection B.5.3. The stakeholders also agreed less on the Transparency criterion, in which the stakeholder H noted that for auctions it depends on the bidding format. For system-determined mechanisms the stakeholder indicated that transparency is dependent on the specific type of mechanism, as some mechanisms could be experienced as black box, however, When the mechanism is opened up completely, privacy concerns could become an issue subsection B.5.2. Stakeholder A indicated that auctions allow for a transparent price formation process as in general most people understand the basic principles of an auction, although strategic bidding might be an issue. Negotiation-based mechanisms are characterised as the least transparent mechanism by the stakeholder due to the decentral nature of the mechanism. Lastly, system-determined mechanisms allow for a high degree of transparency as long as the underlying mechanism is published for the public and in general complies with conceptual simplicity subsection B.5.1.

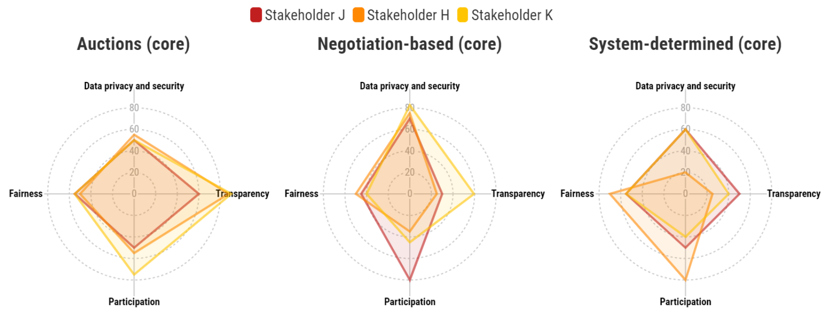

Figure 4.17: Criteria scoring for the Academic perspective

Core criteria weighting

In Figure 4.18, the weighting of the core criteria for the academic sector can be observed. The weighting by both stakeholders from Tilburg University is similar, with both weighting Data Privacy and Security as the least important criterion and Fairness as the most important criterion by stakeholder K and both Fairness and Participation as the most important criterion by the stakeholder from the economics department. Stakeholder H weighted the criteria differently, with Fairness as the least important criterion, stating that 'fairness can be addressed using external social rules that should not be incorporated in the trading mechanism' subsection B.5.2. The stakeholder weighted Transparency as the most important criterion and Data Privacy and Security and Participation as equally important.

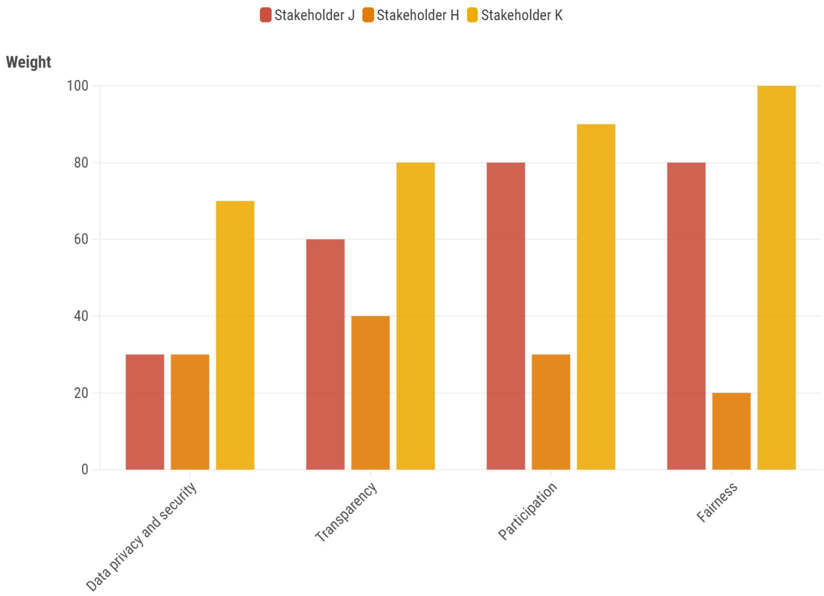

Figure 4.18: Criteria weighting for Academic Sector's perspective

Discretionary criteria scoring and weighting

In Figure 4.19, the discretionary criteria scoring weighting for Academic sector perspective can be observed. A total of 6 criteria where introduced, two by each stakeholder from the perspective: Enhance Grid Resilience, Technical Feasibility, Prone to Market Power, Economic Efficiency, Locality and Accountability. The spread in the scoring is the smallest for the auctions, and similar for the system-determined and negotiation-based mechanisms. Economic Efficiency was introduced by the stakeholder from FSR, in which the stakeholder indicated that auctions are the most economically efficient mechanism. The economic efficiency is, however, dependent on the market structure (market liquidity and a number of competitive actors). Auctions allow for different surveillance options to control the market, such as price caps. In addition, it is possible to switch to a system-determined (cost-based) mechanism when the market conditions are sub-optimal. and switch back to an auction when the market conditions are optimal. This is already possible in the US, where the system operators differ between LMP and cost-based pricing based on the conditions in the market. In negotiation-based mechanisms it is possible to leverage bargaining power and the mechanism is less transparent. Next to that the mechanism operates slowly as the result of the negotiation process. The stakeholder indicated that system-determined mechanisms operate less optimally from an economic perspective as it is not possible to compute the costs for all demand and storage technologies (such as batteries), in addition, the mechanism could work 'over-rewarding'. The mechanism should only be applied when there is no competitive market and when the costs are based on the LCOE there is no coordination subsection B.5.2. Technical Feasability was introduced by stakeholder J, in which the stakeholder indicated that there is a large communication overhead in auctions due to the bidding process. In addition, the stakeholder questioned the scalability of local auctions. In negotiation-based mechanisms, the scalability is dependent on the number of market participants involved in the trading activities and there could be a large communication overhead involved in the mechanism. System-determined mechanisms are dependent on data that should be collected within the LEM, however, there is probably no continuous clearing process such as in an auction, thereby making the mechanism more scalable subsection B.5.1. Accountability was introduced by stakeholder K for which the stakeholder indicated that the centrally operated auctions allow for accountable price formation. The negotiation-based mechanisms result in bilateral contracts that are accompanied by agreements and responsibilities, however, the mechanism is also subject to potential market power issues and information barriers. System-determined mechanisms are one-sided mechanisms that allow for less accountability as there is no input from the market side, as a result, there is one-sided price formation subsection B.5.3. Prone to market power was introduced by stakeholder H, in which the stakeholder indicated that for auctions they can be vulnerable to market power, for example with strategic bidding or withholding. Negotiation-based mechanisms are more subject to bargaining power and there is less oversight in the market clearing process, making the mechanism also less transparent. System-determined mechanisms are more prone to market power, as the mechanisms allow for regulation, however, it could be questioned who determined the regulations for the mechanisms. In addition, there is information asymmetry, which could affect the price formation process subsection B.5.2. As for Enhance Grid Resilience, stakeholder J indicated that auctions could be vulnerable to the synchronisation of prices such that sub-optimal grid conditions can occur. However, as the auction is a centralised mechanism, it is possible to oversee the implications of the auction on the grid performance. As negotiation-based mechanisms are decentral by their nature, it is more difficult to address grid resilience in this mechanism as there is no central overview. System-determined mechanisms allow for the implementation of grid constraints into the price formation process, and it is possible to prevent price synchronisation subsection B.5.1.

Figure 4.19: Discretionary criteria scoring weighting for Academic sector perspective

4.6.1 Conclusions per perspective

In Figure 4.20, the final scoring results per perspective can be observed. The following conclusions can be drawn per perspective:

- **Network Operators**: Based on the median values, the system-determined mechanism is preferred; however, there is a significant uncertainty in the scoring for this mechanism. Auctions and negotiation-based mechanisms show more agreement but narrower ranges. As a result, the stakeholders may have more aligned perspectives and more explicit expectations when it comes to auctions and negotiation-based mechanisms.

- **Public sector**: Observing the scoring of the medians, auctions receive the highest score, followed by system-determined mechanisms and negotiation-based mechanisms. All mechanisms have a similar uncertainty range, presumably as the scoring is conducted by a single stakeholder.

- **Market**: The market institutions show varying levels of uncertainty. System-determined mechanisms have the smallest range and highest median score, followed by auctions and negotiation-based mechanisms.

- **Cooperative sector**: In terms of medians, system-determined mechanisms have the highest score in the cooperative sector's perspective, followed by negotiation-based mechanisms and auctions. Due to the scoring differences between the two stakeholders, there is a large dispersion of the data. The dispersion of scoring data is higher for system-determined and negotiation-based mechanisms than for auctions, indicating the scoring uncertainty. As a result, it is difficult to appoint a preferred mechanism for the cooperative sector's perspective.

- **Academic sector**: The scoring reveals that auctions have the highest median score, followed by the system-determined mechanism and the negotiation-based mechanism. The interquartile range is the smallest for auctions, indicating less dispersion, while the negotiation-based mechanism exhibits the largest spread.

- **Total**: In the 'Total' plot, the aggregated individual results can be observed. The plot shows that the median score is the highest for the system-determined mechanisms, followed by the auction and the negotiation-based mechanism. The interquartile range is the smallest for the auctions, whilst the system-determined mechanism has a slightly smaller IQR (46.06) as compared to the negotiation-based mechanism (46.34). Overall, the results indicate that the system-determined mechanism is the most preferred mechanism, followed by the auction and negotiation-based mechanism.

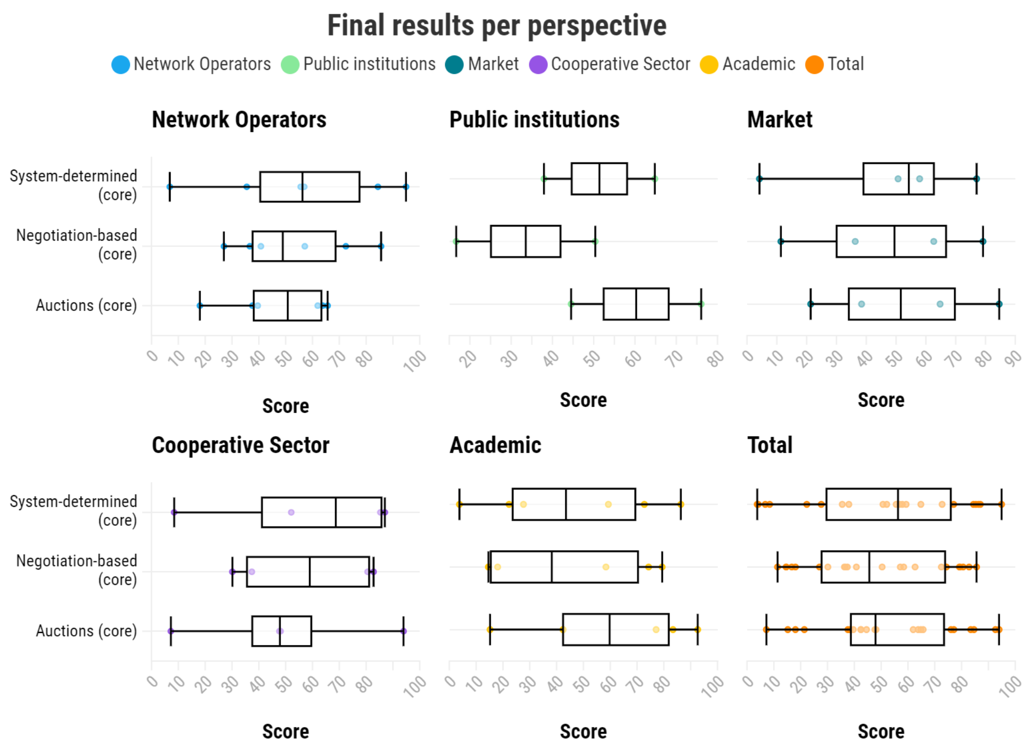

Figure 4.20: Final scoring results per perspective

In Figure 4.21, all introduced discretionary criteria can be observed. In Appendix C, the definitions for all introduced discretionary criteria are listed. The width of the Sankey flows are in proportion to the weighting by the stakeholders within the perspective, also taking the weight of the core criteria into account. A total of 20 criterion's were introduced, of which 5 were explicit of quantitative nature: cost/benefit distribution, operation under low-liquidity conditions, market power considerations, economic efficiency, and the ability to enhance grid resilience. A selection of these criteria will form the basis of a quantitative validation in Chapter 5.

4.6.2 Reflections and observations

- **Market perspective**: After completion of the MCM process, the stakeholder from the Wholesale Market indicated that auctions were the most optimal mechanism for price formation from the economic perspective. However, in Local Electricity Markets, the market conditions might not always be similar to the conditions in the wholesale market about market liquidity and the balance between demand and supply. As a result, the stakeholder indicated that system-determined mechanisms, in which price formation is not the result of market forces, might be a more fitting solution as the mechanism can provide fair and transparent prices, which was a new insight for the stakeholder that has worked with auctions

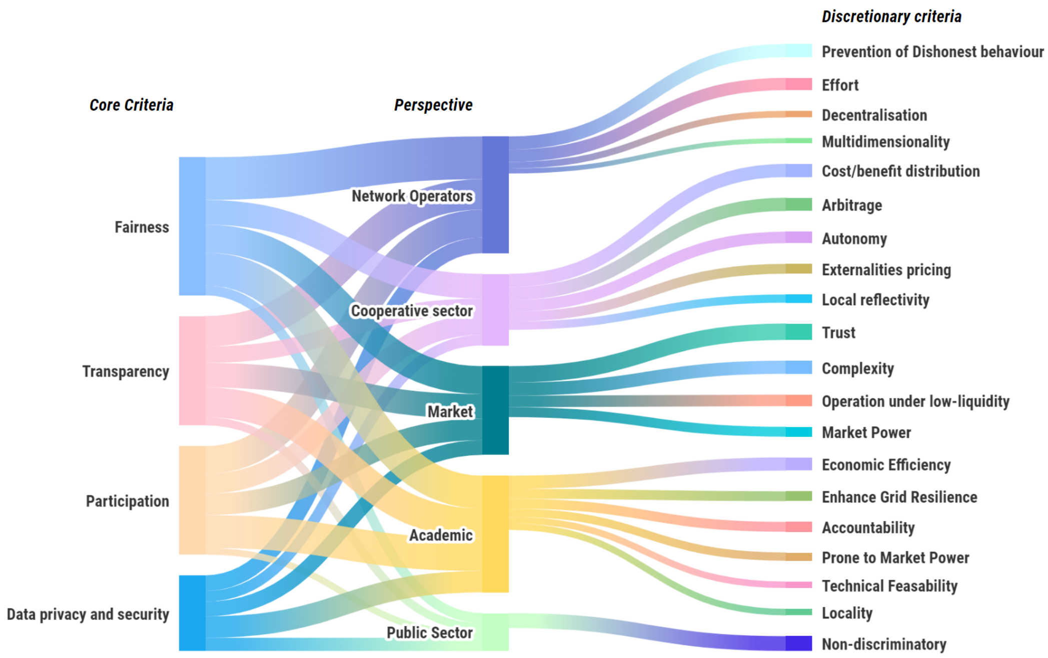

Figure 4.21: Sankey diagram for all introduced discretionary criteria by perspectives relative to their weighting

during his career in the energy sector subsection B.4.1.

- **Academic perspective**: Stakeholder H noted that auctions allow for the most ideal price formation process from an economic perspective when the market conditions allow for the optimal operation of an auction. However, when the conditions within the market are sub-optimal, a cost-based mechanism such as the system-determined mechanism could be a better solution for price formation as the operation of the mechanism is not dependent on the conditions within the local electricity market. The stakeholder indicated that a combination between an auction and system-determined mechanism based on the conditions in the market is the most optimal solution subsection B.5.2.

- **Public perspective**: Purchasing electricity by the requirements of the tender procedure is an important aspect for a public institution such as Stakeholder E. As a result of the tendering procedure, the stakeholder mentioned that the price formation mechanism should not discriminate between the different market participants in the matching process; a price formation mechanism that prioritises renewable energy production with consumption over non-renewable energy production units is an example of discrimination and unequal chances in the matching process and it not in accordance with the tendering process. As a result, the stakeholder indicated that auctions are the only mechanism that could allow for non-discriminatory price formation as the bids and offers are cleared in a non-discriminatory manner, which is in accordance with the requirements in a tender subsection B.2.1.

- **Network Operators**: In the interview, the stakeholder from Stakeholder D emphasised the difference between the economic and infrastructure valuations of electricity. The stakeholder discussed how electricity storage can benefit the network operator by reducing peak demand on the grid but cautioned that participating in balancing markets could sometimes reinforce grid peaks, conflicting with the operator's interests. To address this, the stakeholder proposed incorporating a locational component in pricing, not solely based on grid topology due to future changes. The stakeholder also advocated unrestricted electricity exchange between locations, such as Maastricht and Groningen (social dimension of energy sharing), to incentivise local energy sharing while allowing for longer distance transactions subsection B.1.2. In addition, the only discretionary option was introduced by the stakeholder from Stakeholder C: 'ownership-based mechanisms'. In this type of mechanism, energy is exchanged within a local market in a voluntary manner, free of charge. The mechanism could, for example, be applied in a situation in which an energy community invests upfront in a renewable energy project and exploits the installation during the operation for no expenses. The energy community thereby has a shared ownership of the installation, and the collective receives the profits from the investments. This mechanism could be applied in markets where energy surpluses are exchanged or supplied to, for example, a social institution for no financial re-numeration.

- **Cooperative Sector**: The stakeholder from Stakeholder I indicated that the energy cooperation booked profits by selling their excess renewable energy on the wholesale market last year during the period with increased energy prices in 2022. The profits were locally reinvested in Loenen in the form of a poverty fund and membership-fee reductions. The stakeholder also indicated that the negative wholesale prices also affect the local community, as some members seek to curtail their solar PV systems to avoid paying for feeding their surplus electricity into the grid. The stakeholder indicated that the price for electricity in a local market should reflect the conditions in the local market, as compared to being exposed to the volatile wholesale market prices subsection B.3.2.

- **Total**: The stakeholders from the five perspectives all had different interpretations of a suitable mechanism for price formation in a LEM, however, the preference for a mechanism alternated between the auctions and system-determined mechanisms. Auctions allow for fair and transparent price formation, among other aspects, as noted in the introduced discretionary criteria. System-determined mechanisms are also expressed by stakeholder perspectives as the preferred mechanism for price formation in a local electricity market due to their conceptual simplicity, fairness, and transparency. Negotiation-based mechanisms allow for participative price formation but raise concerns about market power abuse and transparency. Ultimately, the selection of a suitable price formation mechanism for a local electricity market is dependent on the conditions within the market relating to low liquidity and market concentration which will be the focus of Chapter 5.

Chapter 5

Performance of the price formation mechanisms

5.1 Introduction

The following chapter will assess the performance of the price formation mechanisms in a real-life case study.

As described in subsection 2.10.1, in the Local4Local consortium, a new price formation mechanism is proposed: cost price plus. This is the total charged price of the costs to cover all aspects of generation and administrative processes, with some margin allowing for future investments. The umbrella organisation of energy cooperatives, EnergieSamen, has launched the Local4Local project. The goal is to 'share locally generated energy with the members of an energy community at cost price plus' as stated in a project description in the subsidy application submitted in autumn 2022 under the framework of the Mooi scheme. In December 2022, the Local4Local project was granted a total of 4.6 Million euros by the Dutch Government [119]. The direct cause of this project is the increasing difference between the cost price of the energy produced by energy communities and the price that members have to pay to their energy suppliers; this leads to the desire of the cooperative energy sector to organise this better fundamentally. Achieving such a local energy supply requires disruptive process innovation in the coming years to overcome complex institutional, organisational, economic, and legal barriers [115].

As indicated by the stakeholder interviews with stakeholders from EnergieSamen (Stakeholder A) and Loenen Energie Cooperative (LEC)(Stakeholder I), the Dutch energy communities are seeking an alternative price formation mechanism in which the cooperations do not book vast profits, as was the case with selling electricity for the wholesale prices in 2022 subsection B.3.2. For reference, the Betuwewind Cooperative from Geldermalsen made €5 million in pure profit in 2022 with seven wind turbines. The Zuidenwind Cooperative from Nederweert reports that they made a profit of €4.5 million in Limburg with five wind turbines, whilst the members of the cooperatives were struggling to pay their energy bills [119].

The innovative Local4Local model allows for a new format of exchanging electricity for a transparent, affordable price against the cost price plus. A total of 7 cooperatives are involved in the pilot, one of which is the Achterhoekse Gemeentelijke Energie Maatschappij (AGEM), a cooperative of eight municipalities in the Achterhoek. In collaboration with a cooperative energy supplier, EnergieVanOns, AGEM is already applying the Local4Local model in its BioZon pilot [119].

5.1.1 BioZon Pilot

The BioZon Pilot is an application of the Local4Local model in the Achterhoek by AGEM since January 1st 2023, in which renewable energy is produced for local consumers. BioZon produces green electricity from a landfill gas extracted from a former landfill site in the Achterhoek village of Zelhem, northeast of Doetinchem. Organic waste produces methane, used as green gas in a gas-fired power plant located beneath a cover layer. However, to provide electricity at a price significantly lower than the market price, it is essential for BioZon members to consume electricity at the very moment when it is produced. Every kilowatt hour that a cooperative member consumes while, for example, the power plant is idle due to repairs must be purchased by BioZon from the wholesale market at the market price. AGEM has signed a fixed-price contract with BioZon for €55/MWh to proceed with the installation, which was well below the market price at that time and the price is based on the costs of producing electricity using the BioZon installation.

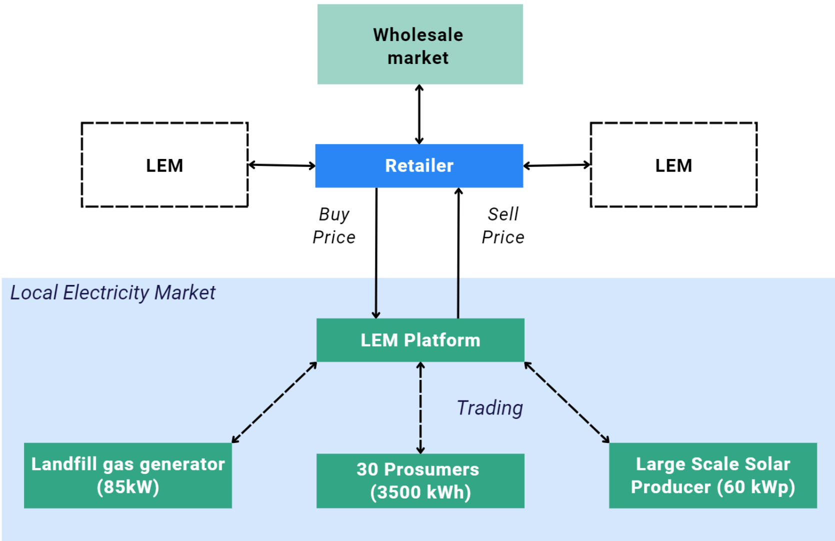

Figure 5.1: Schematic overview of the BioZon pilot and the involved market participants

The first Local4Local project achieved a successful simultaneous production first three weeks of this year (99%), as only 12 kWh (1%) had to be imported from the wholesale market. The landfill generator produces a power output of 85 kW and supplies the municipality and 30 households with energy. The Local4Local model can be applied in a local electricity market by allowing market participants to sell the electricity they produce to their local market at a cost price plus a small markup. This means that instead of selling the electricity to the national grid. The local4local model also allows for a more decentralised and community-based approach to energy production and consumption. It also enables greater community involvement in the energy transition, which can lead to more sustainable and equitable outcomes.

5.2 Methodology

The simulation of the price formation mechanisms will be conducted using LEMLAB and Py-Market. LEMLAB is a multi-agent-based, open-source tool for simulating local energy markets in which different market-clearing algorithms and pricing mechanisms are available. The Python-based tool has been used in different studies related to local energy markets, for example, in studying new auction-based clearing algorithms for community-based local energy markets [124]. Python is a cross-platform and open-source programming language that has experienced increased popularity rate over the last few years. The first release of the programming language was in 1991, and it can currently be used for a range of applications such as simulations, calculations and scientific computing. Furthermore, the Python programming language has been widely used for the simulation of (local) electricity markets and clearing mechanisms. The LEM was simulated in LEMLAB using PyCharm, after which the generated bids and offers were cleared with the three price formation mechanisms in a separate Python notebook (in Kaggle) in which the PyMarket mechanisms are modelled based on the PyMarket instruction as described in [62]. The bids and offers are imported as CSV files after they were created in the LEMLAB environment and served as input for the PyMarket algorithms. The visualisations and plots are made using the Flourish tool, in which the simulated data is also imported as CSV. In Figure 5.2, a schematic representation of the simulation methodology can be observed.

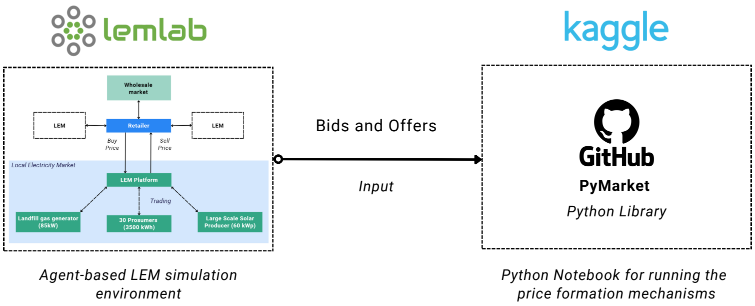

Figure 5.2: Schematic representation of the simulation methodology.

5.2.1 Local Electricity Market configuration

Similar to other methods applied in simulating price formation mechanisms for Local Electricity Markets in academic papers, the trading bandwidth for trading electricity within the local electricity market is set between a buy and sell price. The costs for the market participants for importing electricity from the market are equal to the wholesale day-ahead spot price. In addition, the price for selling electricity to the retailer is set equal to the feed-in tariff [32]. The data for day-ahead spot prices were gathered as a data sheet from ENTRNCE. The feed-in tariff was set as the average feed-in tariff in the Netherlands in March 2023, and all individual feed-in tariffs per retailer can be observed in Table D.2. In Figure 5.3, the trading range for a local electricity market between the feed-in tariff and the wholesale price can be observed [9]. The trading range allows for:

- LEM sellers making a profit by placing offers above the feed-in tariff;
- LEM buyers making a profit by placing bids below the wholesale prices.

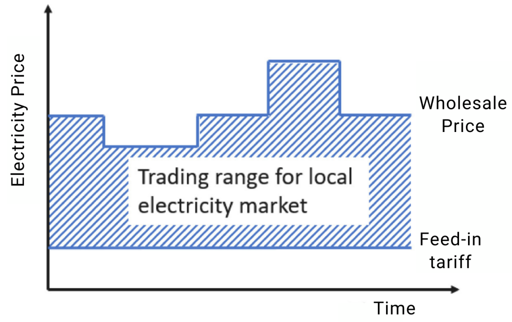

Figure 5.3: Trading range for local electricity market between feed-in tariff and the grid tariff [9].

5.2.2 Market actors

The market actors within the simulation are based on the BioZon pilot, in which there are a total of 30 households (prosumers) participating. Next to that, electricity is produced by a landfill gas generator (85 kW) and a large-scale solar PV park (60 kW). A retailer is simulated in the market in order to facilitate the allocation of deficit and surplus volume in the LEM. The following market actors are modelled in LEMLAB:

- **Prosumers**: A total of 30 households are simulated that both consume and produce electricity (prosumers). All prosumers are modelled according to the standard settings of LEMLAB and have a uniform power consumption of 3500 kWh per household, however, per household, the load curve differs. The prosumers have distributed energy resources such as small-scale PV, small-scale wind, household batteries, heat pumps and electric vehicles. The specific configuration of the prosumers according to the standard LEMLAB configuration can be observed in Table D.1. The prosumers are modelled as zero-intelligence agents, and they submit random bids and offers within the LEM trading range;

- **Landfill gas generator**: The landfill gas generator is modelled as a large-scale fixed generator with a peak power production of 85 kW (constant 1 p.u. over time). The power of the generator cannot be controlled in LEMLAB;

- **Large scale solar PV park**: The large scale solar PV park is modelled as a 60 kW large scale PV generator that is not controllable;

- **Retailer**: The retailer facilitates the market equilibrium by both selling additional energy and purchasing surplus energy (being the earlier defined trading range). The price set by the supplier for buying and selling energy establishes the trading boundaries for market participants, as depicted in Figure 5.3. Participants are unwilling to pay more than the guaranteed price set by the supplier, ensuring that their transactions remain within these limits. Similarly, participants are unwilling to sell their energy below the supplier's minimum price to the market, ensuring fair pricing within the market.

5.2.3 Auction-based mechanism

The double auction will be simulated using the PyMarket library [63], and in general, two types of double auctions can be distinguished: a periodic and continuous double auction (as described in section 2.8). In the simulation, a periodic double auction (PDA) will be operated, as the auction is operated on an ex-ante basis, and there is no need to match the bids and offers in real-time. In the PDA, the bids and offers are collected in an order book and at clearing time, the buy bids are sorted from low to high price, and the bid is matched with an offer if the buy price is equal to or larger than the offer price. This process is continued until the demand quantity is equal to the supply quantity. As described in section 2.8, two pricing mechanisms can be applied for double auctions: uniform pricing and discriminatory pricing. In this simulation, uniform pricing will be applied, such that there is a single clearing price per clearing interval, which is a similar mechanism as applied in the wholesale day-ahead markets. A uniform price PDA will be applied to simulate the double-auction in the simulations. The process in an auction can be described using the following steps and Figure 5.4:

1. Buyers submit bids expressing their willingness to pay, which are collected by the platform;
2. Sellers submit offers expressing their underlying costs, which are also collected by the platform;
3. The bids and offers are matched in order to find the intersection between demand and supply, which is the uniform clearing price for the clearing interval. All buyers pay this price, and all sellers receive this price.

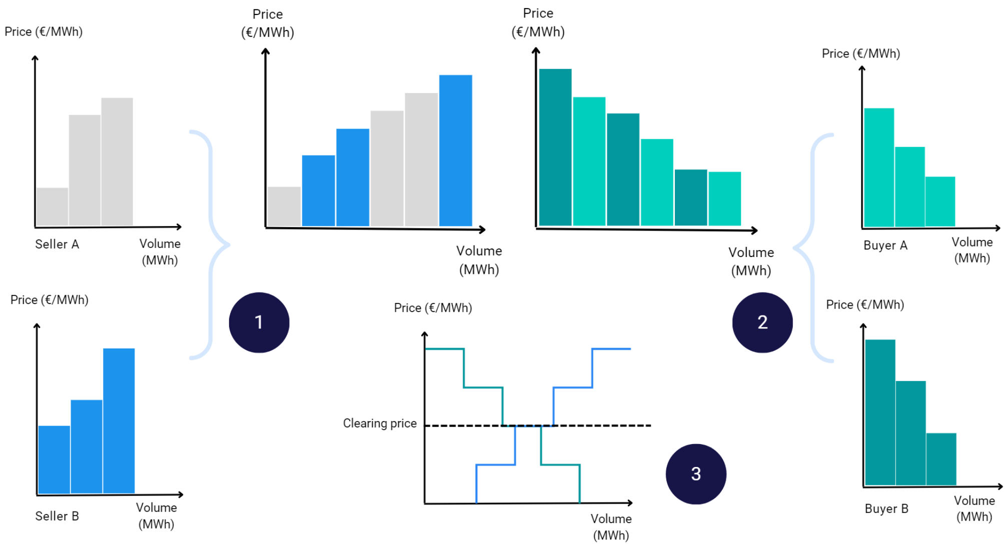

Figure 5.4: Working principles of a double auction.

5.2.4 Negotiation-based mechanism

The negotiation-based price formation mechanism will be simulated using the mechanism proposed by Mengelkamp, E. Staudt, P. Garttner, J. et al. (2017) [85], and the foundations for the mechanism have been established by Blouin and Serrano (2001) [11]. The mechanism will be simulated using the PyMarket P2P mechanism module [63]. In this mechanism, consumers and prosumers (peers) trade on a pay-as-bid basis with other peers in a randomised order. Orders are matched when the bid price of a consumer is larger than or equal to the asking price of the seller. When a bid is matched to an offer, the consumer pays the bid price (hence pay-as-bid) and is allocated with the amount of electricity from the offer. The matched volume is equal to the minimum amount of the sellers bid, and buyers ask amount [85]. As the bids cannot be altered after submission, the bid submission can be classified as a 'sealed-bid process' [51]. As not all bids will be matched in the first matching run, the mechanism performs multiple iterations. Suppose a bid or offer is not matched, or not all quantity is traded. In that case, the participants will enter the next matching iteration which continues until all unmatched bids and offers trade all the quantity or no possible pairs remain to engage in trading. Demand that is not able to be acquired in the P2P matching algorithm will be allocated from an external market at the retail price [85]. When a bid and an offer are matched, the trading price can be computed as defined in Equation 5.1:

$$\mu_{p2p} = \mu_{buy} \cdot k + (1-k) \cdot \mu_{sell} \quad k \in [0,1] \tag{5.1}$$

In Equation 5.1, the price coefficient k determines the trading price; if $k = 0$ all profit goes to the buyer and if $k = 1$ all profit goes to the seller. In the simulations, the coefficient is set to $k = 0.5$.

As the mechanism operates using discriminatory pricing, each transaction results in individual prices, and there is no uniform market price. As a result, peers can end up with varying prices for the same quantity of electricity in the same trading round. However, due to the randomisation of the matching, competitive advantage can be avoided, thereby ensuring fairness in the trading process [85]. As a result, the P2P matching algorithm has a similar working principle as compared to a periodic double auction (PDA) with discriminatory pricing. However, the bids and offers are not sorted in the P2P algorithm but are matched in a random manner. The P2P matching algorithm could yield a higher number of trades compared to the PDA as a result of the possibility of advantageous matching [51]. In Figure 5.5, a flowchart of the pay-as-bid matching procedure of the bilateral trading mechanism can be observed.

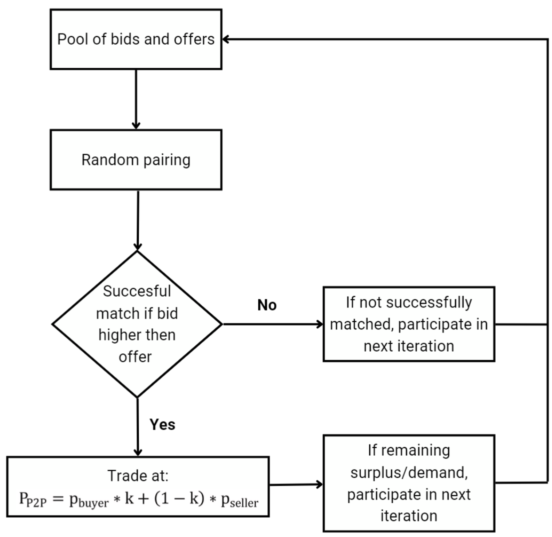

Figure 5.5: Illustration of pay-as-bid matching in the negotiation based mechanism (adapted) [51].

5.2.5 System-determined mechanism

The system-determined mechanism is based on the price formation mechanism that is applied in the Local4Local pilot. The definition for system-determined mechanisms is 'a mechanism in which a market operator establishes prices on the basis of pre-defined mathematical formulas or mechanisms' [18]. Reflecting this to the Local4Local model, the pre-defined mechanism is the cost price plus module. The cost price plus includes the costs to cover all aspects of generation and administrative processes, with some margin allowing for future investments [77]. In this pilot, the cost prices for the renewable energy assets are computed by AGEM and used in the simulations and can be observed in Table 5.1. The cost price for prosumers is set equal to the feed-in tariff, which is currently the price for which prosumers are able to sell their surplus electricity to the retailer. For future work, the cost price for prosumers can be computed by assessing the total cost of ownership for generating electricity for prosumers over a specified period of time.

Table 5.1: Cost prices for types of market participants

Type	Cost Price (€/kWh)	Notation
Landfill gas generator	0.055	μ_{GM}
Large scale PV field	0.078	μ_{PV}
Prosumers	0.09	μ_{HH}

The system-determined mechanism clears the market as follows and works using the principles of the electricity market that ”clears” when the amount of electricity offered matches demand, and dispatching units by lowest cost price allows the LEM to meet energy demand at the lowest possible cost for the consumers.

1. Selling offers of the market are collected and grouped by clearing interval (e.g., 15 min, 30 min, or 60 min).
2. Cost prices for different types of sellers (prosumer, large-scale PV, fixed generator) are assigned based on predefined agreements.
3. The demand is calculated for each clearing interval.
4. The offers are sorted in ascending order within each clearing interval, starting with the lowest cost price.
5. The cleared volume is determined by summing the volumes of offers in ascending order until the total volume meets the demand.
6. If the offers in the market cannot fulfill the demand, the residual volume is imported from the retailer at the retail cost.
7. The final cost price for the clearing interval is computed using Equation 5.2.

$$\mu_{sys} = (\frac{q_{PV} \cdot \mu_{PV}) + (q_{GM} \cdot \mu_{GM}) + (q_{HH} \cdot \mu_{HH}) + (q_{Ret} \cdot \mu_{Ret})}{q_{Demand}} \tag{5.2}$$

5.2.6 Performance Metrics

The performance metrics for the simulations will be formulated in accordance with a selection of the quantitative discretionary criteria. The selection is based on the input and concerns of the stakeholders for the mechanisms as identified in the Multi Criteria Mapping process. The selected criteria are Operation under low liquidity, (prone to) Market Power and economic efficiency. The introduced criteria will be reflected in the simulation as follows:

- **The Weighted Average Price**: The Weighted Average Price (€/kWh) for a specific interval;
- **Volatility**: The Volatility of the Weighted Average Price (€/kWh) for a specific interval;
- **Order Book Depth**: The order book depth is a measure of liquidity in the market, as it refers to the number of bids and offers within the clearing interval in the cleared order book.
- **Market concentration**: Measured as the squaring of the market share of each market participant in the LEM and then summing the resulting numbers, resulting in the Herfind-

ahl–Hirschman index (HHI). The HHI is a common measure for assessing market concentration in markets [125].

- **Trading volume**: The total amount of traded electricity (kWh) within the market for a specified time interval;
- **Imported volume**: The total amount of imported electricity (kWh) from the retailer to meet the demand for a specified time interval;

The simulations will be conducted for three different clearing period intervals: 15 minutes, 30 minutes and 60 minutes. The clearing periods are the intervals between which the market is cleared. The market is cleared by running the price formation algorithm over the bids and offers within the clearing period resulting in cleared volumes at a uniform or discriminatory clearing price, depending on the specific mechanism.

Weighted Average Price

The weighted average price performance criterion is the weighted average price within the LEM over the clearing interval [96]. The weighted average price can be computed using Equation 5.3:

$$\mu_{wavg} = \frac{\sum_{i=1}^{t}(\mu_i \cdot q_{ti})}{\sum_{i=1}^{t} q_{ti}} \tag{5.3}$$

Volatility

The volatility of the weighted average price represents to the degree of fluctuation or instability in the LEM price within the clearing period. The volatility of the weighted average price can be computed as the standard deviation of the weighted average price and is depicted in Equation 5.4:

$$\sigma_{std} = \sqrt{\frac{\sum_{i=1}^{T}(\mu_i - \mu_{wavg})^2}{n}} \tag{5.4}$$

Trading volume

The trading volume criterion represents the total amount of cleared volume within the clearing interval in the LEM [51] and is depicted in Equation 5.5:

$$q_{trade} = \sum_{i=1}^{t}(q_{clear,ti}) \tag{5.5}$$

Imported volume

The imported volume criterion represents the total amount of imported volume within the clearing interval needed to meet the demand [51] and is depicted in Equation 5.6:

$$q_{imported} = \sum_{i=1}^{t}(q_{demand,ti} - q_{clear,ti}) \tag{5.6}$$

Order book depth

The order book depth measures the number of cleared orders in the cleared order book (transactions). The order book depth can be computed using Equation 5.7:

$$D = \sum_{i=1}^{t} (n_{cleared}) \tag{5.7}$$

Herfindahl–Hirschman index

As noted in 'Market Mechanisms and Trading in Microgrid Local Electricity Markets: A Comprehensive Review' [125], HHI measures market concentration by squaring the market share of each participant and summing the values per clearing period. In Equation 5.8, in which N is the number of LEM participants and s_i the market share per participant as noted in Equation 5.9.

$$HHI = \sum_{i=1}^{t} \sum_{i=1}^{N} s_i^2 \tag{5.8}$$

$$s_i = \frac{q_i}{q_{clear}} \tag{5.9}$$

As a result, the HHI is equal to the total sum of market shares s_i of all market participants in the LEM, being the proportion of traded volume as part of the total amount of cleared volume. The Herfindahl–Hirschman index is a well-used indicator for market concentration by both the European Commission (EC) and Department of Justice-federal trade Commission (DOJ-FTC) in the United States. In Table 5.2, the HHI measures according to the European Commission can be observed [17]. As market concentration increases, market power increases and thereby competition and efficiency within the market decrease therefore it is insightful to assess the HHI in the context of market power analysis. As a result, the relation between the HHI and market shares is non-linear, as the HHI follows a quadratic dependence on the market shares of the market participants. Consequently, when the market is a monopoly s_i is equal to 1 and the HHI to 10.000 and when the market is a perfect competition, the HHI will approach 0 (but always stays larger than 0), as depicted in Equation 5.10 [90].

$$s_i = \frac{1}{N} \Rightarrow HHI = \sum_{i=1}^{N} \left(\frac{1}{N}\right)^2 = \frac{1}{N} \tag{5.10}$$

Table 5.2: HHI measures according to the European Commission [17].

Concentration Degree	European Commission
Low	0-1000
Medium	1000-2000
High	2000-10000

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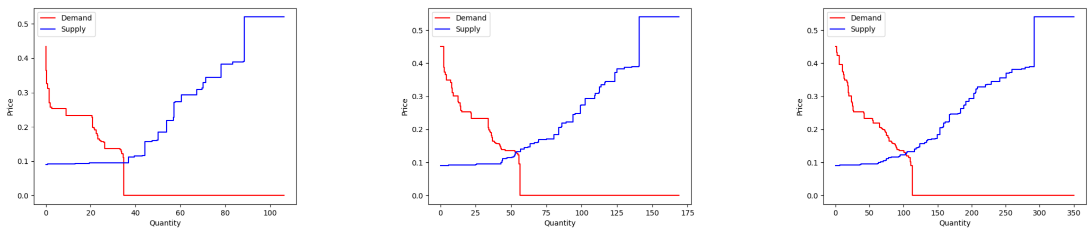
5.3 Simulation Results

In this section, the results of the simulations will be discussed. The structure of the section consists of four subsections: Overview of the mechanisms, Impact of Clearing Interval, Impact of Order Book Depth, and Impact of Market Concentration. The first subsection will elaborate on the working principles of the mechanisms under different clearing intervals, the second subsection on the impact of the clearing intervals on the weighted average prices and volatility of the mechanisms, the third subsection on the impact of order book depth on cleared volume, imported volume and average prices. The last subsection elaborates on the relation between the order book depth and the market concentration.

5.3.1 Overview of the mechanisms

Double auction

The auction-based mechanism clears the market at a uniform price per clearing period. In 5.6a, the auction is cleared for a 15-minute interval (09:15 - 9:30), in 5.6b, for a 30-minute interval (09:15 - 9:45) and in 5.6c for a 60-minute interval (09:15 - 10:15) at 2021-02-24. It can be observed that the market is cleared at the intersection between demand (red) and supply (blue), the point at which the bid ladders reach an intersection. In section D.3 the transactions data frame for the double auction for the clearing period 2021-02-24 09:15:00 at a 15-minute clearing interval can be observed.



(a) Uniform Double auction cleared for 15 min interval.

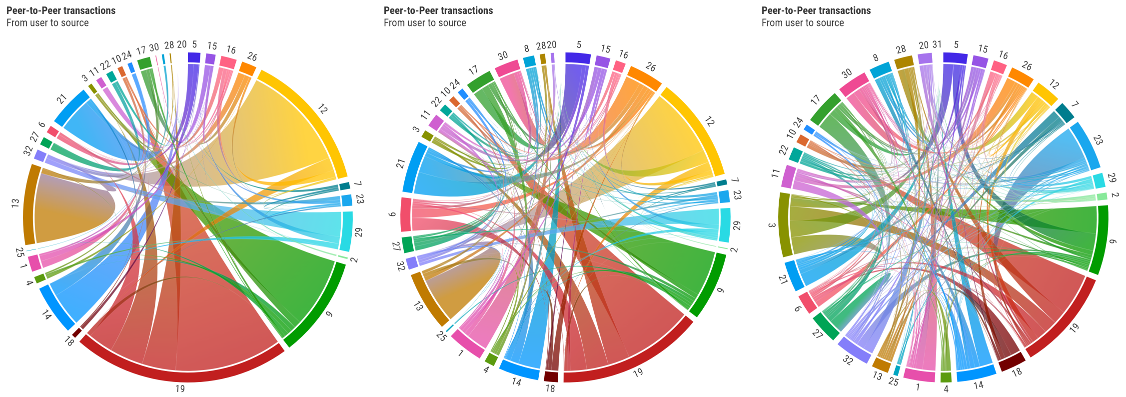
(b) Uniform Double auction cleared for 30 min interval.

(c) Uniform Double auction cleared for 60 min interval.

Figure 5.6: Uniform double auction mechanism clearing for 15 min, 30 min and 60 min intervals for 2021-02-24.

Negotiation-based mechanism

The negotiation-based mechanism clears the market on a peer-to-peer basis with individual transactions per peer-to-peer trade. As a result, all transactions are unique, with a unique price and volume contract per clearing period. In 5.7a, the mechanism is cleared for a 15-minute interval (09:15 - 9:30), in 5.7b, for a 30-minute interval (09:15 - 9:45) and in 5.7c for a 60-minute interval (09:15 - 10:15). In the figure, the flows represent the quantity of energy traded from one market participant to another. It can be observed that for longer clearing intervals, more market participants can engage in trading and that fewer dominant market participants control the market as compared to the 15-minute clearing scenario. In section D.4 the transactions data frame for the negotiation-based mechanism for the clearing period 2021-02-24 09:15:00 at a 15-minute clearing interval can be observed. Later in this Chapter, the relation between market power and clearing intervals will be further analysed.



(a) Negotiation-based mechanism cleared for 15 min interval.

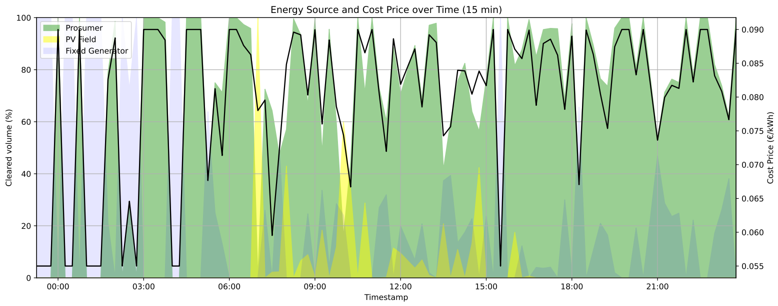
(b) Negotiation-based mechanism cleared for 30 min interval.

(c) Negotiation-based mechanism cleared for 60 min interval.

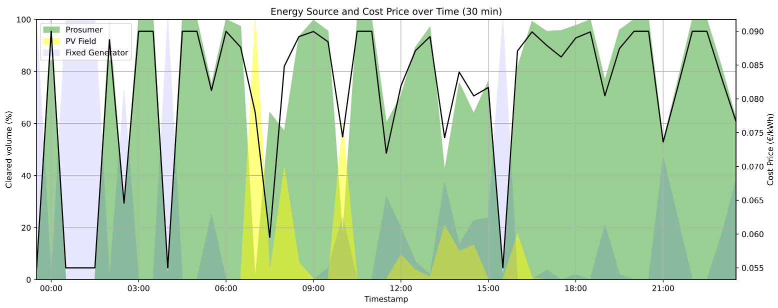
Figure 5.7: Negotiation-based mechanism clearing for 15 min, 30 min and 60 min intervals at 2021-02-24.

System-determined mechanism

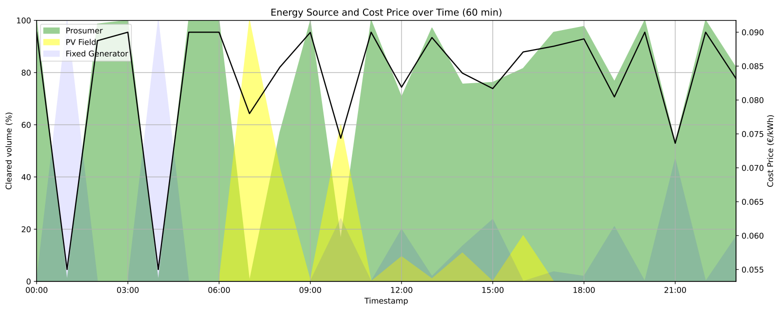
In Figure 5.8, the final cost prices over the time period of a day for the three different clearing periods can be observed. The cost price per clearing period depends on the energy sources and their cost prices. It can be observed in the figure that the cost price follows the cleared energy sources (prosumer, PV field or the fixed generator). As the clearing interval is increased from 15 minutes to 60 minutes, the cost price becomes increasingly less volatile as there is less variation in the cleared energy sources per clearing interval. In section D.5 the transactions data frame for the system-determined mechanism for the clearing period 2021-02-24 09:15:00 at a 15-minute clearing interval can be observed.



(a) Cost prices and energy sources of the system-determined mechanism for a clearing interval of 15 minutes.



(b) Cost prices and energy sources of the system-determined mechanism for a clearing interval of 30 minutes.



(c) Cost prices and energy sources of the system-determined mechanism for a clearing interval of 60 minutes.

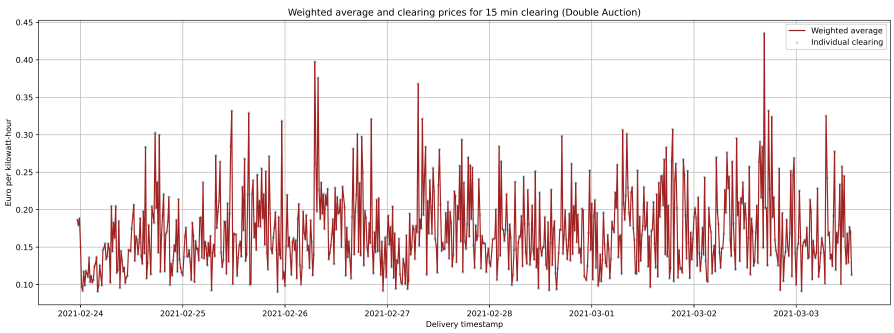
Figure 5.8: Cost prices and energy sources for the system-determined mechanism for the 15-minute, 30-minute and 60-minute clearing intervals.

5.3.2 Impact of Clearing Interval

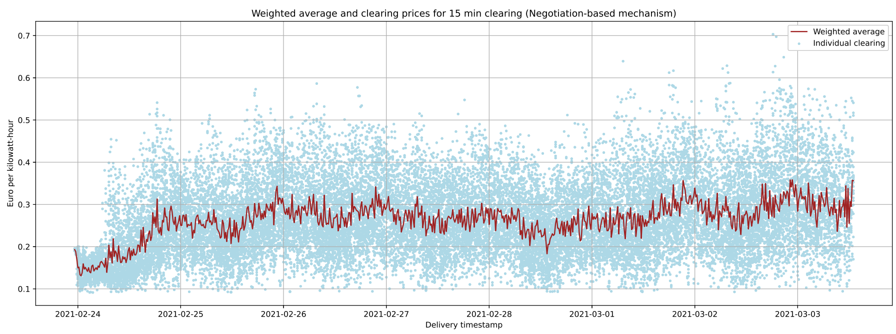
The following section will evaluate the influence of the clearing interval on the weighted average price and volatility of the mechanisms. The simulations will be conducted for a simulation period of 7 days between 2021-02-23 and 2021-03-03 (this period is selected as input data was available for this period) for the 15-minute, 30-minute and 60-minute clearing intervals.

The 15-minute clearing interval

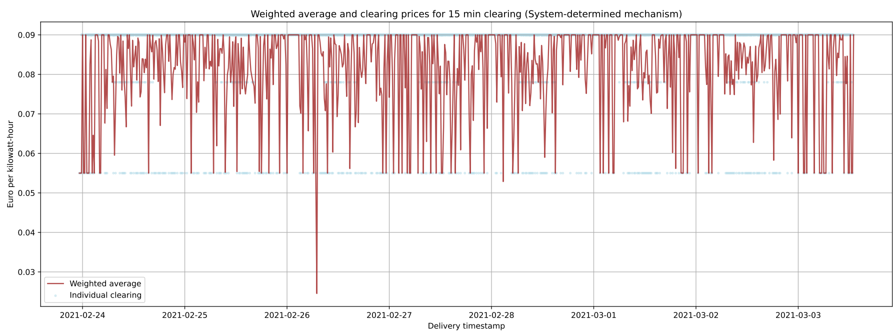
In Figure 5.9, the weighted average prices of the double auction, negotiation-based mechanism and system-determined mechanism can be observed. In Figure 5.6a, the clearing prices for the double auction for a 15-minute clearing interval can be observed, in Figure 5.9b for the negotiation-based mechanism and in Figure 5.9c for the system-determined mechanism. In Figure 5.9c, the individual clearing prices per peer-to-peer transaction are represented by the blue dots, whilst the red line depicts the weighted average price per clearing interval. As the double auction operates using uniform prices per clearing interval, the weighted average simply follows the individual clearing prices. In Figure 5.9c, the individual cost prices per cleared energy source can be observed in the plot, whilst the weighted average cost price is dependent on the quantity of energy transacted per energy source (prosumer, PV field or fixed generator).



(a) Clearing prices of the double auction for a clearing interval of 15-minutes



(b) Clearing prices of the negotiation-based mechanism for a clearing interval of 15-minutes

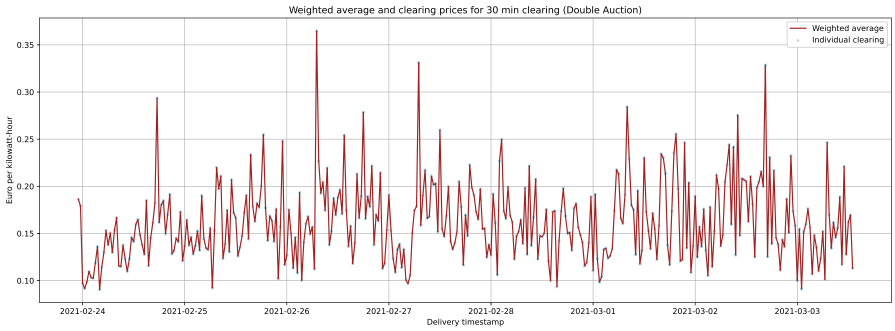


(c) Clearing prices of the system-determined mechanism for a clearing interval of 15-minutes

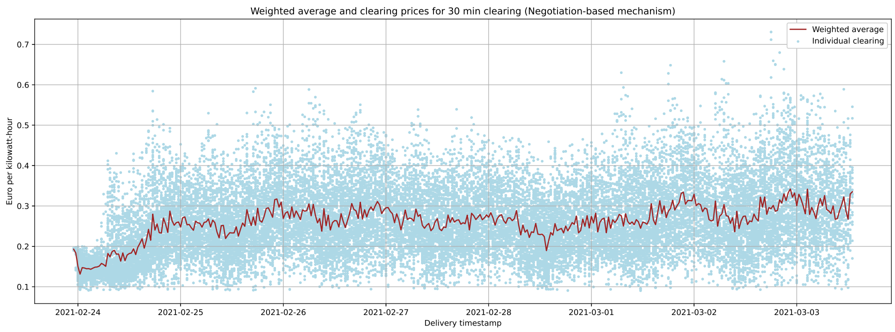
Figure 5.9: Clearing prices for the three mechanisms for the 15-minute clearing interval

The 30-minute clearing interval

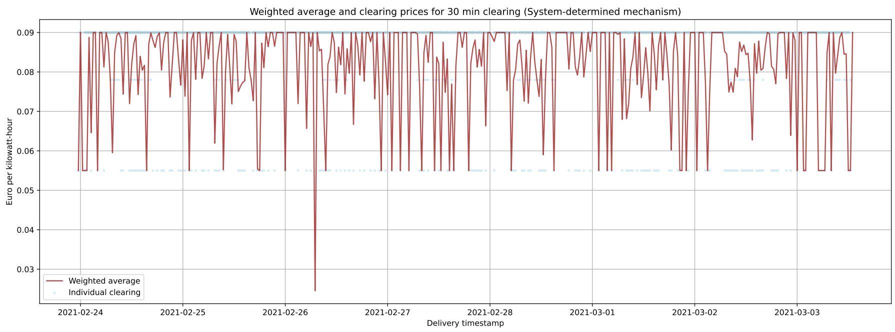
In Figure 5.10, the prices of the double auction, negotiation-based mechanism and system-determined mechanism for the simulation period of 7 days between 2021-02-23 and 2021-03-03 can be observed. In Figure 5.6b, the clearing prices for the double auction for a 15-minute clearing interval can be observed, in Figure 5.7b for the negotiation-based mechanism and in Figure 5.10c for the system-determined mechanism.



(a) Clearing prices of the double auction for a clearing interval of 30-minutes



(b) Clearing prices of the negotiation-based mechanism for a clearing interval of 30-minutes

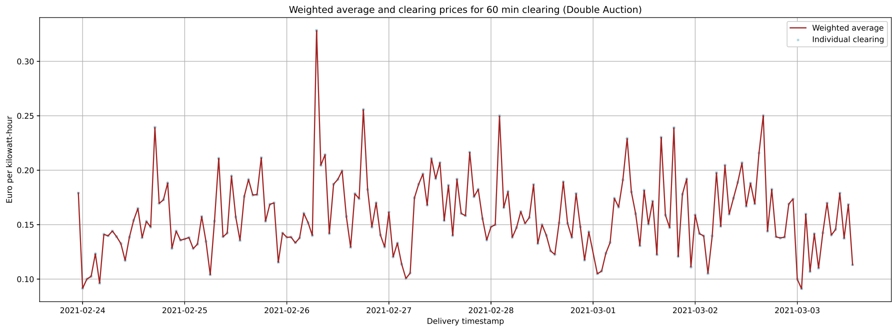


(c) Clearing prices of the system-determined mechanism for a clearing interval of 30-minutes

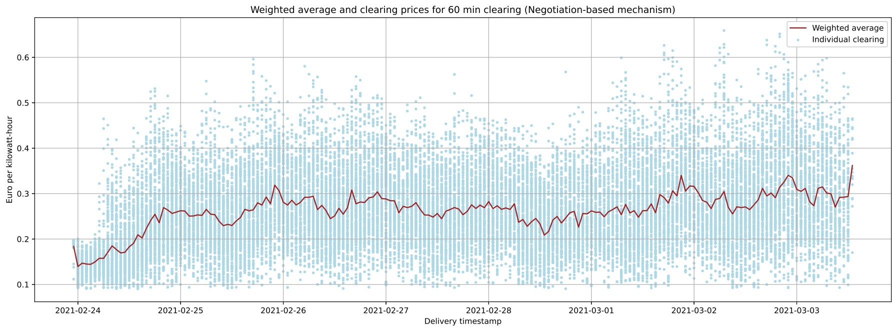
Figure 5.10: Clearing prices for the three mechanisms for the 30-minute clearing interval

The 60-minute clearing interval

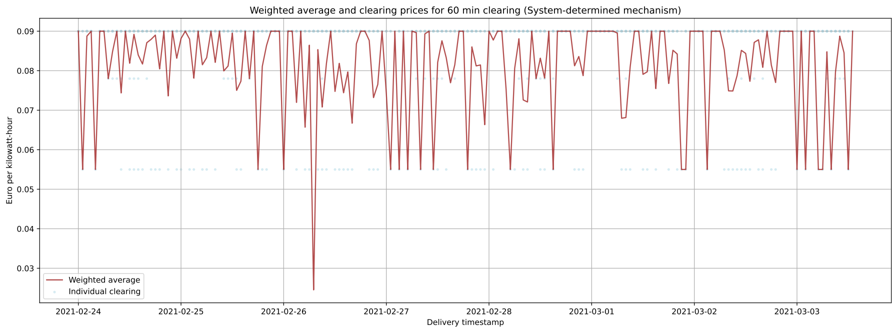
In Figure 5.11, the prices of the double auction, negotiation-based mechanism and system-determined mechanism for the simulation period of 7 days between 2021-02-23 and 2021-03-03 can be observed. In Figure 5.6c, the clearing prices for the double auction for a 60-minute clearing interval can be observed, in Figure 5.7c for the negotiation-based mechanism and in Figure 5.11c for the system-determined mechanism.



(a) Clearing prices of the double auction for a clearing interval of 60-minutes



(b) Clearing prices of the negotiation-based mechanism for a clearing interval of 60-minutes



(c) Clearing prices of the system-determined mechanism for a clearing interval of 60-minutes

Figure 5.11: Clearing prices for the three mechanisms for the 60-minute clearing interval

In Table 5.3, the Weighted Average Prices and Volatility for the three different mechanisms for the 15-minute, 30-minute and 60-minute clearing intervals can be observed. The negotiation-based mechanism has the highest weighted average price across all three clearing intervals, followed by the double auction and system-determined mechanism. The weighted average prices decrease for the double auction as the clearing interval increases, whilst the prices for the negotiation-based mechanism remain relatively constant and the prices for the system-determined mechanism only decrease as the clearing interval is prolonged from 15 minutes to 30 minutes. The standard deviation (volatility) is the smallest for the system-determined mechanism over the three clearing intervals. The standard deviation of the double auction and negotiation-based mechanism also decreases as the clearing interval is increased, indicating that the mechanisms become less volatile as the clearing period is prolonged. It is important to mention that the performance of the system-determined mechanism is dependent on the selected cost prices, as a market with large differences between the cost prices could negatively impact the weighted average price and standard deviation of the mechanism.

Table 5.3: Weighted Average Prices and Volatility for the three different mechanisms for the 15-minute, 30-minute and 60-minute clearing intervals

	Double Auction		**Negotiation-based**		**System-determined**	
Clearing Interval	μ_{wavg}	σ_{std}	μ_{wavg}	σ_{std}	μ_{wavg}	σ_{std}
15 min	0.1701	0.0526	0.2637	0.0415	0.0812	0.0115
30 min	0.1622	0.0419	0.2619	0.0392	0.0693	0.0126
60 min	0.1580	0.0351	0.2625	0.0388	0.0694	0.0125

In Figure 5.12, the weighted average price for the three mechanisms as well as the trading range for the local electricity market for 2021-02-24 can be observed. The trading range is located between the feed-in tariff and grid tariff (being the wholesale prices) and is represented by the blue-shaded area. Within the trading range, the market-based mechanisms that clear the submitted bids and offers, the double auction and negotiation-based mechanism, clear the market per clearing interval. Alternatively, the system-determined mechanism clears the market outside the trading range as the submitted cost prices are equal to or below the feed-in tariff. As was noted in Table 5.3, the clearing prices of the system-determined mechanism are the lowest and least volatile, however, this observation can be explained by the fact that the cost-prices are lower than or equal to the feed-in tariff and the cost prices are relatively close to each other which results in low volatility. The double-auction and negotiation-based mechanisms are market-based mechanisms and the auction clears the market for lower prices as compared to the weighted average of the negotiation-based mechanism. As a result, the system-determined mechanism is not operating using the submitted bids and offers within the trading range but is operating outside of the trading range with the lower cost prices. The weighted average of the negotiation-based mechanism, however, shows lower volatility as compared to the double auction in Figure 5.12. In the market-based mechanisms, the shape of the grid tariff can roughly be observed as the prices increase and decrease as the grid tariff fluctuates over the day. This pattern is the result of the clearing of the underlying bids and offers in the market, that capture the conditions within the market. As a result, the market-based mechanisms more accurately represent the real-time conditions in the market and there is a smaller chance of overpaying or underpaying for electricity as compared to the system-determined mechanism.

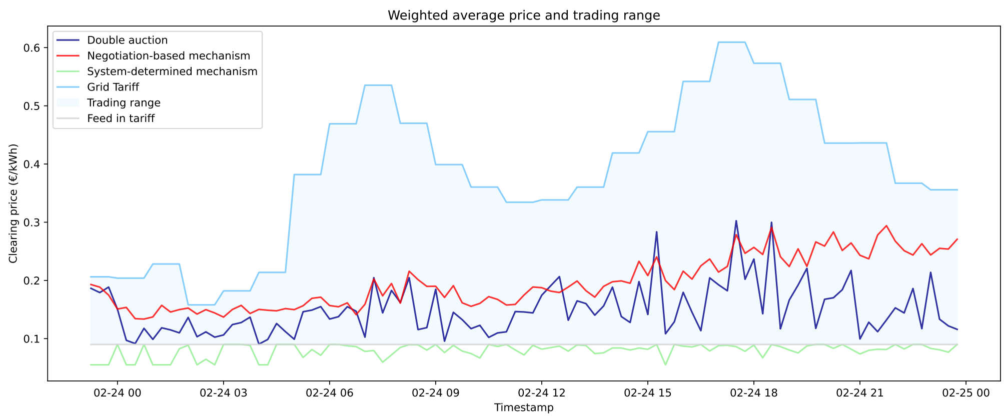


Figure 5.12: The Weighted average price and trading range simulated between 2021-02-24 and 2021-02-25.

5.3.3 Impact of Order book depth

In the following section, the double auction, negotiation-based mechanism and system-determined mechanism will be assessed on the basis of trading volume, imported volume and average price criteria against the order book depth. As noted in subsection 5.2.6, the order book depth represents the collection of all cleared buy and sell orders for the clearing intervals. Three simulations are run, for three different clearing intervals 15 minutes, 30 minutes and 60 minutes. In Figure 5.14, the performance of the mechanism for the Trading Volume criterion against the order book depth can be observed, in Figure 5.15 the imported volume against order book depth and in Figure 5.13 the average prices against the order book depth.

In the figures it can be observed that the system-determined mechanism typically clears the market with the smallest order book depth, followed by the double auction and lastly the negotiation-based mechanism. As described in subsection 5.2.5, in the system-determined mechanism, the sellers submit a cost price (prosumers, landfill gas generator and PV park), which is consequently used to clear the market. As a result, the cleared order book only contains the matched offers needed to clear the demand. The order book of the transactions by the double auction is based on all matched bids and offers necessary to meet the demand within the clearing interval (15 minutes, 30 minutes or 60 minutes). The negotiation-based mechanism operates as a peer-to-peer mechanism in which market participants can engage in multiple transactions in order to meet the demand, explaining the deeper order book depth accompanied by this mechanism. As noted earlier, 'the P2P matching algorithm could yield a higher number of trades compared to the PDA as a result of the possibility of advantageous matching' [51]. In addition, the order book depth of the cleared transactions by the system-determined mechanism remains constant over the three different clearing intervals, indicating that the order book depth is not dependent on the clearing interval as in all clearing intervals a comparable number of selling orders are cleared per interval. Both the double-auction and negotiation-based mechanism show that as the clearing interval increases, the cleared order book also becomes deeper. This observation can be explained by the fact that as the clearing interval is prolonged, more orders will be available to be matched.

Average prices

In Figure 5.13, the average clearing prices of the three mechanisms against the order book depth can be observed. In the double auction, the average price decreases as the order book depth increases, indicating that an increasing number of transactions could result in lower prices as cleared by the double auction. Furthermore, for the negotiation-based mechanism, it can be observed that a deeper order book correlates with a decrease in the average clearing price. The system-determined mechanism shows a relatively constant average price as the order book depth increases indicating that the average clearing prices are not largely affected by the order book depth. It should be noted, however, that for the system-determined mechanism, the clearing prices are dependent on the submitted cost prices of the cleared volumes in the market, which is not the case for the clearing prices of the double auction and the negotiation-based mechanisms that operate using the submitted bids and offers.

Trading volume

In Figure 5.14, the performance of the mechanism for the Trading Volume criterion against the order book depth can be observed. The traded volume criterion represents the total amount of cleared volume within the clearing interval by the mechanism. As for the double auction, it can be observed that there is a positive relation between the order book depth and the traded volume, as a deeper order book results in more traded volume. The results of the negotiation-based mechanism do not suggest a strong relationship between the traded volume and cleared order book depth, as an increase in the clearing interval does not necessarily result in a larger amount of traded volume. In addition, the negotiation-based mechanism clears less volume as compared to the double auction, suggesting a lower matching efficiency. The system-determined mechanism

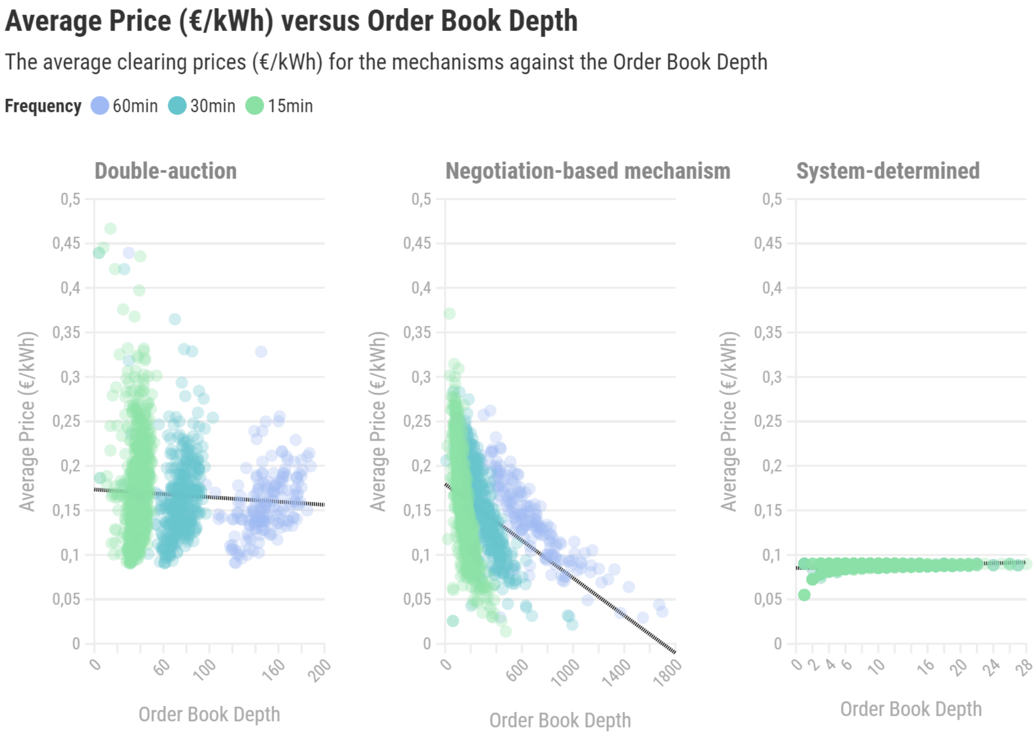


Figure 5.13: The average clearing prices (€/kWh) for the mechanisms against the Order Book Depth simulated between 2021-02-23 and 2021-03-03.

shows a positive relationship between the order book depth and trading volume, however, the traded volume criterion is less dependent on the clearing interval. This observation can possibly be explained by the fact that the order book depth is not dependent on the clearing interval, as the order book depth remains constant over the different clearing intervals such that the total amount of cleared volume also remains relatively constant. The total amount of cleared volume is comparable to the double auction, indicating that the system-determined mechanism and double auction clear a similar amount of volume per clearing interval.

Imported Volume

In Figure 5.15, the performance of the three mechanisms for the Imported Volume criterion against the order book depth can be observed. As for the double auction, the imported volume criterion against the order book depth does not show a strong relation, as in general the double auction did clear most of the demand in the simulations and importing volume from the retailer was not significantly needed (this is dependent on the LEM setup and will be further discussed in the discussion). Similar to the results of the Trade Volume criterion for the negotiation-based mechanism, the mechanism clears the market on a less efficient basis as compared to the other two mechanisms such that more volume needs to be imported from the retailer in order to meet the demand. This observation can possibly be explained by the presence of a growing number of trades within the order book that cannot be efficiently cleared on a pay-as-bid basis. Lastly, the system-determined mechanism scores similar to the double auction, as the mechanism already cleared most of the demand as depicted in Figure 5.14.

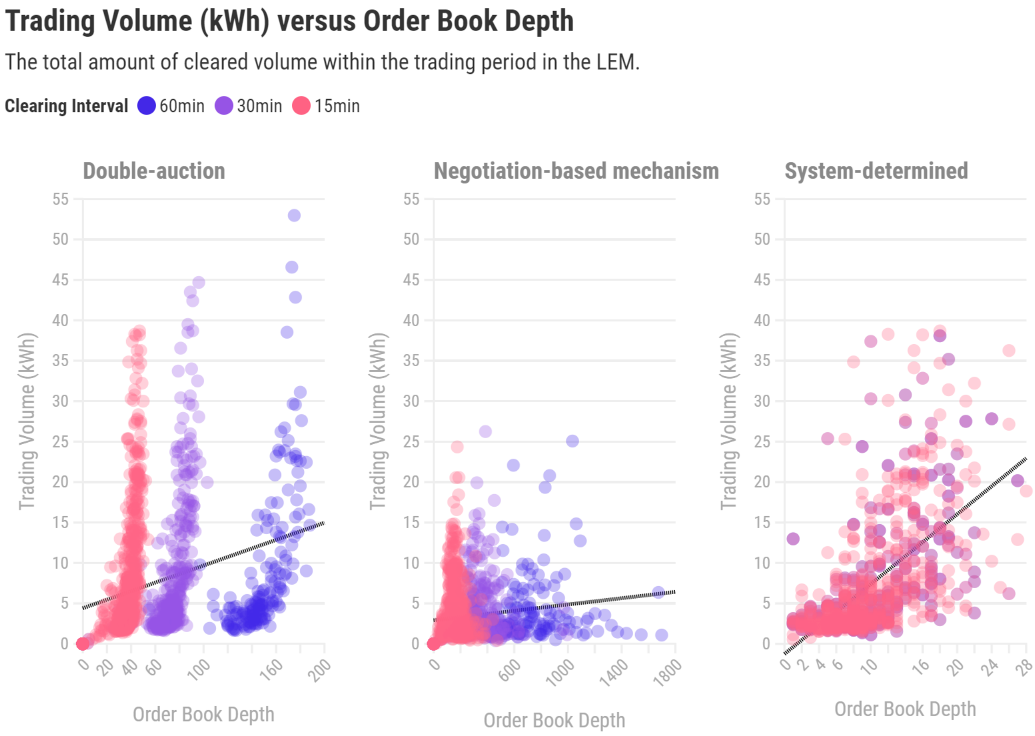


Figure 5.14: Trading Volume (kWh) versus Order Book Depth performance simulated between 2021-02-23 and 2021-03-03.

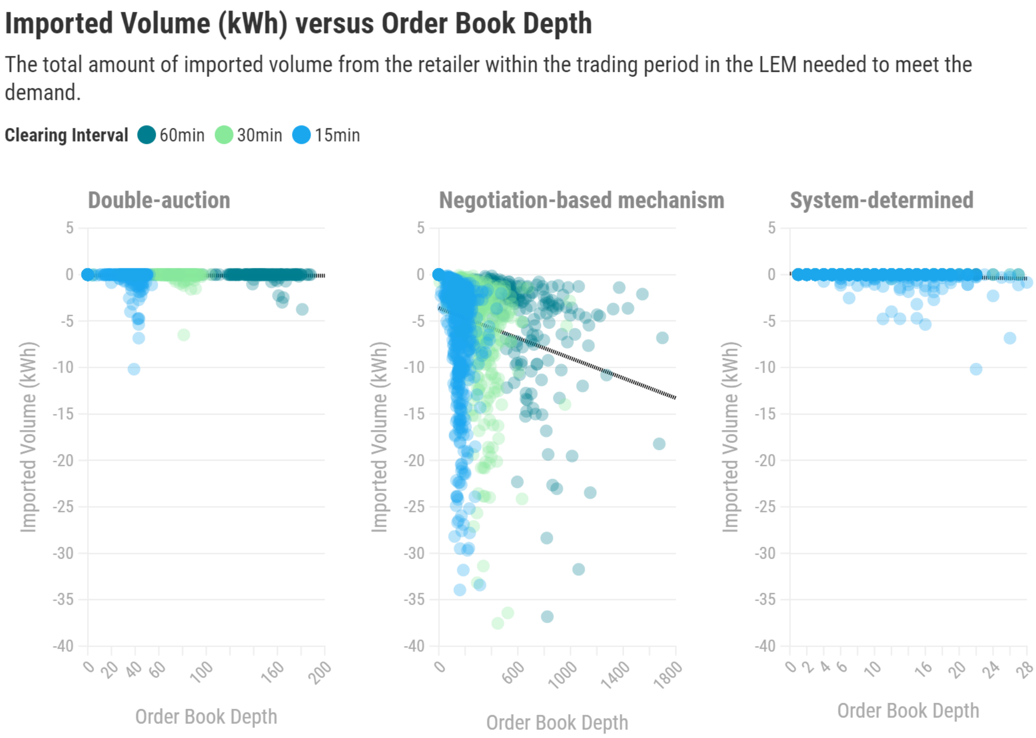


Figure 5.15: Imported Volume (kWh) versus Order Book Depth performance simulated between 2021-02-23 and 2021-03-03.

The results of double-auction for the traded volume against cleared order book depth simulations indicated a positive relationship between the total amount of traded volume and cleared order book depth, such that more volume is traded as the clearing interval increases. The negotiation-based mechanism revealed a different pattern for the traded volume criterion against the order book depth simulations, as the amount of traded volume did not necessarily increase as the clearing interval was prolonged. The order book depth of the system-determined mechanism remained constant as the clearing interval increased, such that an increase in the clearing interval did not impact the amount of traded volume for the mechanism. As for the imported volume criterion against the order book depth, the double auction and system-determined mechanism did not indicate a significant relation, as in general both mechanisms cleared most of the demand in the simulations, and importing volume from the retailer was not significantly needed. The negotiation-based mechanism did not show a significantly increased matching efficiency as more volume had to be imported as the order book depth increased, This observation can potentially be explained by the presence of a growing number of trades within the order book that cannot be efficiently cleared on a pay-as-bid basis. Lastly, in the simulations for the average clearing prices against the order book depth, the double auction and negotiation-based mechanism indicate that a deeper order book results in lower average clearing prices. This observation can possibly be explained by the fact that a more liquid market allows for the more efficient matching of trades and a smaller chance of large transactions affecting the prices in the market. The system-determined mechanism shows convergence towards a relatively stable average price, indicating a more reliable and consistent clearing process that is less subject to market fluctuations and other external factors. The behaviour of the system-determined mechanism can be helpful in a local electricity market where prices are subject to significant volatility or where market power is a concern.

5.3.4 Impact of Market Concentration

The following section will assess the performance of the three mechanisms against market power. A measure of market power is market concentration, indicating how concentrated a market is by a small number of players.

The Herfindahl measures the market concentration–Hirschman index as described in Equation 5.8, being the sum of squares of the market shares of the different market participants within a clearing interval (15min, 30min or 60min). As noted in Table 5.2, the European Commission identified different thresholds for the concentration of a market based on the HHI score: a score from 0-1000 indicates a market with low concentration, 1000-2000 medium concentration and 2000-10000 high concentration [17]. As a result, a low HHI score indicates a competitive market whilst a high HHI indicates a concentrated market with a few dominant market participants. To investigate the relationship between market concentration and the cleared order book depth in the market, the HHI and order book depth were computed for the different clearing intervals for the double auction, negotiation-based mechanism and system-determined mechanism.

In Figure 5.16, the simulations for the Herfindahl–Hirschman index against the order book depth for the mechanisms for a clearing interval of 15 minutes can be observed. In subsection 5.3.3, it was noted that the order book depth increased for both the double-auction and negotiation-based mechanism for a longer clearing interval, whilst the order book depth remained constant for the system-determined mechanism when the clearing interval was extended (to the 30-minute and 60-minute intervals). The HHI was computed for each 15 min clearing interval and the order book depth for the three mechanisms and subsequently plotted against each other in the form of a scatter plot, with the order book depth on the x-axis and the HHI on the y-axis. The x-axis is a logarithmic axis to better visualise the different magnitudes of order book depth and their impact on the HHI. The order book depth results align with the observations from subsection 5.3.3, with the system-determined mechanism typically clearing the market with the smallest order book depth, followed by the double auction and the negotiation-based mechanism. As a result, the system-determined mechanism clears the market with the least amount of transactions, as the mechanism is modelled as a seller-based mechanism in which only the sellers submit offers which are subsequently cleared until they meet the demand. The market-based mechanisms such as the double-auction and negotiation-based mechanisms allow buyers to participate in the market as well (participative mechanisms) such that the order book depth increases as more transactions are possible. The negotiation-based mechanism allows for peer-to-peer trading where market participants can engage in multiple transactions, thereby allowing for a deeper cleared order book than the double auction.

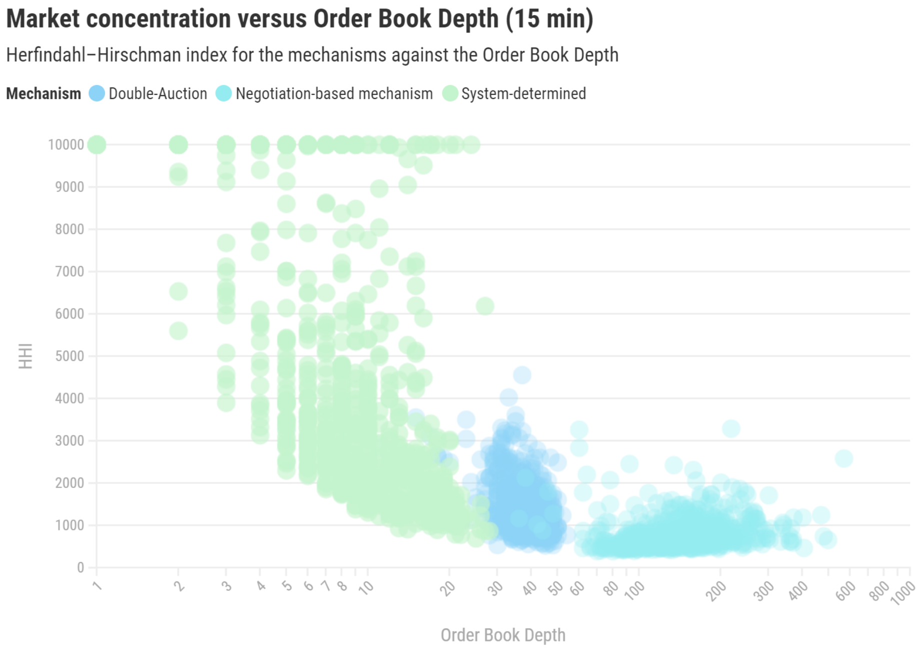


Figure 5.16: Herfindahl–Hirschman index against the Order Book Depth for the mechanisms for a clearing interval of 15 minutes

In Figure 5.16, the HHI is plotted against the order book depth for the 15-minute clearing interval, with the colours indicating the specific results for the type of mechanism. The system-determined mechanism typically clears the market with a small number of transactions in the order book. Hence it is located in the order book depth range of 1 to 30, being the minimum and maximum amount of sellers (a total of 30) in the market necessary to meet the demand. The HHI computes the market concentration for the clearing interval, and it can be observed that a small order book depth results in a high HHI score. This can be explained by the formula for the HHI, which approaches 10.000 when the market shares are dominated by a small number of market participants N, which is the case for the system-determined mechanism when a single seller can meet the demand (the PV park, for example).

As the order book depth increases, the HHI approaches more competitive levels with a less concentrated market (HHI score between 2000-1000 or 1000-0), as more market participants can engage in trading, and the market shares are distributed more evenly. The simulations of the double auction indicate that the order book depth of the market typically ranges between 30 and 60, such that the HHI scores between 3000 and 1000, thereby approaching a more competitive market with less concentration. The negotiation-based mechanism typically operates with a significant number of cleared orders in the order book depth, ranging from 60 to 600, as market participants can engage in multiple trades to meet the demand. With the deeper order book, the HHI scores between 3000 and 500, indicating that the mechanism operates in a medium to low-concentrated market.

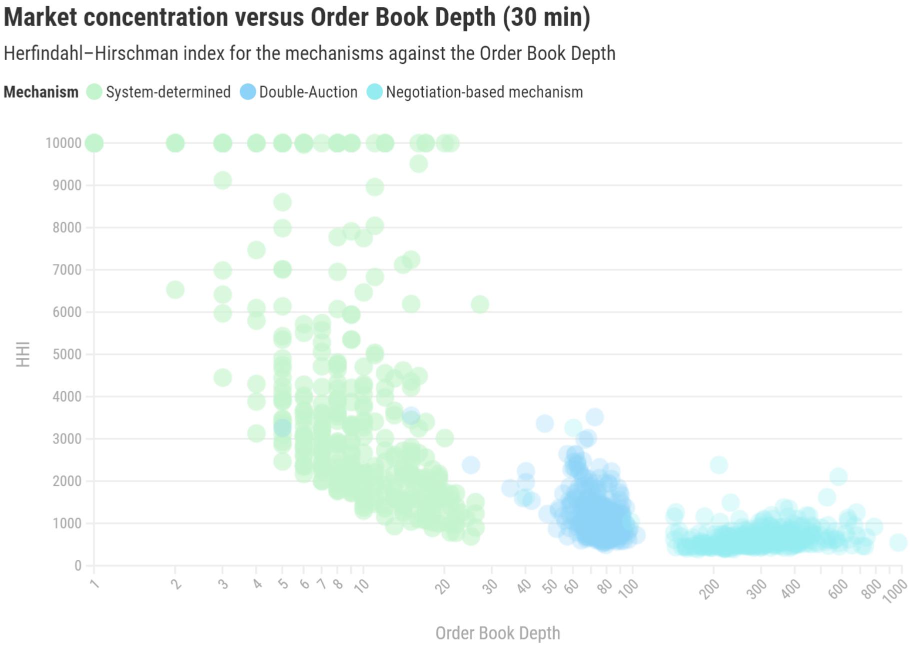


Figure 5.17: Herfindahl–Hirschman index against the Order Book Depth for the mechanisms for a clearing interval of 30 minutes

Earlier in this Chapter, the relation between market dominance and clearing interval was already visualised in Figure 5.7, in which it was already possible to observe that as the clearing interval increases, the market dominance is more evenly distributed among the market participants.

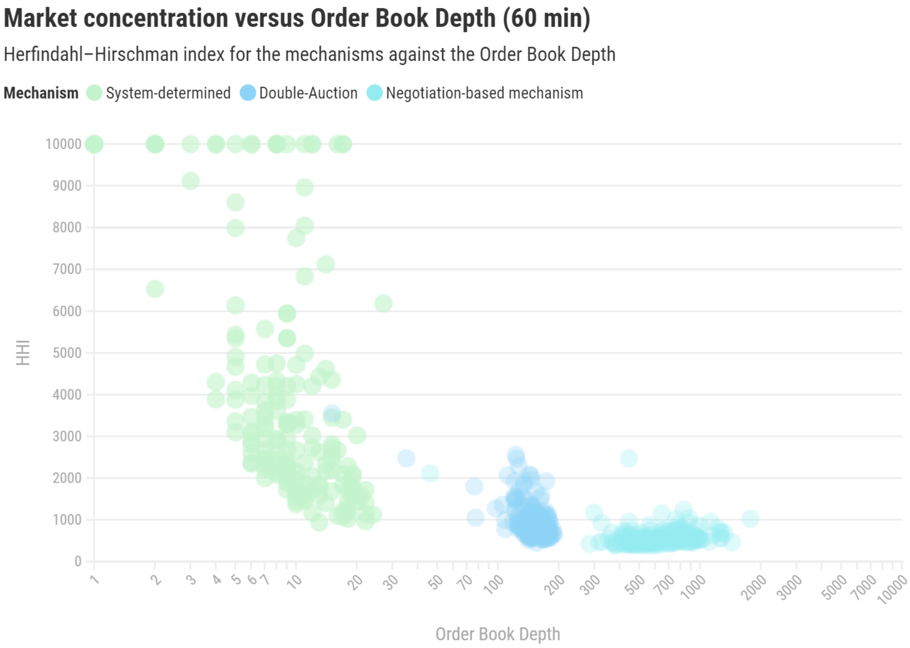


Figure 5.18: Herfindahl–Hirschman index against the Order Book Depth for the mechanisms for a clearing interval of 60 minutes

5.4 Implications for Local Electricity Markets

In Figure 5.19, a schematic representation of the market concentration against the order book depth can be observed with the three mechanisms placed in their corresponding location in the figure. An arrow is depicted that shows the process of the local electricity market as it evolves from a non-competitive market towards a competitive one, with the low market concentration and a deep order book. The figure indicates that there are tipping points for the mechanisms related to the maturity of the local electricity market. The observations can be summarised as follows:

1. **Highly Concentrated market**: In a highly concentrated (HHI 2000-10000) local electricity market, only a small number of market participants N are active in trading. In this type of market, the behaviour of the system-determined mechanism can be helpful in a local electricity market where prices are volatile, or market power is a concern (high HHI score). The system-determined mechanism should be set up to allow for stable prices (the bandwidth between cost prices in the market should be small, or a long clearing interval should be applied (60 min)). In a highly concentrated market, a small number of market players have a significant market share, and any changes in their behaviour can significantly impact prices. Therefore, it is important to have a system that can help stabilise prices and prevent market power abuse. This can, for example, be a board that monitors the behaviour of the market participants, consisting of multi-disciplinary stakeholders that monitor the criteria identified in the multi-criteria-mapping process. As a result, the regulated (cost-based) system-determined mechanism can help to ensure that prices are fair and reasonable for all market participants.

2. **Medium Concentrated market**: In the medium concentrated local electricity market (HHI 2000-1000), the market is less subject to a small number of players with a significant market share as is the case in the highly concentrated LEM, and therefore a market-based mechanism for price formation can be introduced such as the double auction. Introducing a double auction makes it possible to promote competition and ensure that prices are determined through market forces. This can help to protect consumers and promote a more efficient and competitive market. As a result, the medium concentrated market is less vulnerable to potential market manipulation by a small number of players and to strategic bidding by market participants.

3. **Low Concentrated market**: In the low concentrated local electricity market (HHI 1000-0), there is sufficient liquidity and competition to introduce a negotiation-based mechanism, operating using peer-to-peer trading principles. In this market, the market participants can trade on a peer-to-peer basis with each other, in which they have more opportunities to match trades based on heterogeneous preferences such that individual trades can be arranged. Peer-to-peer energy trading can help to create a competitive market among the LEM market participants without the intervention of a third party (allowing decentralisation), where market participants can conduct energy trading autonomously according to personal preferences.

Locality

An essential criterion for setting up a Local Electricity Market is establishing 'local' boundaries in which the local market operates. As described in section 2.7, the concept of 'local' refers to a 'close social or geographical proximity' of the actors engaging in the exchange of electricity [86], and there are four ways to define this concept: network-based, distance-based, administrative and ad-hoc. The definition of local also impacts the performance of the LEM, as in general, a more 'concentrated' LEM allows for more market power-related issues, implicating that a LEM defined in a smaller area with few market participants is subject to a higher degree of market power issues as compared to a LEM with more market participants with larger proximity and thus more liquidity. In Figure 5.20, a schematic representation of the impact of locality on market

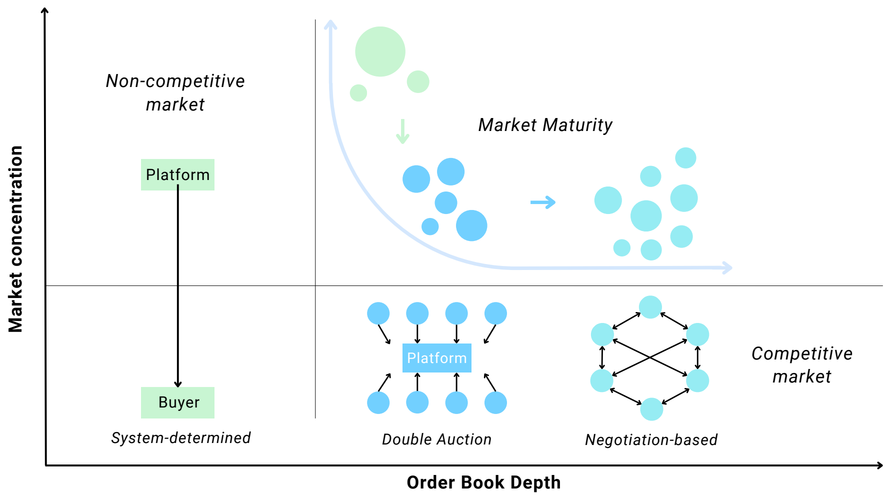


Figure 5.19: Schematic representation of the market concentration against the order book depth and implications for the mechanisms

power and liquidity in the market can be observed. This topic will be discussed further in the recommendations section, and recommendations will be made for defining the locality.

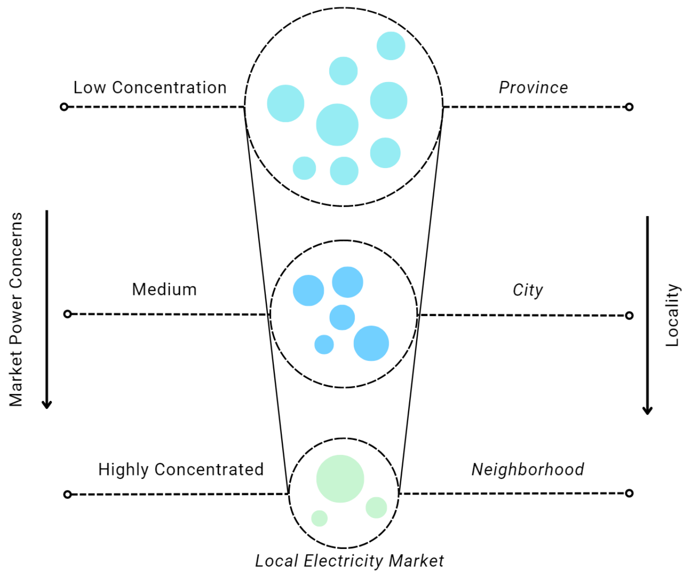


Figure 5.20: Schematic representation of the impact of locality on market power and liquidity in the market

5.4.1 Road map for Local Electricity Markets

In Figure 5.21, the road map for Local Electricity Markets from initiation to maturity, as based on the findings in this research, can be observed. In accordance with the evolution of a LEM from a highly concentrated market to a medium concentrated market and low concentrated market, a road map can be constructed in which four different stages are represented. The stages can be defined as follows:

1. **Initiation & Motivation**: This is the first step in setting up a LEM, in which the initial market participants have a shared vision to develop a local market for the exchange of electricity, for example, sparked by the ambition to trade to locally generated electricity by an energy community or address congestion in the distribution network. Market participants like energy communities, prosumers, large producers and DSOs are involved. A board that represents the stakeholders from different perspectives define 'locality' in line with their vision and identifies potential LEM participants based on complementary production and consumption profiles (for example, by matching a solar park with a wind farm to complement the portfolios).

2. **Mobilisation**: After the Initiation & Motivation stage has been completed, the concept of the LEM can be mobilised. A pilot LEM is created with the first market participants with residual volumes (production surpluses or deficits) available to trade. Simplistic and stable price formation is facilitated by a system-determined price formation mechanism, which determines the prices within the LEM. A multi-disciplinary monitoring board is established that monitors the conditions within the LEM. Dishonest behaviour, transparency and fairness are monitored with market metrics such as order book depth and the Herfindahl-Hirschman Index (HHI). The HHI is computed by summing and squaring all the market shares of the market participants (being the share of traded volume over total traded volume), and the number of individual market participants is monitored to assess the potential number of trades per clearing interval (order book depth). In this stage, the LEM is characterised by a small number of market participants, posing a risk to market power issues (HHI 10.000-2000), which underlines the need for implementing system-determined price formation.

3. **Growth Stage**: After completing the Mobilisation stage, the LEM can grow, and more market participants enter. As the market conditions are monitored, it is found that the HHI approaches competitive levels (HHI 2000-1000), indicating that the market shares are distributed more evenly. As a result, a market-based price formation mechanism can be introduced: auction-based price formation. In this medium-concentrated market, it is possible to promote competition and ensure that prices are determined through market forces. This can help to protect consumers and promote a more efficient and competitive market. As a result, the medium concentrated market is less vulnerable to potential market manipulation by a small number of players and to strategic bidding by market participants.

4. **Maturity**: The LEM has completed the growth stage and established a mature Local Electricity Market. It is up to the market participants to decide if they want to introduce a negotiation-based price formation mechanism instead of the auction. In this market, market power is no longer a concern (HHI 1000-0). If a negotiation-based mechanism is selected, the market participants can arrange individual peer-to-peer trades based on heterogeneous preferences (for example, only matching with solar-generated electricity). The market participants reflect on their initial vision defined in the Initiation & Motivation stage and assess whether the LEM performs as initially envisioned.

This is the first stage in which market participants explore the potential of a LEM, followed by the mobilisation stage, growth stage and final maturity stage in which a competitive LEM is established with market-based price formation. In the figure, the mobilisation stage corresponds to the highly concentrated market, the growth stage to the medium concentrated market and the maturity stage to the low concentrated market. Locality can be defined underneath a 110 kV substation, within a distance of 20 km or a municipality. Market monitoring is conducted by multi-disciplinary stakeholders that monitor the HHI, order book depth, transparency and fairness.

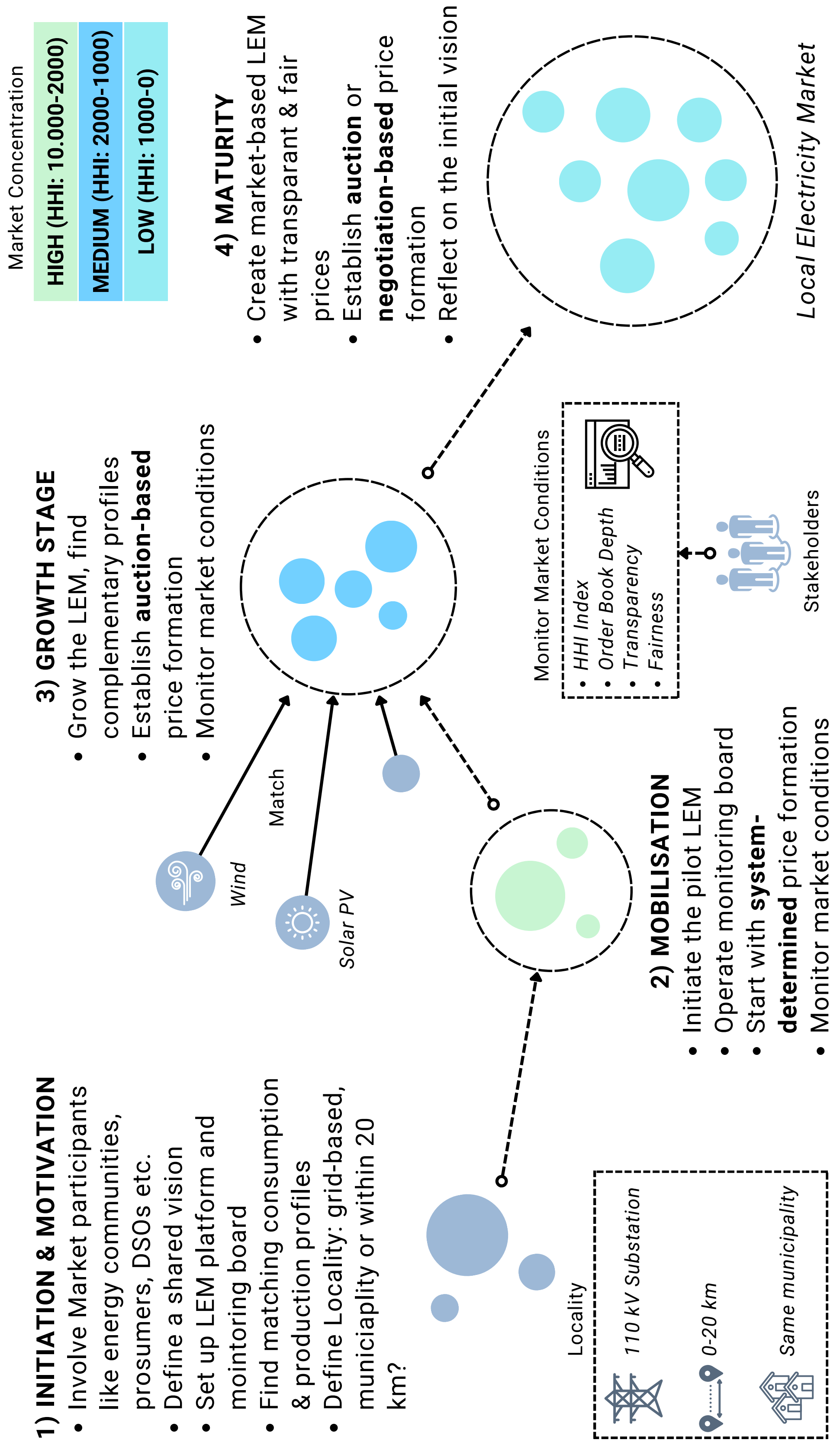


Figure 5.21: The road-map for Local Electricity Markets from initiation to maturity

Chapter 6

Discussion, Conclusion & Recommendations

6.1 Discussion and Limitations of the Study

The thesis applied a mixed-methods approach to address the leading research question. The threefold goal of the thesis was constructed around three methodologies to allow for a comprehensive analysis of the thesis subject. The literature review served to establish the fundament of the thesis and gather insight into how wholesale markets operate and, consequently, LEMs. During the literature review, it was found that papers focused on price formation or market mechanisms for LEMs typically select a mechanism (often the double-auction) without further elaboration on why the mechanism was selected and what other alternatives there were. Most of the papers were focused on the working principle of the mechanisms and their performance. Still, there was not necessarily a 'birds-eye-view' of the benefits and merits of the different mechanisms that could be applied. As a result, academic work on comparing different price formation mechanisms for LEMs would be a valuable contribution to LEM literature. The application of MCM in electricity markets was also a new contribution to academic literature. As the methodology has not been applied in many fields, there was a learning curve in applying the methodology in the specific field of Local Electricity Markets. Establishing the structure of the interviews and processing the MCM results were important steps in the methodology, and it can be helpful to provide more comprehensive guidelines for these aspects for further academic work. The translation of the MCM results to the final simulation methodology is also subject to discussion points, as the focus of the simulations was on market concentration, as this was a core subject that kept returning in the interviews. Alternative approaches that could have been taken in the simulations could have been focused on the impact on grid performance, cost-benefit distribution and further investigation of economic efficiency. Other discussion points will be further discussed per methodology.

6.1.1 Literature Review

The findings of the literature review, especially relating to the advantages and disadvantages of the price formation mechanisms, did not always correspond with the findings of the MCM and simulations. For the system-determined mechanisms, it was noted that the mechanisms are subject to low transparency, whilst a large proportion of the stakeholders indicated that the mechanism can be characterised as transparent as long as the working principles are disclosed. The findings of the negotiation-based mechanism were, in general, by the findings of the other methods, as stakeholders indicated that they allow for privacy and autonomy. However, they might be subject to conceptual complexity, and there is no single market price as found in the simulations. The auction's findings also aligned with the results of the other methods, as auctions allow for information revelation to the market and yield efficient outcomes, whilst they might be intimidating to some market participants.

6.1.2 Multi Criteria Mapping

Different discussion points can be raised for the MCM process, with the first two points reflecting the core criteria used in the methodology as the stakeholders interpreted some of the core criteria differently. The criterion 'participation' was interpreted by some stakeholders as direct participation in the price formation process in the form of actively submitting bids and offers and trading electricity. However, other stakeholders interpreted participation more indirectly, as in 'participation in the market' and not necessarily participating in the price formation process. This primarily affects the scoring of participation for system-determined mechanisms, as they do not necessarily allow for direct participation in the form of submitting bids and offers but rather for indirect participation in the LEM, as no participation structures are necessary for market participants to participate in a system-determined based LEM. Similarly, the transparency criterion was also interpreted differently by the stakeholders, especially relating to the negotiation-based mechanism. Negotiation-based mechanisms allow for transparent price formation for the two directly involved market participants but not for third parties (that are not directly involved in the trading). As a result, the mechanism allows for transparent price formation for the market participants rather than for the complete market, which affects the scoring by the stakeholders. It can be speculated that the stakeholders from different perspectives may have introduced discretionary criteria that capture the interests of the stakeholders from that particular perspective. Stakeholders from the market perspective introduced the 'operation under low liquidity and 'market power' criteria, which are market-related criteria. Similarly, The cooperative sector introduced criteria such as 'arbitrage', 'autonomy', and 'local reflectivity, which reflect the specific concerns and priorities of the cooperative sector.

Next to that, the number of stakeholders that were interviewed per perspective differed, with some perspectives having a total of 3 individual stakeholder perspectives, whilst the public sector's perspective was only based on one interview. For a fair comparison, it is desirable to interview an equal amount of stakeholders per perspective and strive for a minimum of three interviews per perspective. Due to time limitations, this was unfortunately only achieved for some perspectives in the MCM procedure.

The MCM methodology allows for several degrees of freedom in the uncertainty ranges between the minimum and maximum scores for the mechanisms. As a result, some stakeholders scored the mechanisms on criteria with a bandwidth of 20 points, whilst others did this using 60 points. Consequently, the scores of stakeholders with small bandwidths could be diluted if scores from stakeholders with a larger bandwidth were included in the perspective, making it difficult to compare scores across stakeholders with different bandwidths. A suggestion for the MCM methodology could be to set a standard scoring bandwidth for all stakeholders, ensuring that all scores are equally comparable.

Overall, the MCM methodology allows for a reflexive and iterative process, as stakeholders can address and adapt their individual scores and weights for the different criteria during the MCM process. The final results allow for an optimal representation of the stakeholders' perspective. Thereby, the MCM methodology is able to capture the perspectives of a diverse range of stakeholders, making it a fitting and dynamic methodology for assessing complex topics in niche academic fields, such as LEMs, that require participative stakeholder engagement for the analysis of a transition in a sector with large incumbent market participants to a more decentral, bottom-up energy system.

6.1.3 Simulations

The simulations that assessed the performance of the price formation mechanisms in a case study resulted in interesting findings. However, the results are subject to a number of discussion points. First and foremost, only a single case study was simulated to obtain the results due to time limitations. For the purpose of collecting results that capture the complete complexity and performance of the price formation mechanisms, it is recommended to simulate multiple case studies that differ in their setup. For example, a small-scale LEM with only 5 participants, a medium-scale LEM with 100 participants and a large-scale LEM with 1000 participants. Next to that, only a week as the clearing period was simulated in March; however, it is also important to simulate longer time periods (months or years) in other seasons to investigate the impact on the price formation mechanisms more elaborately. It can be expected that the performance of the fixed generator will not be affected by the seasonality. However, the behaviour of the large-scale PV park the prosumers are expected to differ, which could impact the final results. The LEM setup now had a surplus of generation to meet the demand of only 30 households; it might be of added value to also research the impact of a LEM setup with a surplus of demand on the performance of the mechanisms. In addition, the market participants in the simulation are modelled as zero-intelligence agents; for future research, it may be interesting to investigate the impact of agents motivated by strategic behaviour on the performance of the price formation mechanisms. This will also help better predict the performance of the mechanisms in real-life environments.

The negotiation-based mechanism was simulated as a peer-to-peer mechanism with individual transactions. In the literature review, the mechanism was defined as a 'one-to-one interaction between market participants that result in a mutually agreed upon bilateral contract consisting of both price and quantity specifications'. Consequently, the behaviour of the mechanism in the simulation is comparable to the definition identified in the literature review; however, now, the negotiation is automated (based on the pay-as-bid rule) and not necessarily an interaction between the two market participants. For the purpose of this study, it was decided that the modelling of the mechanism is in accordance with the mechanism as discussed in the literature review and MCM process.

The system-determined mechanism was modelled after the Local4Local mechanism using the cost-plus pricing methodology. However, as described in the literature review, the system-determined mechanisms could encompass a broader range of mechanisms that vary in their complexity as compared to the cost plus mechanism, as the system-determined mechanisms could be fixed and pre-determined mechanisms, optimisation and game-theory based mechanisms or demand-based mechanisms. In this case, a fixed and pre-determined mechanism was modelled. However, it could be insightful also to collect results for other types of system-determined mechanisms in future research. Within the system-determined mechanism, the cost price of prosumers was equal to the Netherlands' average feed-in tariff. However, this price may not capture the total cost of ownership for a prosumer that engages in trading in a Local Electricity Market. For the purpose of this study, it was decided that the average feed-in tariff is the minimal cost that a prosumer is willing to receive for electricity, as it also represents the lower bandwidth of trading within a LEM and all prices for selling above the feed-in tariff result in a financial benefit for the prosumer.

6.1.4 Reflection to academic literature

Further research is necessary to understand the relation between the order book depth and HHI; however, as indicated by Naldi, M. & Flamini, M. (2014) [90], the relation between the HHI and market shares is non-linear, as the HHI follows a quadratic dependence on the market shares of the market participants. Consequently, the cleared order book depth is composed of all cleared bids and offers of the market participants N such that when the order book depth is equal to 1, a monopoly situation is present in the market as a single market participant has a market share of 1 (and the HHI is equal to 10.000). As the order book depth increases, the distribution of market shares becomes more competitive as more participants have a share in the traded electricity, which is also reflected in a lower HHI score. As noted in Market Structure, Industry Concentration, and Barriers to Entry by Tremblay, V.J. & Tremblay, C.H. (2012), 'An increase in the size of the market (TR) causes concentration to fall' [116][p.201]. In Figure 6.1, a figure can be observed from the book, in which a similar relation between the concentration in the market and the market size is present as in the plots in this thesis, visualising that the market concentration decreases as the market size increases. Reflecting this to the price formation mechanisms, when a smaller number of market participants hold the surplus of market shares, collusive pricing behaviour becomes more accessible. O'Shaughnessy, E. (2018) found that market participants increase their prices as there is an increasingly smaller number of market participants in the market, which is a phenomenon also known as 'strategic bidding'. In the context of an auction, strategic bidding implies that market participants submit higher bids as the number of rivals in a market decreases [97].

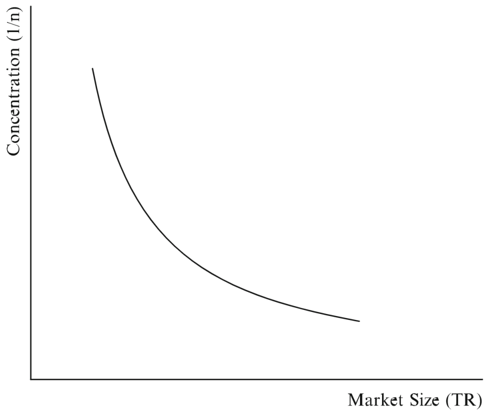


Figure 6.1: The relationship between concentration and market size [116]

6.2 Conclusion

The goal of the thesis was threefold, with the first section being the foundation of the report in the form of a literature review. The literature review explored the fundamentals of wholesale and local electricity markets to outline the price formation mechanisms applied in academic literature in the field of Local Electricity Markets. After the identification of three classifications of price formation mechanisms, an extensive stakeholder involvement process was conducted. Eleven multi-disciplinary stakeholders from five distinct perspectives were involved in the Multi Criteria Mapping (MCM) process in which they mapped out the different technical, social and economic aspects of the previously identified price formation mechanisms. As a result, 20 discretionary criteria were introduced. Each perspective established an interpretation of suitable price formation from their perspective in combination with a final ranking of the three core mechanisms. To reach a well-considered conclusion to the research question, the performance of the price formation mechanisms was assessed through the simulation of a case study. As indicated in the stakeholder interviews, the stakeholders raised concerns about how the price formation mechanisms would operate under sub-optimal market conditions.

These three research goals were addressed by the formulated research question that guided this thesis:

> **What is a suitable mechanism for price formation in a Local Electricity Market?**

To reach a conclusion for the leading research question for the thesis, the threefold thesis structure was related to three sub-questions. The first sub-question was defined as:

> *What are potential price formation mechanisms for Wholesale and Local Electricity Markets?*

The first sub-question was answered using a literature review of academic literature, producing a twofold answer: one relating to wholesale markets and the other to local electricity markets.

Traditionally, wholesale electricity markets were designed in a vertically integrated manner, in which a single firm was responsible for the generation, transmission and supply processes without competition until the late 1990s. A total of four legislative packages were introduced in Europe to increase competitiveness in the market, higher economic efficiency, reduce prices, lower entry barriers in supply chains, and unbundle vertically integrated companies such that the market evolved to be more consumer-centred, competitive and non-discriminatory. The Fourth Energy Package, also known as the Clean Energy For All Europeans package, prioritises consumer empowerment by placing them at the centre of the European energy system, allowing them to make decisions on producing, sharing, and trading their energy, with the aim of active consumer participation and increased implementation of renewable energy, improved security of supply, and enhanced governance and efficiency. The European Directives steer towards increased local participation from prosumers in the distribution grid, which could help Distribution System Operators alleviate congestion issues in the distribution grid in the shape of a local market next to active prosumer participation in the grid.

Transactive energy systems operating in distribution grids are called Local Electricity Markets (LEMs), which are proposed as a solution for integrating Distributed Energy Sources (DERs) and enabling the trading of locally generated electricity among local market participants. The academic literature agrees on the different price formation mechanisms that can be applied in local electricity markets, and the mechanisms were classified into participative mechanisms: auctions and negotiation-based mechanisms and the non-participative mechanisms system-determined mechanisms. Auctions are defined as well-specified negotiation mechanisms in which market participants submit bids and offers, and the market is cleared at the intersection between demand and supply. It has been widely applied in LEM literature. Negotiation-based mechanisms allow for peer-to-peer interactions between market participants, resulting in a mutually agreed upon bilateral contract consisting of price and quantity specifications. Lastly, System-determined mechanisms are defined as mechanisms in which a market operator establishes prices based on pre-defined mathematical formulas or mechanisms. System-determined mechanisms typically allow for a conceptually simplistic and time-efficient mechanism that is relatively understandable for the end consumer compared to the more demanding mechanisms such as auctions and negotiation-based mechanisms.

The identified price formation mechanisms in the literature review were used as inputs for the Multi-Criteria-Mapping (MCM) process to gather insights from stakeholders and to answer the second sub-research question:

> *What are suitable price formation mechanisms from a stakeholder perspective?*

A total of five perspectives were established to conduct the MCM process, thereby representing a total of eleven stakeholders originating from the public sector, cooperative sector, system operators, market or academic perspective. As a result, the views represent multi-disciplinary actors from the university, business or government sectors, allowing for a comprehensive analysis of the price formation mechanisms in the context of local electricity markets. Including diverse perspectives ensures a holistic understanding of the challenges, opportunities, and trade-offs associated with each mechanism. All stakeholders assessed the mechanisms based on four core criteria: Data Privacy and Security, Transparency, Fairness, and Participation, and were allowed to introduce discretionary criteria for the mapping process. The mechanisms were assessed based on all criteria, which were subsequently weighted such that a final score per perspective was achieved (stakeholders were allowed to make iterations in the scoring process and adapt the scores to reflect their findings in the result optimally).

The findings of the network operator's perspective indicated a preference for the system-determined mechanisms based on the median scoring values. However, it is essential to note that the scoring for this mechanism has a significant degree of uncertainty. Auctions and negotiation-based mechanisms show more agreement but narrower scoring ranges, indicating that the stakeholders have more consistent perspectives and explicit expectations for these mechanisms. In conclusion, the stakeholders may have more aligned perspectives and clearer expectations regarding auctions and negotiation-based mechanisms but a preference for the system-determined mechanisms. The stakeholders preferred the system-determined mechanism as it scored well on data privacy and security and has the potential for fair and transparent price formation compared to the other two mechanisms. However, it was noted that the scoring depended on the specific implementation of the mechanism.

The public sector's perspective revealed a tendency to favour auctions, as auctions allow for non-discriminatory price formation and fair and transparent price formation. A downside of auctions is the non-practical participation of end-users in the price formation process, as indicated by the stakeholder. Negotiation-based mechanisms are more vulnerable to concerns related to market power but allow for participation in the price formation process. System-determined mechanisms do not allow participation in the price formation process according to the stakeholder; however, when the underlying mechanism or formula is disclosed to the end consumer, the mechanism could allow for transparent price formation. After the auction, the system-determined mechanism was the second preferred mechanism, and all mechanisms had a similar uncertainty range, presumably as a single stakeholder conducted the scoring.

The perspective of the market sector showed varying levels of uncertainty in the scoring process. System-determined mechanisms have the smallest range and highest median score, followed by auctions and negotiation-based mechanisms, revealing a slight preference for the system-determined mechanisms. As noted by the stakeholders, auctions are the most optimal mechanism for price formation from the economic perspective. However, in LEMs, the market conditions might not always be similar to the conditions in the wholesale market in relation to market liquidity and the balance between demand and supply. As a result, the stakeholder indicated that system-determined mechanisms, in which price formation is not the result of market forces, might be a more fitting solution as the mechanism can provide fair and transparent prices. It was noted that auctions could be experienced as a complex process, which may create entry barriers for market participants, whilst system-determined mechanisms allow for a more accessible market as they do not require specific information or expertise to participate. System-determined mechanisms were considered more transparent, but the stakeholders noted that the disclosure of the mechanism was crucial.

As for the cooperative sector, in terms of medians, system-determined mechanisms have the highest score, followed by negotiation-based mechanisms and auctions. Due to the scoring differences between the two stakeholders, there is a large dispersion of the data indicating uncertainty in the scoring process and conclusions. The stakeholders expressed their concerns about the application of market forces for the price formation of electricity and that not all market participants have the same capacity to navigate the market, which might be relevant for a market-based mechanism such as an auction, thereby raising concerns related to fairness. The stakeholders had contrasting viewpoints regarding the transparency and fairness criteria, and further stakeholder engagement will be necessary to establish a clear conclusion from this perspective.

The scores of the last perspective, the academic perspective, revealed that auctions have the highest median score, followed by the system-determined and negotiation-based mechanisms. Similar to the market perspective, a stakeholder from the academic perspective noted that auctions allow for ideal price formation under optimal market conditions. However, under sub-optimal market conditions, a cost-based (system-determined) mechanism that is not dependent on conditions in the LEM may be more suitable for price formation. Therefore, a combination between an auction and a system-determined mechanism, dependent on the conditions within the market, might allow for effective price formation. The stakeholders indicated that system-determined mechanisms could allow for transparent price formation when the underlying mechanism is disclosed, and all agreed that auctions allow for transparent and fair price formation. Negotiation-based mechanisms allow for participative price formation but not transparent price formation for third parties in the LEM.

In summary, suitable price formation from the stakeholder perspectives can, in general, be achieved by auctions as they allow for fair and transparent price formation, among other aspects, as noted in the introduced discretionary criteria. However, system-determined mechanisms are also expressed by stakeholder perspectives as the preferred mechanism for price formation in a local electricity market due to their conceptual simplicity, fairness and transparency, with the underlying requirement that the working principles of the mechanism are disclosed to the market participants. Although negotiation-based mechanisms allow for participative price formation, the stakeholders raised concerns about market power abuse and transparency. In addition, the selection of a suitable price formation mechanism for a local electricity market is also dependent on the conditions within the market relating to liquidity and market concentration, as expressed by the stakeholders from the market and academic perspective.

Consequently, the performance of the price formation mechanism was assessed through the simulation of a real-life case study to analyse the mechanisms' suitability under varying market conditions, as indicated by the stakeholders. The findings of the third and final sub-question provide insights into the performance of the price formation mechanisms under varying market conditions. The third sub-question is formulated as follows:

How do the price formation mechanisms perform in a case study?

The selected case study for the simulations is the application of a new price formation mechanism proposed in the Local4Local consortium: cost price plus, in which market participants charge the cost price plus a small markup for their generated electricity. The model facilitates decentralisation and community involvement in energy production and consumption, contributing to a more sustainable and equitable energy transition. The case study is modelled using a landfill gas generator, a large-scale solar PV park, and 30 prosumers that trade locally generated electricity in the form of a local electricity market in the LEMLAB simulation environment. However, it is important to note that the simulations are based on a single case study, and therefore, the results should be interpreted with caution.

The results of the simulations indicate that the system-determined mechanism typically clears the market with the smallest cleared order book depth, as the mechanism relies on sellers submitting a cost price, resulting in a cleared order book containing only the necessary matched offers to meet the demand. The auction-based mechanism clears the market with a deeper order book, in which all matched bids and offers for the clearing interval are collected. In the negotiation-based mechanism, all individual market participants can engage in peer-to-peer trading to meet the demand, resulting in the most significant order book depth per clearing interval. Furthermore, the simulations indicate that order book depth is increased, more volume is traded, and the average clearing prices for the auction and negotiation-based mechanism decrease. The system-determined mechanism shows convergence towards a relatively stable average price as the order book depth increases, indicating a more reliable and consistent clearing process that is less subject to market fluctuations and other external factors. The behaviour of the system-determined mechanism can be helpful in a local electricity market where prices are subject to significant volatility or market power is a concern. As noted in the literature review, An advantage of system-determined mechanisms is that the prices are predictable and they are not prone to manipulation by market participants; however, they do not account for the implementation of efficiency improvements and overpaying or underpaying for electricity is plausible as the mechanism does not accurately represent real-time market conditions.

To examine the effect of market concentration on the performance of the mechanisms, the Herfindahl–Hirschman (HHI) index was computed per clearing interval. The Herfindahl–Hirschman index is a well-used indicator for market concentration and is used by the European Commission to assess market power within a market. An HHI score between 10.000 and 2000 indicates a market with high concentration, 2000-1000 a market with medium concentration and 1000-0 a market with low concentration. For the three clearing intervals (15 min, 30 min and 60 min), the HHI and order book depth per mechanism were computed and plotted against each other. The results indicated that the typical cleared order book depth ranges of the mechanisms correspond to HHI scores that indicate the level of concentration in the market and can be summarised as follows:

1. **Highly Concentrated market**: In a highly concentrated (HHI 2000-10000) local electricity market, there typically are only a small number of market participants active that engage in trading. In this type of market, the behaviour of the system-determined mechanism can be helpful in a local electricity market where prices are volatile, or market power is a concern (high HHI score). The system-determined mechanism should be set up to allow for stable prices (the bandwidth between cost prices in the market should, for example, be small, or a long clearing interval should be applied (60 min)). In a highly concentrated market, a small number of market players have a significant market share, and any changes in their behaviour can significantly impact prices. Therefore, it is important to have a system that can help stabilise prices and prevent market power abuse. This can, for example, be a board that monitors the behaviour of the market participants, consisting of multi-disciplinary stakeholders that monitor the criteria identified in the multi-criteria-mapping process.

2. **Medium Concentrated market**: In the medium concentrated local electricity market (HHI 2000-1000), the market is less subject to a small number of players with a significant market share as is the case in the highly concentrated LEM, and therefore a market-based mechanism for price formation can be introduced such as the double auction. By introducing a double auction, it is possible to promote competition and ensure that prices are determined based on market forces. This can help to protect consumers and promote a more efficient and competitive market. As a result, the medium concentrated market is less vulnerable to potential market manipulation by a small number of players.

3. **Low Concentrated market**: In the low concentrated local electricity market (HHI 1000-0), there is sufficient liquidity and competition to introduce a negotiation-based mechanism, operating using peer-to-peer trading principles. In this market, the market participants can trade on a peer-to-peer basis with each other, in which they have more opportunities to match trades based on heterogeneous preferences such that individual trades can be arranged. In addition, there is a smaller chance for market power abuse in the negotiation-based mechanism in this market as the market shares are more evenly distributed among the market participants, which was a concern of the stakeholders in the MCM interviews.

To answer the overarching research question:

> Suitable price formation in a Local Electricity Market is dependent on both the varying stakeholder perspectives and market conditions. The stakeholders expressed their preference for both auctions and system-determined mechanisms, whilst negotiation-based mechanisms also have preferable aspects. The choice for a price formation mechanism for a Local Electricity Market should be made in collaboration with stakeholders from the network operators, public sector, market, cooperative sector, and academic

perspective such that all discretionary interests and concerns of stakeholders are represented in the decision-making process. The market conditions in the Local Electricity Market should be monitored in order to assess market dominance, efficiency, transparency, and fairness. If the market conditions are sub-optimal, for example, due to high market concentration, a stable, disclosed and transparent system-determined mechanism should be implemented until effective price formation by an auction-based mechanism can be implemented. As indicated by the stakeholders, auctions allow for fair and transparent price formation and promote a competitive market with efficient price formation. This framework allows for the robust, fair, and efficient pricing of electricity within a Local Electricity Market, thereby ultimately contributing to the transition towards a sustainable energy supply.

6.3 Recommendations

After drawing conclusions based on the findings in the thesis, several recommendations can be drawn for the sector, regulatory perspectives and future research.

6.3.1 Recommendations for the sector

The sector is ultimately responsible for implementing LEMs, and different systems and infrastructures should be in place to allow for the adoption of the local market structures. Market monitoring and stakeholder involvement are identified as important recommendations, and an important first step is establishing a multi-disciplinary board responsible for the organisation and monitoring of the LEM. A recommendation for setting up of the board is to incorporate established energy communities in a local region and assess the potential of the residual volumes that they have, after which a matching process should be organised in which the optimal energy sources are matched to the consumption profile of the community. When setting up a LEM, the production and consumption patterns of the market participants must be complementary such that a high degree of self-sufficiency can be achieved. Consequently, other market parties can also be invited to the LEM in order to allow for the optimal matching of local production and consumption. Other recommendations for the sector are:

- **Market Monitoring**: Establish a robust system in which the conditions within the Local Electricity Market are frequently monitored. Through market monitoring, the decision to alternate between a stable system-determined mechanism and an auction can be made, for example, by responding to sub-optimal market conditions in which a small number of market participants manipulate the prices within the market. The system should ensure that the price formation mechanism represents fair and transparent prices and monitor the submitted bids, offers, and cost prices so that market participants do not exhibit speculative behaviour at the expense of other market participants.

- **Communication infrastructure**: Communication infrastructure should be in place that allows market participants to exchange information and communicate bids and offers to a central entity. This infrastructure is a crucial component to establishing price formation, as it supports efficient LEM clearing, enhances transparency and competition, and enables stakeholders to participate in the market actively.

- **Bidding Horizon**: Start with a LEM clearing interval of 60 minutes, thereby allowing market participants and communication infrastructure to establish market clearing on an hourly basis. A longer clearing interval allows for a more significant number of bids and offers to be submitted to the local electricity market, thereby allowing for more liquidity in the market which consequently allows for more efficient price formation. If the market is evolving and more bids and offers are available in smaller clearing intervals, such as 30 minutes or even 15 minutes, the market clearing can be conducted on a more granular basis which allows for the more optimal matching of renewable energy sources. However, this adjustment should only be made if there is enough liquidity in the market to prevent volatility and inefficient clearing.

- **Entry Barriers**: As indicated by the stakeholders, the technical entry barriers in submitting bids to the LEM by market participants should be low, such that decentral market parties such as energy communities and prosumers can participate in the trading process with their decentral assets. These barriers relate to the minimum volume requirements for submitting a bid to the LEM so that smaller bids can be incorporated into the bidding process.

- **Order book disclosure**: To create a level playing field for all LEM participants, it is crucial to disclose price information such as the order book. Market participants must have insight into the conducted trades so that they can anticipate the events in the market and transparent price formation can be established.

6.3.2 Policy recommendations

To ensure the success of Local Electricity Markets (LEMs), it is crucial to have appropriate regulatory frameworks that enable and support the new market structures. The regulatory frameworks should depict who can engage in local electricity trading (consumers, prosumers, energy communities, market parties etc.) and what the physical requirements are (smart meters and grid connections). It is also essential to allow market participants to trade with market participants connected with different Balance Responsible Parties (BRPs)(thereby allowing multi-BRP trading). Next to that, the following recommendations can be made for policy implications:

- **Monitoring framework**: Regulatory agencies should establish regulatory frameworks that allow for monitoring conditions within the Local Electricity Market and facilitate the possibility of intervening in the market if necessary to protect the interests of the market participants within the LEM. The market monitoring institution should be comprised of multi-disciplinary stakeholders such that a holistic perspective is considered when making decisions that affect the price formation process within the LEM. For example, stakeholders that could be included can originate from the public sector, cooperative sector, system operators, market or academic perspective.

- **Trading framework**: A legal framework should be established that allows market participants within a Local Electricity Market to engage in trading. The specific rules for the participants that engage in trading must be specified, including the rules concerning information that should be provided by the market mechanism (for example, bids and offers structures), rules for matching supply and demand, and the price formation mechanism. The legal framework should ultimately be represented in the Dutch 'Energiewet'; however, lobbying is still necessary to ensure that the interests of LEMs are represented in the new legislation (which is up to the sector).

- **Disclosure and Transparency**: As indicated in the stakeholder interviews, the stakeholders suggest that the price formation mechanisms and their working principles are of great importance to the public, such that market participants have insight into how the mechanisms operate. Transparency is a key criterion in the functioning of the price formation mechanisms. Therefore it is recommendable to set up clear regulatory guidelines on how the working principles of the mechanisms can be disclosed and allow for transparent price formation.

- **Training and education**: As new, decentral market participants (such as energy communities and prosumers) will participate in LEMs, it is essential to minimise information and access barriers that impact participation. This can, for example, be facilitated by setting up training courses for market participants on how the price formation process works and how the market participants can best contribute to the LEM to prevent information asymmetry.

- **Prevent Supplier lock-in** To allow for freedom of choice in local electricity trading, peer-to-peer trading should be possible between market participants that have a different supplier (and BRP). This will prevent lock-ins where end-users can only engage in peer-to-peer trading with customers of the same supplier, which is the current status quo in the energy market. By enabling local energy trading between customers of different energy suppliers, the energy market will become more competitive, and end-users will have more options to choose from. Independent parties such as network operators and network companies can play a crucial role in facilitating the process. They can provide a LEM platform where everyone can come together and exchange information and data.

6.3.3 Recommendations for Future Research

During the study, it was found that several relevant topics could be subject to future academic research in the emerging field of Local Electricity Markets. One of the more critical topics is defining 'local' within the context of LEMs. The definition of local represents the interests of different perspectives of stakeholders. System operators would be interested in defining local based on network topology, as this allows for alleviating grid-related issues. Alternatively, public institutions (such as municipalities) would be more interested in defining local based on administrative boundaries such that, for example, a municipality can participate in the LEM. Ultimately, to allow for successful large-scale LEM implementation, the interests of all involved stakeholders should be represented in defining local as this will ultimately allow for participative markets with more trading opportunities. Additional recommendations for future research are:

- **Define Locality**: Both in the context of energy communities and LEMs, there is no widely agreed upon definition for 'locality' or 'proximity'. Different suggestions have been made, such as network-based, distance-based, administrative-based or ad-hoc; however, a uniform definition is still lacking. It is advised to set up a LEM in which the local boundaries both serve the interests of the grid operator (for example, setting a sub-station as a boundary to address congestion in the grid) whilst also considering market power issues. Next to that, it is of great importance that the LEM boundaries are understandable for the market participants, which might be more simplistic for administrative or distance-based boundaries as compared to network-based boundaries. Because why can a neighbour not trade with a market participant in the following street in a 'local market' when connected to different sub-stations? Ultimately, the boundaries of a LEM should incorporate the interests of all market participants while alleviating grid-related issues. For future research, it will be of great relevance to further define the concept of the locality as it allows for effective comparison and evaluation of different energy communities and LEMs.

- **Research positive grid impact**: To underline the potential benefit of LEMs, it is important to quantify the positive impact of local energy trading on the grid. Currently, congestion issues are a relevant topic in distribution and networks, and energy markets can play a crucial role in implementing congestion management and balancing the energy system. Local energy trading can enable a larger number of participants and flexible capacity to contribute to preventing congestion problems, as more market participants have access to congestion marketplaces (GOPACS). The same applies to balancing the energy system: the more parties become active in the energy markets, the more parties can directly be exposed to the imbalance price. This encourages them to adjust their behaviour in favor of the energy system and is rewarded for doing so. Researching how LEMs can benefit the grid can further facilitate the uptake of local energy trading applications.

- **Tipping Point Identification**: identifying the tipping points for selecting a system-determined mechanism, auctions, or negotiation-based mechanisms. The tipping points could be identified based on economic criteria such as liquidity in the market, market concentration, bid-ask spread, matching efficiency and volatility. However, qualitative criteria should also be considered to map the tipping points further, as identified in this research: transparency, fairness, complexity, participation, and autonomy.

- **Prosumer Cost Price**: The true cost price for prosumers should be computed. These costs should include financing household heat pumps, PV panels, EV chargers, and batteries, for example, over the lifetime period of the products, in combination with interest rates and other relevant investments that should be made to participate as a prosumer in a Local Electricity Market. This cost price can be used in a cost-based mechanism in which all market participants are represented by their true cost price of generating and selling electricity, as envisioned in the Local4Local project.

- **Cost-Based Mechanisms**: Further research could be conducted that investigates the application of cost-based mechanisms in local electricity markets, which provide stable and reliable prices. Most research is currently focused on market-based mechanisms such as auctions or negotiation-based mechanisms. However, a gap in the literature is presently related to the absence of analysis for non-competitive price formation mechanisms.

- **Risk of imbalance**: Further research is necessary to investigate the risk of imbalance (mismatch in planned and actual consumption and or production) caused by the price formation mechanisms in the LEM. In a LEM it is often assumed that market participants have perfect forecasting for their consumption and production profiles, however, this might not always be the case due to a lack of resources. This also relates to responsibility, in which market participants have the most responsibility regarding their predicted profiles in a negotiation-based mechanism due to the decentralised nature of the mechanism. The imbalance costs can also affect the profitability for market participants that engage in local energy trading, as the caused imbalance ultimately has a negative financial consequence for the market participant. As a result, a negotiation-based mechanism with individual trading arrangements results in delegated responsibilities to the market participants, accompanied by a potential negative impact on the profitability of trading.

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Appendix A

Literature review keywords

Table A.1: Keywords for the literature review

Section	Keywords
Electricity Markets: Reform	Electricity market roles liberalisation, EU directives, European energy market, Power Exchange, Day-ahead market, Auctions
Local Electricity Markets	Local electricity markets, P2P electricity trading, Local energy trading, Market Design, Microgrid energy market, Peer-to-peer trading, Price Formation, Auctions, Local market, Energy Communities, Energy Trading, Bidding, Transactive Energy

Appendix B

Stakeholder interviews

In this appendix, the descriptions of the stakeholders and their individual scoring on the different criterions is listed.

Table B.1: Stakeholders interviewed in the MCM interviews and their perspective

Code	Stakeholder	Perspective
A	Umbrella Organisation for energy cooperatives	Cooperative Sector
B	Dutch Network Company	System Operators
C	Dutch DSO	System Operators
D	Umbrella organisation for Dutch DSO's & System Operators	
E	Public Institution	Public Sector
G	Wholesale Market institution	Market
H	Academic	Academic
I	Energy Cooperative	Cooperative Sector
J	Academic (Economics Department)	Academic
K	Academic (Energy Justice Department)	Academic
L	Market Party	Market

B.1 Network Operators

B.1.1 Stakeholder C

Stakeholder C description

Stakeholder C is an employee of a Dutch DSO, which is a network company in the Netherlands that operates the distribution networks for both natural gas and electricity. The stakeholder works in the market services department within the sector Strategy and Innovation and is responsible for the innovation portfolio. The stakeholder is involved in developing new contract formats for the local exchange of electricity, collective self-consumption and markets for local energy systems. As the company from the stakeholder is a network company, it is not allowed to trade electricity. A role that the company could full-fill, however, is supporting and facilitating local market structures with the ultimate goal of enhancing the utilisation of transport capacity in the grid.

After the introduction of the three core mechanisms to the stakeholder the stakeholder noted that he agreed with the classification of the different mechanisms, however the three categories were 'broad'. The stakeholder introduced a discretionary option named 'ownership-based mechanisms'.

In this type of mechanisms, energy is exchanged within a local market in a voluntary manner, free of charge. The mechanism could for example be applied in a situation in which an energy community invests upfront in a renewable energy project and exploits the installation during the operation for no expenses. The energy community thereby has a shared-ownership of the installation and collective receives the profits from the investments. This mechanism could be applied in markets where energy surpluses are exchanged or supplied to for example a social institution for no financial re-numeration. In this mechanism there is not necessarily direct price formation, however, the mechanism can be applied in local market structures for the exchange of electricity within a community and was therefore included as a discretionary option. The stakeholder also introduced two discretionary criteria: Multidimensionality and Efficiency (matching). Multidimensionality was introduced in order to address the non-monetary aspects of the price formation mechanisms, such as the environmental, local and social implications of price formation. A multidimensional price formation mechanism would for example also take community aspects and the matching of sustainably generated electricity into account. Efficiency was established in order to evaluate the mechanisms on the actual matching of supply and demand using the mechanisms.

Stakeholder C scoring

The first criteria that was evaluated by the stakeholder was Multidimensionality. In Negotiation-based mechanisms the transacting parties can find each other on the basis of the characteristics (heterogeneous preferences) that market participants seek in the transaction (score 60-90), similar to Ownership-based mechanisms in which participants can choose to engage with the project as the result of social aspects (community formation or collective investment) for example (score 80-100). System-determined mechanisms could implement non-monetary dimensions in the price formation process (preference for renewable energy sources or local generation) (score 40-70). Auctions typically require a bidding format consisting of price and volume specifications, and no further heterogeneous preferences (score 30-60). The second discretionary criterion, Efficiency (matching) was scored the highest for Auctions (score 80-90), as auctions allow for efficiently matching of supply and demand. negotiation-based mechanism allow for less efficient matching of supply and demand (30-40), as less information is available compared to auctions. In Ownership-based mechanisms, the matching of supply and demand is dependent on the participation of end-consumers in the market structure (score 50-60) that engage in self-consumption. The system-determined mechanisms where scored the highest against the Matching criterion, as the stakeholder indicated that this mechanism can optimise the market to achieve optimal supply and demand matching (score 70-100). As for Data Privacy and Security, Auctions could provide for relatively anonymous and aggregated information revelation, however information must always be disclosed (score 20-40). In Negotiation-based mechanisms, information must also be disclosed, however, only to the counterparty (less information revelation to the public) (score 30-50). In Ownership-based mechanisms, there is no data sharing as no information needs to be disclosed by the market participants (score 80-90). System-determined mechanisms had a relatively large uncertainty interval on the Data Privacy and Security criterion, as Optimisation-based mechanisms require consumer and producer information in order to operate, however, more simplistic mechanisms such as Cost price+ requires only very small amounts of data in order to set prices (score 10-90). As for Fairness, Auctions allow for a relatively fair price formation process as market power could be mitigated (score 60-80), whilst Negotiation-based mechanisms are more sensitive to market power abuse due to strong bargaining positions from market participants (score 30-60). Ownership-based mechanisms are less sensitive for fairness issues as after investment, the collective exploitation phase is less vulnerable for market power misconduct (score 70-90). System-determined mechanisms are again subject to a broader uncertainty range, as Fairness is dependent on the implementation of the specific System-determined mechanism, an optimisation could achieve relatively optimal price formation from a fairness perspective however less extensive mechanisms could achieve sub-optimal results (score 20-80). The stakeholder did not see Auctions as highly participative mechanisms, as the submitted bids are simply submitted to the platform with no further participation (score 40-60). In Negotiation-based mechanisms, stakeholders are able to take achieve more participation in the price formation process as they have the possibility to actively negotiate in the price formation process (score 70-90). In System-determined mechanisms there is no participation for the end-consumer in the price formation process (score 20-30), which was characterised by the stakeholder as the same for Ownership-based mechanisms (score 20-30). The last criterion, Transparency, was scored relatively optimal for Auctions as the stakeholder mentioned that auctions establish transparent price formation (50-70). Negotiation-based mechanisms also allow for transparent price formation, as both parties that engage in a bilateral transaction have insight in the price formation process, however, for outsiders the price formation process is less transparent as there is no information revelation to third parties (score 70-90). System-determined mechanisms can operate as a black box, when the operating principles of the mechanism are not published, and were therefore scored low on the criterion (score 20-30). Lastly, Ownership-based mechanisms also allow for transparent price formation as all involved parties have insight in how the mechanism works during the exploitation phase and what they can expect from the mechanism in terms of non-monetary returns (agreements on energy volume sharing could be established) (score 80-90).

B.1.2 Stakeholder D

Stakeholder D description

Stakeholder D is the Manager Strategy at the Umbrella organisation for Dutch DSO's & System Operators is the sector organization of national and regional electricity and gas network operators. Members of this association are all legally designated national and regional network operators for electricity and gas. The network operators are publicly owned companies that perform an important social task: a reliable, affordable and sustainable energy supply. The network operators have two main tasks: they facilitate the operation of the market and they manage the physical network infrastructure.

At the start of the interview, the stakeholder mentioned the importance of underlining the difference between the economic valuation of electricity and the infrastructure valuation of electricity. To illustrate the twofold valuation of electricity, the stakeholder indicated that electricity storage could provide value for the network operator in terms of peak reduction in the grid. However, when storage solutions participate in balancing markets, there could be instances where these technologies reinforce peaks in the grid and thereby counteract the interests of the network operator. The stakeholder mentioned that it is important to implement a locational component in price formation in order to couple the different valuations of electricity. The locational component could be based on the grid topology, however, the grid topology is subject to changes and reinforcements in the future and should therefore not be the leading locational definition of local electricity markets. The stakeholder mentioned that trade between Maastricht and Groningen should be possible as exchanging electricity should be a right for all market participants, and should not be restricted by grid topology or the boundaries of a municipality. There should be an incentive to exchange electricity locally, but it should not be restricted to exchanging electricity over long distances.

The stakeholder did not introduce a discretionary option, however two discretionary criteria where introduced. The first discretionary criteria was Prevention of dishonest behaviour. This criteria is concerned with preventing market behaviour that could be perceived as dishonest by other market participants (such as exploiting batteries in the local electricity market for financial benefit at the expense of other market participants). The second discretionary criteria was Decentralisation: to what extend is the mechanism able to operate in a decentral manner without the need of a central market party?

Stakeholder D scoring

The first criteria that was evaluated by the stakeholder was Prevention of Dishonest Behaviour, on which auctions were more subject to dishonest behaviour from the stakeholder's perspective as there is more freedom for market participants and less control (score 10-30). Negotiation-based mechanisms were less subject to dishonest behaviour as in bilateral negotiations behaviour is included in the agreements (for example agree to not exploit batteries at the expense of the grid)(score 40-80). The stakeholder mentioned that costs and benefits of the behaviour of market participants could be fairly accounted for in system-determined mechanisms (score 40-80). The second discretionary criterion that was assessed was Decentralisation. The stakeholder scored auctions relatively low against decentralisation as the result of the central nature of auctions, in which a centralised platform is necessary to operate the mechanism (score 30-60). Negotiation-based mechanism typically have a decentral nature through which the transactions are organised, thereby allowing for a higher score on the criterion (60-90). System-determined mechanisms scored lower than negotiation-based mechanisms on Decentralisation, as similarly to an auction, there is always a central party necessary to establish price formation on the basis of formulas or another mechanism. Auctions scored relatively higher on Data Privacy and Security as market participants should be able to trust the central platform to guarantee the security of data and privacy (anonymous trading in auctions)(score 80-100). Negotiation-based mechanisms require information revelation towards the counter party in the trade and is thereby subject to a lower score for Data Privacy and Security (score 30-60), System-determined mechanisms are typically dependent on the submission and usage of data for the operation of the mechanism and was therefore scored lower on the Data Privacy and Security criterion by the stakeholder (score 40-70). As for Fairness, the stakeholder indicated that a larger Local Electricity Marker allows for a fairer auction process as there is more liquidity in the market and an increased chance of matching supply and demand in a fair manner (score 30-60). Negotiation-based mechanisms and System-determined mechanisms were scored equally on the Fairness criterion as the stakeholder mentioned that establishing prices should be possible in a fair manner in both mechanisms (60-80). Auctions scored well on the Participation criterion as the stakeholder indicated that the threshold to participate in an auction is relatively low for market participants (score 70-90). Negotiation-based mechanisms were scored the highest on participation as stakeholder actively participate in price formation in this mechanism (score 80-100). The stakeholder mentioned that system-determined mechanisms allow for more indirect participation of the market participants in price formation as compared to the other two mechanisms, and therefore scored the mechanism equal to auctions on this criterion (score 70-90). The last criterion that was assessed by the stakeholder was Transparency. The stakeholder indicated that auctions are a relatively transparent mechanism for price formation as the process is well understandable for the market participants (score 90-100). Negotiation-based mechanisms scored lower on Transparency as the stakeholder indicated that the negotiation process is less structured and transparent as compared to an auction (score 40-60). Lastly, System-determined mechanisms scored well on Transparency as the mechanisms or formula used in the mechanism should be published and understandable in order to allow for a transparent price formation process (score 70-90).

B.1.3 Stakeholder B

Stakeholder B description

Stakeholder B has both positions at a Dutch network company and Eindhoven University of Technology. Within the network company, the stakeholder oversees a range of research and innovation initiatives aimed at creating new ideas and products that will be essential for the future energy system. This includes developing a regulatory framework and market design that can accommodate an integrated energy system that is sustainable, inclusive, and meets the expectations of society. The ultimate goal is to create an energy system that can operate seamlessly and efficiently while also addressing environmental and social concerns. At Eindhoven University of Technology, the stakeholder is a Research Fellow for Electrical Engineering and is thereby able to provide expertise from both the practical and academic disciplines.

The stakeholder indicated that participative price formation can be facilitated in smaller local electricity markets (LEMs) as the market participants have a relatively larger influence on the establishment of prices as compared to larger markets. Concretely, a LEM that is defined using the geographical boundaries of a municipality allows for a more impacting participation as compared to a LEM defined by the boundaries of a province in which the effect of participation might be smaller in the price formation process. Furthermore, the stakeholder also introduced a discretionary criterion: Effort. This criterion is concerned with the effort required by market participants in order to operate the mechanism. For example, bilateral negotiations could imply a process with high opportunity costs (investing time in order to set up an agreement) which could lead to an entry barrier for market participants to engage with the mechanism. The stakeholder indicated that the mechanism should allow for effortless price formation in which market participants can easily and quickly engage without a significant investment of time or resources. The stakeholder did not introduce a discretionary mechanism.

Stakeholder B scoring

The first criteria that was evaluated by the stakeholder was Transparency. The stakeholder indicated that auctions are a transparent mechanism for price formation as market participants have insight in how the mechanism operates and on which economic principles (matching supply and demand) (score 80-90). Negotiation-based mechanisms are a less transparent mechanism as market participants by definition hold back information in the negotiation process in order to allow for a strong bargaining position, in addition there is no information revelation to third parties (score 40-60). System-determined mechanisms allow for transparent price formation as long as the mechanism is published to the public (for example insight in how the mechanism establishes prices)(score 90-100). The second criterion, Participation, was scored with a broader range of uncertainty on auctions. The stakeholder indicated that auctions become increasingly more participative in smaller market structures, as market participants are consequently increasingly able to influence price formation with their participation. For example, in a smaller LEM, market participants can use their participation to influence the market price however in a larger LEM their influence becomes increasingly smaller (score 50-90). Negotiation-based mechanisms allow for participative price formation due to the nature of bilateral negotiations, which is a participative process in itself. The stakeholder indicated that negotiation-based mechanisms allow for more participation in the price formation process compared to auctions (score 90-100). System-determined mechanisms scored with a relatively large uncertainty on the Participation criterion, as in some system-determined mechanisms participation is possible (energy communities could determined their own cost-price using a predefined formula) whilst other system-determined mechanisms only allow for very little to no participation (locational marginal pricing does not allow for participation from the end-consumers) (score 0-70). Thirdly, Fairness was assessed for the three different mechanisms. In auctions, scarcity on the supply side can lead to lead to market power issues next to market participants with more financial resources being able to take on higher risks in bidding as compared to market participants with less financial resources. The stakeholder indicated that the market forces used in auctions could negatively affect social aspects such as energy poverty, however from the market perspective auctions could be considered fair as they optimally match supply and demand (score 40-60). In negotiation-based mechanisms, market participants have more capacity to influence the outcome of the bilateral negotiation and are less dependent on the actions of other market participants for a fair outcome of the transaction (score 70-90). System-determined mechanisms allow for fair and transparent price formation in which societal concerns (abuse of market power) can be considered. It is for example possible to construct the price formation mechanism in accordance with the principles of an energy community. A risk for fairness in system-determined mechanisms is lobbying or conflicts of interest by the organisations that can influence the mechanism (score 60-100). As for Data Privacy and Security, auctions cored relatively well on the criterion as clear rules are set by the auction platform and anonymity can be ensured (score 90-100). In Negotiation-based mechanisms, more information should be published in order to engage in a bilateral negotiations (score 40-70). System-determined mechanisms were scored with positively on Data Privacy and Security as some specific mechanisms require more data (for example locational marginal pricing) and others less (cost-plus pricing requires only a one time communication of the costs of operating an asset) however there are clear rules on how to manage and store the data (score 70-90). The last criterion that was evaluated by the stakeholder was the discretionary Effort criterion. The stakeholder indicated that auctions require effort from the market participants in order to operate, for example related to setting up a bidding strategy (score 60-70). Negotiation-based mechanisms are more effort intensive as compared to auctions, due to the negotiation process that market participants should participate into which is typically non-standardised (score 30-50). System-determined mechanisms, on the contrary, are less effort-intensive as the mechanisms can operate without too much end-user participation by definition (score 90-100).

B.2 Public Sector

B.2.1 Stakeholder E

Stakeholder E description

Stakeholder E is the director of a Public Institution, that purchases electricity for several Frisian instituations and organisations, including the Province of Fryslân, 17 municipalities, BV Sport, the Fries Museum, Omrop Fryslân, Tresoar, Security Region Fryslân and FUMO. The institution purchases electricity through a tendering procedure, as is a requirement for governmental institutions. Purchasing electricity in accordance with the requirements of the tender procedure is an important aspect for a public institution. As a result of the tendering procedure, the stakeholder mentioned that the price formation mechanism should not discriminate between the different market participants in the matching process, a price formation mechanism that prioritises renewable energy production with consumption over non-renewable energy production units is an example of discrimination and unequal chances in the matching process and it not in accordance with the tendering process. Stakeholder E introduced a discretionary criteria, Non-discriminatory: the different market participants should not be discriminated in the price formation mechanism. The stakeholder did not introduce any discretionary options, as the stakeholder agreed with the formulation of the core mechanisms.

Stakeholder E scoring

The first criteria that was evaluated by the stakeholder was the Non-discriminatory criterion. In auctions, discrimination between market participants is not possible due to the equal bidding structure in the auction process in which no preference for the matching procedure can be incorporated (score 60-90). The stakeholder mentioned that negotiation-based mechanisms are not in line with the procedure of tenders as market participants can be selected for the bilateral contracts, which is not in accordance with the non-discriminatory characteristics of tendering procedures (score 1-5). System-determined mechanisms do also not meet Non-discriminatory aspects as the mechanism also appoints a single party for setting the price and there is no objective selection process (score 1-5). Auctions also performed well on the Fairness criterion (score 70-90), as auctions establish price formation in a market based-manner, whilst negotiations do not necessarily always result in fair market outcomes due to for example strong or weak bargaining positions (score 20-40). System-determined mechanisms were assessed as 'fair' as the system could optimise for the fairest price for the end-consumer and no bargaining power could affect the price formation process (score 80-90). The stakeholder saw limitations in the Transparency criterion of the auctions, as the mechanism does not operate in a conceptually simplistic manner for the end-consumer (score 30-50), whilst negotiation-based mechanism could provide more transparency in the price formation process and into the counter-party (score 50-70), which is not necessarily known in auctions. System-determined mechanisms could provide transparent price formation, as long as the mechanism or formula is disclosed (for example cost price+) for the end-consumer (score 60-80). The stakeholder saw no practical Participation of the end-consumer in the price formation process in auctions as active participation in auctions is more a theoretical concept (score 10-

30). Negotiation-based mechanisms allow for participation in the price formation process from the market participants, for example in the form of bargaining (score 60-70). System-determined mechanisms do not allow for active participation of the market participants in the price formation process by definition, and scored lower on the Participation criterion (score 10-30). The last criteria that was subject to evaluation was Data Privacy and Security, the stakeholder envisioned that auctions would operate on the basis of aggregated data, which allows for maintaining privacy and security (score 60-70). A negotiation-based mechanism requires information revelation of the parties involved in the transaction by definition, however the information is typically kept between the two transacting parties (score 40-70). System determined mechanisms allow for price formation on the basis of aggregated, anonymous data and information such that it allows for price formation that respects data privacy and security (score 60-80).

B.3 Cooperative sector

B.3.1 Stakeholder A

Stakeholder A description

Stakeholder A is the Cooperative Director of the Umbrella Organisation for energy cooperatives. This organisation is the national umbrella organization for local sustainable energy initiatives in the Netherlands. As a result, the organisation represents the interests of local organizations for cooperative and private sustainable energy generation in the Netherlands. The umbrella organisation has a total of 729 direct members (energy cooperatives, foundations and individuals) and, directly or indirectly via regional umbrella organisations, represents the majority of energy cooperatives and 440 private wind turbine operators and thus the largest share of cooperative and private generation in the Netherlands. The organization strives to strengthen the position of local sustainable energy and greater citizen involvement in the transition to a sustainable energy system [39].

The stakeholder from the cooperative organisation represents the concerns of cooperative and private sustainable energy generation in the Netherlands and was thereby able to introduce several discussion points related to the interests of these institutions in price formation in local electricity markets. At the start of the interview, the stakeholder indicated that electricity is a primary need for end-consumers and should therefore not be subject to market forces from economic theory. The stakeholder also highlighted the importance of arbitrage in price formation mechanisms in order to prevent misconduct and market power abuse in price formation. As a result, the stakeholder introduced discretionary criteria: to what extent is it possible to prevent dishonest behaviour and misconduct in the price formation mechanism? This criterion is for example related to preventing market participants from submitting disproportional high prices to the market that prevents a transparent and fair price formation procedure. The stakeholder also introduced a second discretionary criterion: Cost/Benefit distribution. This criterion is concerned with assessing whether the mechanisms distribute the costs and benefits of trading electricity in a local electricity market fairly among the market participants. For example, to which extend does the mechanism allow market participants with excessive production to leverage their position at the expense of market participants at the demand side? The stakeholder also indicated that not all market participants have an equal capacity to navigate a market and this should not impact the price formation process within the local electricity market. The stakeholder did not introduce a discretionary price formation mechanism.

Stakeholder A scoring

The first criterion that was evaluated by the stakeholder was Arbitrage, in which Auctions scored relatively low as the market participants operate relatively unsupervised in this mechanism (score 10-50). Negotiation-based mechanisms are subject to better supervision and the prevention of misconduct as in bilateral negotiations the market participants are subject to more control by the counter party (score 60-80). In the centrally organised System-determined mechanisms, it is in general well possible to implement arbitrage measures in the pre-defined mechanism to prevent misconduct in the market (score 60-90). As for the Cost/benefits Distribution, the stakeholder indicated that auctions allow for the application of market forces in order to establish a price for electricity, however this may not always result in a fair distribution of the costs and benefits among the market participants (score 10-15). In Negotiation-based mechanisms, it is possible to fairly distribute the costs and benefits over the market participants, which can be agreed upon in the negotiation process (score 30-60). However, the stakeholder indicated that the demand side is often in a less power full position as the supply side within the bilateral negotiation, which can lead to an unfair distribution in the costs and benefits. System-determined mechanisms allow for a fair distribution of the costs and benefits as long as the market participants have insight in the pre-defined mechanisms and it operates in a transparent and democratic manner (score 60-100). As for Data privacy and security, the stakeholder indicated that cooperations in general have no objections to the submission of data as they operate using the principles of transparency and accountability. As a result auctions were scored relatively well on the criterion (score 60-90), however more information should be published in Negotiation-based mechanisms (score 20-50). In System-determined mechanisms only a very little amount of data should be published (such as the cost components of a renewable energy asset), thereby explaining the higher score on the criterion (score 70-90). The stakeholder indicated that energy is a basic need for individuals and should not be subject to the principles of market forces. The criterion Fairness was therefore scored low on auctions (10-40), whilst negotiation-based mechanisms could allow for fair price formation, however market participants could be subject to market power abuse, thereby explaining the uncertainty range in the scoring process (score 20-80). In system-determined mechanisms, there are no market forces at work and fair price formation could be established without the possibility of market participants being subject to market power from leveraged market participants (score 60-90). The stakeholder indicated that not all market participants have the same capacity to navigate the market, which could lead to fairness issues with regards to market forces. As a result, the stakeholder scored auctions with a large uncertainty on participation, depending on the capabilities of the different market participants to participate in an auction (score 10-80). Negotiation-based mechanisms inherently allow for participation in the price formation process (score 60-90), whilst system-determined mechanisms typically do not allow for participation in the price formation process (score 0-10). The last criteria that was subject to evaluation was Transparency. The stakeholder indicated that Auctions do not necessarily allow for transparent price formation due to the conceptually complex process (score 20-50), whilst negotiation-based mechanisms allow for very transparent price formation as the market participants have insight in the bilateral negotiation process (score 60-90). The stakeholder indicated that system-determined mechanisms could allow for transparent price formation as long as the used mechanisms and complete price formation process is made public and transparent for all market participants (score 60-90).

B.3.2 Stakeholder I

Stakeholder I description

Stakeholder I is the Chairman of the Energy Cooperation Loenen (ECL), which was founded in 2019 and serves to enhance the utilisation of renewable energy for all residents in Loenen. The stakeholder is experienced in the energy sector and has full filed different positions in the field, thereby gaining knowledge and expertise in the energy transition. The stakeholder indicated that the energy cooperation booked profits with selling their excess renewable energy on the wholesale market last year during the period with increased energy prices in 2022. The profits were locally reinvested in Loenen in the form of a poverty fund and membership-fee reductions. The stakeholder also indicated that the negative wholesale prices also affect the local community, as some members seek to disconnect there solar PV systems in order to avoid paying for feeding their surplus electricity into the grid. The stakeholder indicated that the price for electricity in a local market should reflect the conditions in the local market, as compared to being exposed to the volatile wholesale market prices. Consequently, the stakeholder introduced a discretionary criterion: Local reflectivity. This criterion assesses the mechanism on their ability to accurately reflect the availability and cost of electricity in the local market and is important because it helps to ensure that the prices are fair and reflect the true value of the locally generated electricity. A second discretionary criterion that was introduced by the stakeholder was Autonomy. Autonomy describes the extend to which the local market participants are able to control price formation in a local electricity market. Autonomy is important from the perspective of the stakeholder as the market participants should be able to control and influence the price formation process in order to allow for the fair and transparent formation of prices. A third discretionary criterion that was introduced by the stakeholder was CO2 Pricing, relating to pricing the externalities of carbon emissions. The criterion assesses to what extend the price formation mechanisms are able to account for externalities such as CO2 emissions in the price formation process. The stakeholder did not introduce a discretionary option.

Stakeholder I scoring

The first criterion that was assessed by the stakeholder was Autonomy, in which the stakeholder indicated that auctions could allow for autonomous price formation as market participants are able to place bids and offers in order to come to a price (score 60-80). Negotiation-based mechanisms scored the highest on Autonomy as market participants actively negotiate in order to control the price formation process (score 70-90). System-determined mechanisms scored with a large uncertainty on Autonomy, as the stakeholder indicated that the level of Autonomy depends on the particular system-determined mechanism. If for example an energy cooperation is able to select the mechanism that is used in the local market, the mechanism could allow for autonomy in the price formation process. Alternatively, if a mechanism is selected that does not allow for pro-active control in the price formation process by the market participants, the mechanism would score low on the criterion (score 20-80). The second criterion that was assessed by the stakeholder CO2 (externalities) Pricing. The stakeholder indicated that auctions are able to incorporate the accounting for externalities in the price formation process, however adequate agreements must be made in order to implement this process in the bidding procedure (score 60-90). Negotiation-based mechanisms have the ability to incorporate the accounting of externalities into the negotiation process due to the fact that bilateral negotiations have several degrees of freedom for the negotiable components (score 80-100). The stakeholder also indicated that the pricing of carbon emissions could be facilitated by using Guarantees of Origin. System-determined mechanisms could allow for the accurate pricing of carbon emissions in the price formation process, however it still depends of the mechanism that is selected for the LEM (score 50-80). As for the Data Privacy and Security criterion, the stakeholder indicated that auctions could allow for a relatively save data collection process as no sensitive data is necessary for the bidding process (score 70-90). In addition, the stakeholder indicated that when the cooperation trades on the auction on behalf of the members of the cooperation, the cooperation will ensure that the data collection process will be facilitated in a secure manner. Negotiation-based mechanisms are more vulnerable in the Data Privacy and Security criterion as the mechanism by definition requires more data to operate (score 50-70). The stakeholder indicated that system-determined mechanism would probably require data with more depth, such as smart meter readings in order to operate (for example in an optimisation based mechanism), however the stakeholder did not see any particular security issues (score 60-80). As for Fairness, the stakeholder indicated that auctions could allow for a fair price formation process when all market participants are able to participate on an equal basis in the bidding process (score 80-90). Negotiation-based mechanisms were scored with a larger uncertainty on Fairness as the stakeholder indicated the mechanism is more sensitive to market power issues in a market with a disproportionate distribution of supply and demand. However as the mechanism could also allow for the incorporation of for example CO2 pricing in the negotiation process, fair outcomes could be achieved from a societal perspective (score 40-80). System-determined mechanisms could allow for a fair price formation process, as long as all stakeholders are involved in selecting a system-determined mechanism. The energy cooperation could for example represent local stakeholders and thereby select a system-determined mechanism on the behalf of the local population (score 50-90). As for Local reflectivity, auctions could represent the local market conditions in the bidding process, however the bidding format only consist of price and volume components, However the auction process allow for active price formation by the local market participants and is thereby able to represent the local market conditions to some extend (score 50-80). Negotiation-based mechanisms scored lower on this criterion as although the bilateral negotiation is able to account for local conditions in the price formation process, the mechanism does not reveal the positions of the other local market participants as is the case in auctions and thereby gives a less accurate reflection of the local market conditions (score 40-60). By configuring a system-determined mechanism such that local conditions are Incorporated in the price formation process, the mechanism is able to reflect the local market in the price. The mechanism should thereby accurately reflect the availability and cost of electricity in the LEM, as well as the level of demand for it in order to incorporate the criterion (score 50-80). As for Participation, auctions could allow for a participative price formation process as market participants could actively place bids as form of participation (score 70-90). The stakeholder indicated that negotiation-based mechanisms allow for more indirect participation of market participants in the price formation process, as households are for example represented by an energy cooperation in the price formation process, thereby scoring slightly lower on this criterion as compared to auctions (score 60-90). System-determined mechanisms typically allow for less participative price formation as a central party established a price on the basis of pre-defined formulas or mechanisms. However, when the cooperation is able to participate in selecting the mechanism (such as Cost-price+) the stakeholder indicated that the mechanism could allow for indirect participation of the energy cooperation in the price formation process (score 40-90). As for the last criterion, Transparency, the stakeholder indicated that auctions allow for the transparent formation of prices as long of the order-book is published after the clearing period. However, it is not necessarily transparent how the market participants come to their bids and offers (do they for example use forecasts or not) in the auction process (score 60-100). Negotiation-based mechanisms could allow for transparent price formation as long as the involved parties disclose all necessary information, however this is not required in the mechanism (score 40-80). For the system-determined mechanisms the stakeholder indicated that some mechanisms allow for transparent price formation (such as setting LEM prices 1ct bellow the wholesale market price), however it depends on the chosen mechanism and whether stakeholders are involved in the selection process (score 40-80).

B.4 Market

B.4.1 Stakeholder G (Wholesale Market)

Stakeholder G description

Stakeholder G has 30 years of experience in the Power & Utilities industry and European power markets including 8 years as CEO of the nordic wholesale market. The stakeholder is well experienced in the energy and power markets sector and therefore was able to provide valuable insights relating to price formation in (local) electricity markets. The stakeholder agreed with the classification of price formation mechanisms, however the stakeholder distinguished two groups within the mechanisms: market based mechanisms that are based on market forces and regulation-based mechanisms that are based on rules. Under these two categories, auctions and negotiation-based mechanism operate under market forces and were therefore classified as market based mechanisms whilst system-determined mechanisms operate under pre-defined rules and thereby characterised as rule-based mechanisms. The stakeholder introduced three discretionary criteria: Trust, Operation under Low-liquidity and Complexity. Trust assesses the mechanisms on whether they are perceived as trustworthy by the market participants and whether the market participants trust the prices that are established. Operation under low-liquidity market conditions assesses how the mechanisms operate under sub-optimal market conditions, such as markets with low liquidity (large spread between bids and offers). The criterion assesses to what extend the mechanism is perceived as complex by the market participants. As a result, a conceptually complex price formation mechanism will negatively impact participation by market participants in the price formation process.

Stakeholder G scoring

The first criterion that was assessed by the stakeholder was Operation under low liquidity market conditions, in which the stakeholder indicated that auctions (score 50-70) are less sensitive to larger spreads between buyers and sellers as compared to negotiation-based mechanisms. In negotiation based mechanisms, it might be more difficult to establish bilateral contracts in a thin market with low liquidity (score 20-40). As system-determined mechanisms are characterised as non-market based mechanisms by the stakeholder, the stakeholder indicated that the market mechanism is not sensitive to low-liquidity markets for price formation (score 80-100). The second criterion that was assessed by the stakeholder was Trust, in which the stakeholder indicated that under optimal market liquidity conditions, auctions allow for trustworthy price formation (score 80-100). Negotiation-based mechanisms were scored equally by the market participant on the criterion, as in general trustworthy price formation can be established by the mechanism under good market conditions (score 80-100). The stakeholder indicated that under sub-optimal market conditions (low-liquidity), the price formation process in market based mechanisms becomes increasingly untrustworthy. System-determined mechanisms are not operating under market-based conditions and were therefore characterised as less trustworthy by the stakeholder (score 0-20). As for Complexity, the stakeholder indicated that auctions are typically considered as a complex process in which the underlying economic principles are difficult to understand for the average market participant (score 0-20). Negotiation-based mechanism operate in accordance with the 'normal way of doing business' and are in general perceived as less complex (score 50-70). System-determined mechanisms are not considered as complex from a market participants perspective as indicated by the stakeholder (score 60-80). As for Data Privacy and Security, the stakeholder perceives auctions as a relatively secure process that is not vulnerable for privacy breaches (score 60-80). Due to the decentral nature of negotiation-based mechanisms, the stakeholder indicated that these mechanisms are more vulnerable to risks related to Data Privacy and Security (score 20-40). The more central system-determined mechanisms, similar to auctions, are therefore more secure as stated by the stakeholder (score 60-80). As for Fairness, the stakeholder indicated that in auctions, the market participants are treated equally and have the same opportunities within the market process and therefore the mechanisms could be perceived as relatively fair (score 80-100). Negotiation-based mechanisms are more sensitive to market power issues as market size is more relevant in this mechanism, related to negotiation power (score 40-60). The stakeholder indicated that in theory all market participants should have equal opportunities. The stakeholder scored system-determined mechanisms high against Fairness, as the mechanism is not based on market forces and therefore is not subject to risks related to market power or low-liquidity in the market (score 60-80). The stakeholder saw a risk however related to corruption in the authority that is operating the mechanism. As for Participation, the stakeholder saw issues for the participation in auctions due to the complexity of the mechanism. As a result market participants with less expertise face an entry barrier and might therefore not be able to participate in the price formation process (score 30-50). In negotiation-based mechanisms, the stakeholder indicated that it is possible to actively participate in the price formation process, as the process is less complex as compared to auctions (score 70-90). As system-determined mechanisms allow for a less complex price formation process according to the stakeholder, participation is accessible because there is no information barrier in this mechanism, as you are a price taker (participation in the market)(score 70-90). The last criterion that was assessed by the stakeholder was Transparency, in which the stakeholder that auctions are typically not considered as a transparent process by the market participants as the process is difficult to understand for the average market participant (score 10-30). Negotiation-based mechanism are typically no transparent process for price formation, as the process is a 'black box' for the other market participants (score 10-30). The stakeholder scored system-determined mechanisms high on Transparency as the stakeholder indicated that the mechanism is not dependent on market forces and the mechanisms are published for the market participants (score 80-100).

B.4.2 Stakeholder L

Stakeholder L description

Stakeholder L is an employee of a construction company at the department of Energy and Water. It is a company in the Netherlands, that provides construction services for the residential and non-residential sector. The stakeholder is involved in the TROEF project. The TROEF consortium aims to achieve an Internet-of-Energy to enable the decentralized energy system of the future and thus accelerate the energy transition. In addition, TROEF is committed to the development of large-scale energy communities in the conviction that cooperation is the key to achieving the goals of the climate agreement. Within TROEF, the stakeholder is result leader of the working group: Smartly managed local energy community for electric mobility.

The stakeholder agreed with the classification of the price formation mechanisms under auctions, negotiation-based mechanisms and system-determined mechanisms and did not introduce any additional mechanisms. The stakeholder did, however, introduce a discretionary criteria: Market Power. This criterion assesses to what extend the mechanism is vulnerable to market power and market manipulation. For example, how does the mechanism respond to market participants that seek to leverage their dominant supply position? The stakeholder indicated that this criterion is important for the assessment of the robustness of the mechanism under market conditions in which market participants seek to exploit the LEM for their own benefit.

Stakeholder L scoring

The first criteria that was assessed by the stakeholder was Market Power, in which the stakeholder indicated that auctions are able to address market power as a central institution is in place to engage in arbitrage for the market (score 20-50). Negotiation-based mechanisms are more sensitive to market power as there is no central party in place to control the market and there is more 'playing room' to manipulate the market (score 20-70). System-determined mechanisms could be more sensitive to 'price synchronisation', which can lead to peak reinforcing and gaming of the market participants with more power (for example more demand available)(score 20-60). As for Data Privacy and Security, the stakeholder indicated that auctions allow for the storage of data by a central entity, such as the platform operator, which could pose a risk for data security as the central party could use the data for its benefit (score 30-70). Negotiation-based mechanisms allow for a more peer-to-peer based price formation process, in which the peers are responsible for the storage of data by themselves, which can pose both risks and benefits (score 30-80). System-determined mechanisms might require more data as compared to auctions in order to operate, and are therefore more vulnerable to data privacy and security related risks as indicated by the stakeholder (score 25-65). As for Fairness, the stakeholder indicated that auctions allow for a transparent and fair price formation process as long as the platform operator as long as the platform operator operates the auction in a responsible manner (score 50-90). Negotiation-based mechanisms allow for the freedom by the market participants to influence the price formation process and thereby achieve fair prices from there perspective, however the mechanism is also more sensitive to market power (score 30-70). System-determined mechanisms are characterised as less fair by the stakeholder as compared to the other mechanisms as market participants are not able to actively influence prices by themselves (score 30-50). As for Participation, the stakeholder indicated that auctions allow for participative price formation as long as there are no entry barriers to placing bids in the auction, for example households should bid a minimum of 10 kWh in order to engage in trading in the auction (who will set the rules for trading in an auction)(score 50-80). Negotiation-based mechanisms are less prone to entry barriers as compared to the auction, as market participants could set the rules for engaging in the bilateral negotiation by themselves (score 70-100). System-determined mechanisms allow for more indirect participation in the price formation process, as market participants are more dependent on the auctions of other market participants for the price setting (score 40-70). The last criterion that was assessed by the stakeholder was Transparency, in which the stakeholder indicated that auctions allow for transparent price formation, for example when the market participants have insight into the trading order book (score 50-90). Negotiation-based mechanisms were scored lower on the transparency criterion by the stakeholder as the price formation process is not transparent for third parties that are not involved in the trading process, these market participants are not able 'to inspect the negotiation room' as indicated by the stakeholder (score 30-60). The stakeholder scored system-determined mechanisms between the auctions and negotiation-based mechanisms as the used mechanism could be experienced as a 'black box' when the mechanism is not published to the market participants, which could hinder Transparency (score 40-70).

B.5 Academic

B.5.1 Stakeholder J (Economics Academic

Stakeholder J description

Stakeholder J is an Assistant Professor at Tilburg University within the research section School of Economics and research group Management and the Econometrics and Operations Research. The stakeholder has expertise relating to the fields of Energy Management Systems, Smart Grids, Cost Functions, Resource Allocation and similar fields. The planning of algorithmic applications into smart grids and energy communities are current research interests of Stakeholder J. The stakeholder did not introduce any discretionary options, as the stakeholder agreed with the classification of the mechanisms under Auctions, Negotiation-based mechanisms and System-determined mechanisms. The stakeholder did introduce two discretionary criteria, the first introduced criterion was Enhance Grid Resilience. This criterion addresses the extent to which the mechanisms are able to account for the extreme behaviour of the market participants that affect the resilience of the grid. Examples of impacts of price formation of the resilience of the grid is for example price synchronisation, in which the behaviour of the market participants is synchronised at moments with low prices leading to demand or production peaks that negatively affect the grid. The second criterion that was introduced by the stakeholder was Technical Feasibility. This criterion is concerned with to what extent digital infrastructure is necessary to operate the price formation mechanism, thereby also relating to the scalability of the mechanism. The stakeholder also added the concept of acceptance to the Participation criterion, as acceptance by the end consumer for the mechanisms is a prerequisite for participation. Acceptance is related to what extent the market participants are interested in participation in the mechanism and creating a support base.

Stakeholder J scoring

The first criterion that was assessed by the stakeholder was Enhance Grid Resilience, in which the stakeholder indicated that auctions could be vulnerable to the synchronisation of prices such that sub-optimal grid conditions can occur. However, as the auction is a centralised mechanism, it is possible to oversee the implications of the auction on the grid performance (score 20-60). As negotiation-based mechanisms are decentral by their nature, it is more difficult to address grid resilience in this mechanism as there is no central overview (score 10-40). System-determined mechanisms allow for the implementation of grid constraints into the price formation process, and it is possible to prevent price synchronisation (score 40-90). The second criterion that was assessed by the stakeholder was Technical Feasibility, in which the stakeholder indicated that there is a large communication overhead in auctions due to the bidding process. In addition, the stakeholder questioned the scalability of local auctions (score 20-60). In negotiation-based mechanisms, the scalability is dependent on the number of market participants involved in the trading activities and there could be a large communication overhead involved in the mechanism (score 10-50). System-determined mechanisms are dependent on data that should be collected within the LEM, however there is probably no continuous clearing process such as in an auction, thereby making the mechanism more scalabale (40-80). As for Data Privacy and Security, the stakeholder indicated that auctions are a centralised mechanism in which the bidding and clearing information is centrally stored which allows for more control options (score 30-70). In negotiation-based mechanisms, data is stored in a decentral manner which allows for a more anonymous and secure market clearing process (score 50-90). System-determined mechanisms also rely on the central storage of data, making it more sensitive to security issues (score 40-80). As for Fairness, the stakeholder indicated that auctions are based on classic economic principles of finding the equilibrium between supply and demand and the fact that market participants are able to control their own bids allows for a relatively fair price formation process (score 40-70). The stakeholder indicated that negotiation-based mechanisms will result in a more implicit market, based on the pay-as-bid mechanism such that market participants will estimate their minimum or maximum bid prices (score 30-60). As for system-determined mechanisms, the mechanism could be characterised as fair as long as all market participants have equal access and insight into the working principles of the mechanism such that no information barrier arises for less knowledgeable market participants (score 40-70). As for Participation, the stakeholder indicated that in auctions market participants are more affected by the activities of the other market participants in the auction process (score 30-70), as in negotiation-based mechanisms the market participants have more capacity to influence the prices (score 60-100). The last criterion that was assessed by the stakeholder was Transparency, in which the stakeholder indicated that auctions allow for a transparent price formation process as in general most people understand the basic principles of an auction, all though strategic bidding might be an issue (score 40-80). Negotiation-based mechanisms are characterised as the least transparent mechanism by the stakeholder due to the decentral nature of the mechanism (score 10-50). Lastly, system-determined mechanisms allow for a high degree of transparency as long as the underlying mechanism is published for the public and in general complies to conceptual simplicity (score 30-70).

B.5.2 Stakeholder H (FSG)

Stakeholder H description

Stakeholder H works at the Massachusetts Institute of Technology (MIT) Energy Initiative as a Research Scientist, where he focuses on researching power market design and regulation. Additionally, he teaches a course called "Engineering, Economics and Regulation of the Electric Power Sector" at MIT. He also works part-time as an assistant professor at the Florence School of Regulation (FSR) where he previously worked for 5 years as a research fellow. Furthermore, the stakeholder holds a PhD in energy economics from University Paris-Sud XI.

After discussion of the classification of the price formation mechanisms, the stakeholder indicated that he had some criticism on the classification. First of all, the stakeholder did not agree with the categorisation of game theory as a price formation mechanism, as the stakeholder indicated that game theory is a mathematical framework and not necessarily a price formation mechanism. Furthermore, the stakeholder indicated that a continuous clearing mechanism was missing from the classification, after which it was indicated that this mechanism can be classified as 'continuous double auction' or 'order book mechanism' under auctions.

The stakeholder added two discretionary criterions to the analysis. The first discretionary criterion was 'Prone to market power', which assesses the mechanisms on their vulnerability to market power related issues. A second introduced discretionary criterion was economic efficiency, which assessed mechanisms on their ability to operate under sub-optimal economic conditions. The stakeholder indicated that this criterion can be subdivided in dynamic efficiency and allocative efficiency.

Stakeholder H scoring

The first criterion that was assessed by the stakeholder was Economic Efficiency, in which the stakeholder indicated that auctions are the most economically efficient mechanism (score 70-100). The economic efficiency is, however, dependent on the market structure (market liquidity and number of competitive actors). Auctions allow for different surveillance options to control the market, such as price caps. In addition, it is possible to switch to a system-determined (cost-based) mechanism when the market conditions are suboptimal. and switch back to an auction when the market conditions are optimal. This is already possible in the US, were the system operators differ between LMP and cost-based pricing based on the conditions in the market. In negotiation-based mechanisms it is possible to leverage bargaining power and the mechanism is less transparent. Next to that the mechanism operates slowly as the result of the negotiation process (score 30-60). The stakeholder indicated that system-determined mechanisms operate less optimal from an economic perspective as it is not possible to compute the costs for all demand and storage technologies (such as batteries), in addition the mechanism could work 'over-rewarding'. The mechanism should only be applied when there is no competitive market and when the costs are based on the LCOE there is no coordination (score 10-40). The second criterion to which the mechanisms were assessed was Prone to market power, in which the stakeholder indicated that for auctions that they can be vulnerable to market power, for example with strategic bidding or withholding (score 20-60). Negotiation-based mechanisms are more subject to bargaining power and there is less oversight in the market clearing process, making the mechanism also less transparent (score 20-60). System-determined mechanisms are more prone to market power, as the mechanisms allows for regulation, however it could be questioned who determined the regulations for the mechanisms. In addition, there is information asymmetry, which could affect the price formation process (score 70-90). As for Data Privacy and Security, the stakeholder saw no particular concerns for auctions (score 40-70). In negotiation-based mechanisms there is no transaction information available, which is a counter balance for monitoring and transparency (score 60-90). System-determined mechanisms require more data to operate and are therefore more vulnerable as compared to auctions (score 10-30). As for Fairness, the stakeholder indicated that Fairness depends on the market structure for auctions (fair under optimal market conditions). In addition, fairness can be addressed using external social rules that should not be incorporated in the trading mechanism (score 30-70). The stakeholder had no particular comments on fairness for negotiation-based mechanisms (score 30-70). System-determined mechanisms are fair and a static level but not necessarily on a dynamic level, related to economic efficiency. When a cost-price is computed based on an administrative rule then is that not necessarily fair, algorithms are also not always 'fair' (score 60-80). As for Participation, the stakeholder indicated that auctions allow for a participative market as market actors only have to submit bids in order to participate (score 40-70). In negotiation-based mechanisms more strategy and knowledge is necessary in order to navigate the mechanism, thereby hindering participation (score 20-50). System-determined mechanisms allow for a participative market as their is no participation barrier in the form of bidding, only information should be communicated (score 70-90). The last criterion that was assessed by the stakeholder was Transparency, in which the stakeholder indicated that in auctions it depends on the bidding format, The most transparent auction format is non-linear pricing with multi-part bids. In general the operation process is very transparent for an auction (score 80-95). No notes for negotiation-based (score 10-40). For system-determined mechanisms the stakeholder indicated that transparency is dependent on the specific type of mechanism, as some mechanisms could be experienced as black box. When the mechanism is opened up completely, privacy concerns could become an issue (score 10-40).

B.5.3 Stakeholder K (Tilburg University LAW)

Stakeholder K description

Stakeholder K is a full professor of Economic Regulation and Market Governance of Network Industries at the Law School of Tilburg University since 2015 and currently heads the Tilburg Institute for Law Technology and Society (TILT). The stakeholder has specialized in EU law, competition law, economic regulation, energy law, national constitutional and administrative law and issues of good market supervision.

As for the classification of price formation mechanisms, the stakeholder did not introduce any discretionary options as the stakeholder agreed with the three different mechanisms as options for price formation in LEMs. The stakeholder did, however, introduce two discretionary criterion's and further specified the definition of Fairness to also incorporate Inter-generational fairness, equality, sustainability and affordability. The first introduced discretionary criterion was Accountability, that assesses the mechanisms on their capacity to be held accountable for failures or other unexpected events, thereby also relating to the central or decentral nature of the mechanisms. The second introduced discretionary criterion was Locality, that assesses the mechanisms on their ability to reflect local conditions and to facilitate local transactions.

Stakeholder K scoring

The first criterion that was assessed by the stakeholder was accountability, in which the stakeholder indicated that the centrally operated auctions allow for accountable price formation (score 60-100). The negotiation-based mechanisms result in bilateral contracts that are accompanied with agreements and responsibilities, however the mechanism is also subject to potential market power issues and information barriers (score 20-70). System-determined mechanisms are one-sided mechanisms that allow for less accountability as there is no input from the market side, as a result there is one-sided price formation (score 20-60). The second criterion that was assessed was Locality, in which the stakeholder indicated that auctions allow for local price formation when only local bidders are allowed to place bids (score 30-70). Negotiation-based mechanisms allow the selection of the counter-party for the trading process, which could enhance locality (score 80-100). System-determined mechanisms are one-sided mechanisms in which it is not possible to communicate a preference for specific local trading of electricity (score 20-60). As for Data Privacy and Security, the stakeholder indicated that auctions always require information (bids) in order to operate, for which consent from the market participants is required and there is a possibility for security issues (score 20-80). Negotiation-based mechanisms are by definition more prone the data privacy and security issues due to their bilateral nature, however it is possible that data from the counter-party is misused (score 65-100). In system-determined mechanisms it depends on the specific mechanism whether data privacy and security is an issue, as an optimisation model based on smart meter data is more risky as compared to cost-plus pricing (score 20-100). As for Fairness, the stakeholder indicated that auctions rely on the principle of bringing supply and demand together, which is a fair process however in a less mature market (with a disproportionate balance between supply and demand) auctions might not operate fairly and steering by a central party is necessary (score 30-80). Negotiation-based mechanisms are dependent on the equality between market parties for fairness, as market power can pose issues to fairness. In addition, the mechanisms is accompanied with opportunity costs and transaction costs (score 20-60). System-determined mechanisms are dependent on the structure of the mechanism and involved parties in the construction of the mechanism, however as the mechanism operates in a one-sided manner it is by definition less fair as compared to auctions or negotiation-based mechanisms (score 30-80). As for Participation, the stakeholder indicated that auctions allow for participative price formation as market participants can actively place bids (score 70-80). Negotiation-based mechanisms are more dependent on the structure of the market for participation, for example in a less balanced market there will be less participation as market participants experience market power as deterrence (score 20-70). System-determined mechanisms are a one-sided mechanism and therefore allow for less participation by definition, unless market participants are involved in the upfront structuring of the mechanism. In addition, it is possible that 'boards' monitor the operation of the system-determined mechanism during the usage of the mechanism within a LEM (score 20-60). The last criterion that was assessed by the stakeholder was transparency, in which the stakeholder indicated that auctions allow for transparent price formation for end-consumers (score 80-100). Negotiation-based mechanisms allow for transparent price formation for the involved parties, but not for third parties in the market (score 30-80). Transparency for system-determined mechanisms is dependent on the inclusion of stakeholders in the setting up of the mechanism and on their involvement in boards that monitor the operation of the mechanism during the actual operation of the LEM (score 20-60).

Appendix C

Discretionary criteria definitions

Table C.1: The definitions of the introduced discretionary criteria by the different stakeholders

Discretionary Criteria	Definition	Introduced by
Arbitrage	To what extent is it possible to prevent dishonest behaviour and misconduct in the price formation mechanism?	A
Cost/Benefit distribution	Concerned with assessing whether the mechanisms distribute the costs and benefits of trading electricity in a local electricity market fairly among the market participants.	A
Effort	Concerned with the effort required by market participants in order to operate the mechanism.	B
Multidimensionality	Addresses the non-monetary aspects of the price formation mechanisms, such as the environmental, local and social implications of price formation.	C
Efficiency	Evaluates the actual matching of supply and demand using the mechanisms	C
Prevention of Dishonest Behaviour	Concerned with preventing market behaviour that could be perceived as dishonest by other market participants (such as exploiting batteries in the local electricity market for financial benefit at the expense of other market participants)	D
Decentralisation	To what extend is the mechanism able to operate in a decentral manner without the need of a central market party?	D
Non-discriminatory	Market participants should not be discriminated in the price formation mechanism.	E
Trust	Assesses the mechanisms on whether they are perceived as trustworthy by the market participants and whether the market participants trust the prices that are established	G
Operation under low liquidity	Assesses how the mechanisms operate under sub-optimal market conditions, such as markets with low liquidity (large spread between bids and offers)	G
Complexity	Assesses to what extend the mechanism is perceived as complex by the market participants?	G
Vulnerability to market power	Assesses the mechanisms on their vulnerability to market power related issues.	H
Economic Efficiency	Assesses the mechanisms on their ability to operate under sub-optimal economic conditions.	H
Local reflectivity	Assesses the mechanism on their ability to accurately reflect the availability and cost of electricity in the local market and is important because it helps to ensure that the prices are fair and reflect the true value of the locally generated electricity.	I
Autonomy	Describes the extend to which the local market participants are able to control price formation in a LEM.	I
Externalities Pricing	To what extend is the mechanism able to adress externalities in the price formation proces?	I
Grid Resilience	Addresses the extent to which the mechanisms are able to account for the extreme behaviour of the market participants that affect the resilience of the grid.	J
Technical Feasability	Concerned with to what extent digital infrastructure is necessary to operate the price formation mechanism, thereby also relating to the scalability of the mechanism.	J
Accountability	Assesses the mechanisms on their capacity to be held accountable for failures or other unexpected events, thereby also relating to the central or decentral nature of the mechanisms.	K
Locality	Assesses the mechanisms on their ability to reflect local conditions and to facilitate local transactions.	K

Appendix D

LEMLAB Configuration

D.1 Prosumer configuration

Table D.1: Configuration of the prosumers within LEMLAB

Variable	Fraction	Sizing	Note
Household PV	0.7	1.5	1.5 kWp of PV for every 1000 kwh/a of household consumption. Random variation of 0.2 from the sizing power.
Small scale wind	0.1	0.7	0.7 kWp of wind for every 1000 kwh/a of household consumption. Random variation of 0.2 from the sizing power.
Battery	0.4	1	Battery power is equal to peak PV power and only PV owners have a battery. The efficiency is equal to 0.95 % and the initial SoC 0.1. The battery cannot charge from the grid.
Heat Pump	0.2	1	Thermal power of HP equals ceiled max heat demand. Type is Outdoor Air/Water HP with a storage capacity between 2-3 h.
Electric Vehicle	0.25	Distributed	Charging power between 3.7-11.0 kW, battery size between 40-80 kW and consumption 15 -30 Wh per 100km. Initial SoC 0.8 and no V2G

D.2 Feed-in tariffs

Table D.2: Feed in tariffs for energy suppliers in the Netherlands [40] (13/3/23)

Retailer	**Feed-in Tariff (2023)**
BudgetEnergie	50% van het kale leveringstarief
CleanEnergy	€ 0,08 per kWh
Coolblue Energie	€ 0,08954 per kWh
Delta Energie	€ 0,135 per kWh
DGB Energie	Kale leveringstarief (op basis van het daltarief)
easyEnergie	Kale leveringstarief, afhankelijk van de dynamische energieprijs
Engie	Kale leveringstarief
Energiedirect.nl	€ 0,05 per kWh
Eneco	€ 0,09 per kWh
Energie van Ons	70% van het kale leveringstarief, inclusief btw
Essent	€ 0,055 per kWh
Frank Energie	Gemiddeld gewogen inkoopprijs in de betreffende maand
Green Choice	Kale leveringstarief (maximaal € 0,115 per kWh)
HEM	€ 0,05 per kWh
Innova Energie	€ 0,07 per kWh
Mega	€ 0,05 per kWh
Next Energy	Kale leveringstarief, afhankelijk van de dynamische energieprijs
OM — Nieuwe energie	€ 0,287 per kWh
Oxxio	€ 0,09 per kWh
Powerpeers	€ 0,21 per kWh
Pure Energie	€ 0,15 per kWh (0,095 per kWh bij vast contract)
Shell Energy	€ 0,10 per kWh
United Consumers	€ 0,135 per kWh
Vrijopnaam	€ 0,05 per kWh
Vandebron	€ 0,10 per kWh
Vattenfall	€ 0,168 per kWh
Woon energie	€ 0,09 per kWh

D.3 Transactions Double Auction

Table D.3: Transactions data frame for the double auction for clearing period 2021-02-24 09:15:00 at 15 minute clearing interval

Time	User	Buying	Quantity Transacted	Price Transaction	Source
2021-02-24 09:15:00	1	True	432	0.0956	-1
2021-02-24 09:15:00	11	True	652	0.0956	-1
2021-02-24 09:15:00	23	True	333	0.0956	-1
2021-02-24 09:15:00	2	True	132	0.0956	-1
2021-02-24 09:15:00	18	True	144	0.0956	-1
2021-02-24 09:15:00	14	True	515	0.0956	-1
2021-02-24 09:15:00	28	True	242	0.0956	-1
2021-02-24 09:15:00	9	False	388	0.0956	-1
2021-02-24 09:15:00	10	False	14720	0.0956	-1
2021-02-24 09:15:00	4	True	370	0.0956	-1
2021-02-24 09:15:00	22	True	30	0.0956	-1
2021-02-24 09:15:00	3	True	6720	0.0956	-1
2021-02-24 09:15:00	10	True	624	0.0956	-1
2021-02-24 09:15:00	12	True	88	0.0956	-1
2021-02-24 09:15:00	5	True	292	0.0956	-1
2021-02-24 09:15:00	24	False	609	0.0956	-1
2021-02-24 09:15:00	21	True	53	0.0956	-1
2021-02-24 09:15:00	8	True	432	0.0956	-1
2021-02-24 09:15:00	31	True	6392	0.0956	-1
2021-02-24 09:15:00	31	False	6392	0.0956	-1
2021-02-24 09:15:00	32	False	11731	0.0956	-1
2021-02-24 09:15:00	26	True	617	0.0956	-1
2021-02-24 09:15:00	15	True	490	0.0956	-1
2021-02-24 09:15:00	9	True	194	0.0956	-1
2021-02-24 09:15:00	14	False	515	0.0956	-1
2021-02-24 09:15:00	20	False	226	0.0956	-1
2021-02-24 09:15:00	17	True	75	0.0956	-1
2021-02-24 09:15:00	19	True	1164	0.0956	-1
2021-02-24 09:15:00	24	True	609	0.0956	-1
2021-02-24 09:15:00	30	True	365	0.0956	-1
2021-02-24 09:15:00	32	True	11731	0.0956	-1
2021-02-24 09:15:00	20	True	226	0.0956	-1
2021-02-24 09:15:00	25	True	346	0.0956	-1
2021-02-24 09:15:00	6	True	267	0.0956	-1
2021-02-24 09:15:00	29	True	416	0.0956	-1
2021-02-24 09:15:00	16	True	178	0.0956	-1
2021-02-24 09:15:00	16	False	267	0.0956	-1
2021-02-24 09:15:00	13	True	719	0.0956	-1

D.4 Transactions Negotiation-based mechanism

Table D.4: Transactions data frame for the negotiation-based mechanism for clearing period 2021-02-24 09:15:00 at 15 minute clearing interval

Time	User	Buying	Quantity Transacted	Price Transaction	Source
2021-02-24 09:15:00	1	True	432	0.13815	30
2021-02-24 09:15:00	11	True	652	0.17759999999999998	13
2021-02-24 09:15:00	12	False	176	0.23895	7
2021-02-24 09:15:00	23	True	333	0.29885	34
2021-02-24 09:15:00	2	True	132	0.1593	37
2021-02-24 09:15:00	18	True	144	0.12254999999999999	11
2021-02-24 09:15:00	14	True	176	0.23895	2
2021-02-24 09:15:00	14	True	233	0.1933	30
2021-02-24 09:15:00	14	True	106	0.21465	33
2021-02-24 09:15:00	8	False	2601	0.2358	28
2021-02-24 09:15:00	8	False	423	0.2262	51
2021-02-24 09:15:00	28	True	242	0.1076	29
2021-02-24 09:15:00	9	False	388	0.17615	48
2021-02-24 09:15:00	10	False	144	0.12254999999999999	6
2021-02-24 09:15:00	10	False	490	0.14305	35
2021-02-24 09:15:00	10	False	617	0.1381	32
2021-02-24 09:15:00	10	False	29	0.1766	48
2021-02-24 09:15:00	10	False	6494	0.11595	15
2021-02-24 09:15:00	4	True	370	0.1333	22
2021-02-24 09:15:00	28	False	652	0.17759999999999998	1
2021-02-24 09:15:00	22	True	30	0.2963	33
2021-02-24 09:15:00	3	True	226	0.1135	39
2021-02-24 09:15:00	3	True	6494	0.11595	11
2021-02-24 09:15:00	10	True	490	0.16310000000000002	46
2021-02-24 09:15:00	10	True	134	0.12845	31
2021-02-24 09:15:00	12	True	88	0.12835	37
2021-02-24 09:15:00	5	True	292	0.12619999999999998	37
2021-02-24 09:15:00	24	False	609	0.17215	28
2021-02-24 09:15:00	6	False	346	0.15245	54
2021-02-24 09:15:00	6	False	370	0.1333	12
2021-02-24 09:15:00	6	False	149	0.1202	56
2021-02-24 09:15:00	6	False	365	0.12285	50
2021-02-24 09:15:00	6	False	1489	0.1724	51
2021-02-24 09:15:00	3	False	178	0.22785	58
2021-02-24 09:15:00	3	False	3182	0.18365	28
2021-02-24 09:15:00	21	True	53	0.1432	31
2021-02-24 09:15:00	8	True	432	0.11925	44
2021-02-24 09:15:00	31	True	609	0.17215	21
2021-02-24 09:15:00	31	True	3182	0.18365	23
2021-02-24 09:15:00	31	True	2601	0.2358	8
2021-02-24 09:15:00	31	False	1164	0.12455	42
2021-02-24 09:15:00	31	False	242	0.1076	9
2021-02-24 09:15:00	31	False	267	0.10139999999999999	55
2021-02-24 09:15:00	31	False	75	0.1134	40
2021-02-24 09:15:00	23	False	432	0.13815	0
2021-02-24 09:15:00	23	False	233	0.1933	7
2021-02-24 09:15:00	32	False	53	0.1432	24
2021-02-24 09:15:00	32	False	134	0.12845	16
2021-02-24 09:15:00	32	False	7821	0.16255	51
2021-02-24 09:15:00	26	True	617	0.1381	11
2021-02-24 09:15:00	19	False	30	0.2963	14
2021-02-24 09:15:00	19	False	106	0.21465	7
2021-02-24 09:15:00	19	False	194	0.16765	36
2021-02-24 09:15:00	19	False	1998	0.19624999999999998	51
2021-02-24 09:15:00	2	False	333	0.29885	3
2021-02-24 09:15:00	15	True	490	0.14305	11
2021-02-24 09:15:00	9	True	194	0.16765	33
2021-02-24 09:15:00	14	False	88	0.12835	17
2021-02-24 09:15:00	14	False	132	0.1593	4

D.5 Transactions system-determined mechanism

Table D.5: Transactions dataframe for the system-determined mechanism for clearing period 2021-02-24 09:15:00 at 15 minute clearing interval

Time	Seller	Type	Cost Price	Demand	Cleared Volume	Prosumer Cleared Volume	Large Scale PV Cleared Volume	Fixed Generator Cleared Volume
2021-02-24 09:15:00	32	fixed_generator	0.055	34848	11731.0	0	0	11731
2021-02-24 09:15:00	31	large_scale_pv	0.078	34848	6392.0	0	6392	0
2021-02-24 09:15:00	9	prosumer	0.09	34848	388.0	388	0	0
2021-02-24 09:15:00	10	prosumer	0.09	34848	16337.0	16337	0	0
2021-02-24 09:15:00	24	prosumer	0.09	34848	0.0	0	0	0
2021-02-24 09:15:00	14	prosumer	0.09	34848	0.0	0	0	0
2021-02-24 09:15:00	20	prosumer	0.09	34848	0.0	0	0	0
2021-02-24 09:15:00	16	prosumer	0.09	34848	0.0	0	0	0