MARKET ENABLING INTERFACE TO UNLOCK FLEXIBILITY SOLUTIONS FOR COST-EFFECTIVE MANAGEMENT OF SMARTER DISTRIBUTION GRIDS

# Deliverable: D5.3

## Implications for flexibility services and market mechanisms in a peer-to-peer market setting

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# Abbreviations and Acronyms

| Abbreviation | Meaning |
|---|---|
| **AS** | Ancillary Services |
| **CM** | Conceptual Model |
| **DER** | Distributed Energy Resource |
| **DLMP** | Distribution Locational Marginal Pricing |
| **DSO** | Distribution System Operator |
| **ESCO** | Energy Service Company |
| **EV** | Electric Vehicles |
| **FMO** | Flexibility market operator |
| **FSP** | Flexibility service provider |
| **FSP** | Flexibility service requester |
| **GSF** | Generation Shift Factors |
| **ICT** | Information and Communication Technology |
| **KPI** | Key Performance Indicator |
| **LFM** | Local Flexibility Market |
| **P2P** | Peer-to-peer |
| **PTDF** | Power Transfer Distribution Factors |
| **RES** | Renewable Energy Resource |
| **TE** | Transactive Energy |
| **UMEI** | Universal Market Enabling Interface |

# Executive Summary

The primary goal of the EUniversal project is to overcome existing limitations in the use of flexibility by Distribution System Operators (DSOs). As such, the project goal is (among others) to enhance flexibility use in distribution grids which will need to operate in an overall context of 50% electricity production from renewables in 2030. Furthermore, the EUniversal project aims to further guarantee the security of supply while avoiding unnecessary network investments. Moreover, the evolution towards a more consumer-centric market might require a fundamental shift in the organisation of electricity markets, leading to fully distributed market organisations such as peer-to-peer trading. Peer-to-peer (P2P) markets leverage upon emerging and innovative technologies, business models and empowerment of the demand side, in particular the retail side.

To support this purpose, Task 5.3 of the EUniversal project aimed at analysing the applicability and the impact of the proposed flexibility products and services that were studied in Task 2.1 of the EUniversal project and market mechanisms for the procurement of flexibility from Task 5.1 in a peer-to-peer market context. Task 2.1 provided a list of DSO needs and the flexibility services that are needed to address these needs. These services are predictive and corrective congestion management, predictive and corrective voltage control, as well as islanding and emergency load control. On the other hand, Task 5.1 introduced and described the market mechanisms for acquiring these services such as local flexibility markets, dynamic pricing, flexible access and connection agreements, bilateral contracts, etc. Therefore, the goal of this task was to examine the coordination and information sharing with the DSO, comparing different market mechanisms with different degrees of centralisation in the context of P2P trading. To achieve these goals and as the first step, state of the art literature survey was performed screening the most relevant scientific studies and projects related to the P2P topic. Although P2P trading is a financial trade in its nature, however, recent trends in the study with the subject of P2P have considered the impact of local P2P trading on the energy flow and network status. Therefore, the main focus was held on the network aspect in P2P trading and the role of the DSO in this mechanism.

After a comprehensive review of the literature on the related topics, the common attributes among the models and case studies in the literature were screened. The results of this screening showed some specific elements that can make a difference in the process of flexibility provision to the DSO as well as the coordination and information sharing with the DSO. These elements were identified and introduced as design elements. The design elements are related to the P2P market setting, flexibility service provision, and the aspects that are needed for covering both P2P and flexibility concepts. The defined design elements are:

- P2P trade product
- Network constraints in the process of P2P
- Service provision method from the P2P trades
- Incentivisation schemes of P2P trades
- P2P trade mechanism
- Addressed flexibility service
- The sequence of P2P trading and other flexibility mechanisms
- Geographical scope
- Involved roles

Each of these design elements can have different variations. These variations in the design elements create different combinations of elements together and each of these combinations will lead to a different set of required information-sharing levels and centralisation. To analyse these impactful combinations, conceptual models were defined.

Conceptual models are the combination of design elements on defining the settings of P2P trading and flexibility service provision mechanism. Each conceptual model represents an example of possible co-existence, interaction, and information sharing between the P2P setting, flexibility mechanism, and the DSO. To narrow down the scope of the study and make it more focused on the objectives of this task, a set of assumptions were made. These assumptions helped in creating meaningful and practical implementation examples of interactions between DSO, P2P, and flexibility mechanisms and are listed below:

- It was assumed that the only flexibility mechanism for the DSO to obtain its required services is the local flexibility market (LFM);
- The flexibility services that are needed in the system are assumed to be congestion management and voltage control;
- It is assumed that whenever the P2P energy trade process considers the network constraints, the P2P trade is providing an implicit service to the DSO by not violating the operational constraints of the network.
- It is assumed that the area where the peers are located and trade with each other overlaps with the market area of the LFM.

Based on these assumptions, five different conceptual models were defined and the interactions between the involved roles in each of them are described. Then, the conceptual models were supported by qualitative and quantitative analysis of potential implementation options. The qualitative analysis of the conceptual models compared the advantages and disadvantages of each model in terms of privacy, level of required interactions, the complexity of implementation, total costs, impact on the total required flexibility, and possible market distortion.

To quantitatively analyse the conceptual models, different scenarios were created. The purpose of these scenarios was to show the co-existence of a centralised flexibility mechanism such as LFM and a decentralised trade mechanism such as bilateral P2P together in the system and assess the mutual impact that they can have on each other as well as on the network status and flexibility requirements of the DSO. These scenarios focused on some of the variations in the design elements, namely the incentivisation schemes for P2P trading, the sequential market sequence between P2P and LFM, and congestion management service for the DSO. The scenarios were compared to an initial case where only an LFM runs in the system.

The results showed that the co-existence of P2P and LFM in the system and the outcomes of such markets depend a lot on the characteristics of the network, the grid flow status, the level of available flexibility providers in the system, as well as the incentivization schemes that are deployed. It was shown that depending on the situation and condition of the network and P2P bids, the energy trade can actually help the DSO and improve the network status and resolve the need for any other flexibility mechanism such as LFM. However, this is also dependent on a proper incentivisation scheme and appropriate use of incentives or disincentives. On the other hand, in some conditions, P2P trading can worsen the situation of the network by adding to the number of congested lines.

The ultimate take from the studies carried out in this task is that an appropriate design of the P2P trading while keeping it network-aware by adding the network constraints as a design element, can provide an alternative for the flexibility service provision in the system. It can co-exist with other flexibility markets and paves the way towards more decentralised and consumer-centric flexibility service provisions.

# 1 Introduction

## 1.1 The EUniversal project

The European Union is aiming at transforming the energy system towards a sustainable, low-carbon and climate-friendly economy, while among others putting consumers at its centre. To enable this transformation by putting consumers at its centre and dynamically utilising these distributed resources, distribution grid operators will face new challenges in the way they operate the grid. In order to be able to safely host more renewable energy sources (RES) and to integrate new types of load patterns (such as electric vehicles and heat pumps) and consumer behaviour (e.g., with the advent of energy communities or the introduction of dynamic electricity pricing), the DSOs will need to rely more on **flexibility** and smart grid solutions. Flexibility in the grid has been identified as a key enabler towards a more sustainable, low-carbon and climate-friendly electricity system. In such a scenario, consumers become crucial players due to their potential to relieve grid constraints by adapting their consumption behaviour, reflecting one of the most important European Union priorities. Yet, at the same time, flexibility will create complexity and unpredictable power flows in the distribution networks, and thus demand new solutions to transform the challenges into real opportunities for the sector and society.

The primary goal of the EUniversal project is to **overcome existing limitations in the use of flexibility by Distribution System Operators** (DSOs). As such, the project goal is (among others) to enhance flexibility use in distribution grids which will need to operate in an overall context of 50% electricity production from renewables in 2030. Furthermore, the EUniversal project aims to further guarantee the security of supply while avoiding unnecessary network investments.

Therefore, within the EUniversal project, **a Universal Market Enabling Interface (UMEI)** will be implemented to facilitate the use of flexibility services and interlink active system management of distribution system operators with electricity markets. A set of market-oriented flexibility services from Distributed Energy Resources (DERs) will be implemented to serve DSOs' needs in a cost-effective way, supporting the energy transition.

## 1.2 Scope and objective

This report is part of the fifth work package of the EUniversal project which focuses on the identification and assessment of innovative market mechanisms for DSO grid services. One of the objectives of this work package is to analyse the impact of the delivery of these services in a peer-to-peer (P2P) market setting.

The evolution towards a more consumer-centric market might create a fundamental shift in the organisation of electricity markets, leading to fully distributed market organisations (P2P). P2P markets leverage upon emerging and innovative technologies, new business models and the empowerment of the demand side, in particular the retail side.

This deliverable will analyse the applicability of the proposed flexibility products and services such as congestion management and voltage control from EUniversal Deliverable 2.1 [1] and market mechanisms for flexibility services such as local flexibility markets, dynamic tariffs, fixed agreements, etc. from Deliverable 5.1 [2] in the EUniversal project in a P2P market context. The impact of innovative P2P markets on the DSO needs will be analysed. To this aim, different potential concepts of P2P trading considering DSO services will be examined and compared. Numerical examples will be used to evaluate a) the impact of an independent P2P trading mechanism on a local grid and b) the performance of DSO measures to influence the outcome of the P2P market.

## 1.3 Structure of this document

This deliverable is structured in four main parts. The first part gives some background on P2P trading and flexibility service delivery and explains the methodology. The second part gives an overview of recent P2P literature considering flexibility services and introduces the main design elements of P2P trading considering flexibility services. The third part introduces and compares alternative concepts of P2P trading combined with DSO flexibility services considering some of the design elements introduced in the previous part. The final part presents the numerical examples on quantitative analysis of the conceptual models.

# 2 P2P trading and flexibility services

This chapter studies the fundamental concepts from the two aspects involved in this task: P2P trading and flexibility services. For this purpose an overview on the backgrounds of P2P trading, flexibility services, and the mechanisms to acquire these services are given. Then, the motivation and methodology on how the study in Task 5.3 were carried out and how these two concepts were merged is discussed.

## 2.1 Background on P2P trading and flexibility services

For analysing the implications for flexibility services and market mechanisms in a P2P setting, it is important to first understand the elements from each of these aspects. Therefore, in the following subsections, a background on definitions and concepts in each of these aspects are provided to open the door towards further steps and more technical discussions that are provide in the later chapters. For this purpose, first the roles that are involved in both P2P trading and flexibility services provision mechanisms are introduced. Then, a brief discussion on what is P2P trading and its different market models are provided. After that, the definition of flexibility services and the market mechanisms to acquire them are introduced.

### 2.1.1 Roles Involved in P2P Trading and Flexibility Mechanisms

In the business environment of P2P energy trading, there are several involved actors representing specific roles. Some of these roles we consider in this deliverable when analysing the impact of peer-to-peer markets on the DSO needs are common with the business-as-usual of the distribution networks and other energy or flexibility-related mechanisms, such as DSOs, aggregators, flexibility market operators, etc. However, some specific roles come into existence when the P2P mechanism is implemented in a system. In the following, the important roles that play part in the operation of a P2P trade or may have an impact on it are introduced. The provided definitions follow the EUniversal role model introduced in Deliverable 2.2 [3] for the common roles. However, how these roles impact the P2P trade and further specific P2P-related roles are added.

- **Peers:** A peer in P2P energy trading refers to one or a group of local energy customers, including generators, consumers, and prosumers. The peers buy or sell energy directly with each other with reduced dependency on conventional energy suppliers [4].
- **Distribution System Operator:** The DSO shall be responsible for ensuring the long-term ability of the system to meet reasonable demands for the distribution of electricity, for operating, maintaining and developing under economic conditions a secure, reliable and efficient electricity distribution system in its area with due regard for the environment and energy efficiency (Art. 31, par. 1 of Electricity Directive [5]). The DSO ensures transparent and non-discriminatory access to its distribution network for each user. The DSO is responsible for optimizing its distribution grid by (combined) means of switching and the use of flexibility. The DSO assesses impacts, at a relevant distribution grid level, of a flexibility/balancing order or action to guarantee grid security and its correct operation. The DSO acts as a neutral market facilitator and provides the different market players with data needed for flexibility/wholesale market operations. The DSO is responsible to ensure grid optimization, among others through identifying flexibility needs, technical validation of the solutions provided by the market and grid state estimation. The DSO is responsible for collecting, storing, administrating and validating metered data, and distributing them to authorized users in a transparent and non-discriminatory manner. Most of the time, the P2P trade does not consider the physical aspect of the trade. Therefore, the DSOs are mostly not involved or informed of P2P trades. However, for the specific purpose of this task and considering the provision of services to the DSO through P2P trading or the impact of P2P trading on DSO needs, the role of the DSO and the interactions between the P2P trades and the DSO are significant.

- **Resource Provider:** The RP manages a resource and provides production/consumption schedules for it if required.
- **Aggregator:** In [3], a resource aggregator is defined as a role that aggregates resources for usage by a service provider for energy market services. According to [6], an aggregator groups agents in a power system (i.e., consumers, producers, prosumers or any mix thereof) to act as a single entity when engaging in power system markets (both wholesale and retail) or selling services to the operator. In the context of P2P trading, an aggregator takes on the same role as defined in the mentioned references, however, they represent the peers in different markets and provide services upon receiving a fee.
- **Flexibility Market Operator:** In the EUniversal project the FMO is a neutral party that transparently provides a central service between buyers and sellers to facilitate the communication and coordination of all processes related to the procurement of capacity and/or energy bids, i.e., grid or asset registration on its marketplace, matching of bids, validation (through market monitoring) and settlement. Consequently, in this task, the same definition is used whenever a flexibility market (specifically a local flexibility market) is set up and operated by an entity.
- **Flexibility Service Provider**: The FSP offers explicit flexibility services of one resource managed by a Resource Provider or multiple resources aggregated by an Aggregator to system operators, directly via bilateral agreements or through market operators.
- **Mediator:** In P2P trading, depending on the market model that is used, the entity that manages the trading process and communication of information is called a mediator. The role of the mediator can be taken up by different actors based on the setting in which the P2P trade is being set. For example, in a community of peers, the community manager can take the role of the mediator.

### 2.1.2 What is P2P

Today's grid is characterised by increasing levels of Distributed Energy Resources (DERs), demand response programs, and energy efficiency initiatives. With the increasing penetration of DERs, traditional energy consumers have become prosumers, who can both produce and consume energy. Distribution systems were originally designed assuming power flow from bulk power generation to consumers at the edges of the distribution system. However, integration of DERs progressively violates that assumption, with substantial consequences for grid operations when penetration levels of DERs pass tipping points that are becoming well recognised.

Power flows in multiple directions, as well as loop flows in distribution circuits are other consequences of the integration of DERs in the grid. These changes were not anticipated in the present generation of grid controls, so they introduce new challenges for DSOs. Therefore, it is essential to develop a new framework for power distribution systems to facilitate the use of DERs. Transactive Energy (TE) is a novel framework that enables customers of all sizes to join traditional providers in producing, buying, and selling electricity. TE is a system of economic and control mechanisms that allows the dynamic balance of supply and demand across the entire electrical infrastructure using value as a key operational parameter [7].

With the advancement of Information and Communication Technology (ICT), peer-to-peer energy trading has been introduced and is considered a promising business model for the transactive energy scheme in future power systems. According to the European Commission Renewable Energy Directive [8], 'peer-to-peer trading' of renewable energy means the sale of renewable energy between market participants using a contract with pre-determined conditions governing the automated execution and settlement of the transaction, either directly between market participants or indirectly through a certified third-party market participant, such as an aggregator. The right to conduct peer-to-peer trading shall be without prejudice to the rights and obligations of the parties involved as final customers, producers, suppliers, or aggregators. Therefore, P2P energy trading is the buying and selling of energy between two or more grid-connected parties. Peer-to-peer energy trading allows consumers the choice to decide from whom they purchase electricity, and to whom they sell it via a secure platform. Therefore, P2P energy trading can be enabled through an online marketplace where consumers and producers meet to trade electricity directly, without the need for an intermediary.

In recent years, P2P trading has emerged as one of the alternative mechanisms for prosumers to participate in the energy market actively. P2P energy trading gives more flexibility to end-users, giving more opportunities to consume clean energy, and therefore supports the transition to a low-carbon energy system. Additionally, other actors in the electricity market can obtain benefits as P2P trading has the potential to reduce the peak demand for electricity, thereby reducing maintenance and operation costs, and improving the reliability of the electrical system [9].

The peer-to-peer concept has been used in other fields before being applied to the power system. The comprehensive vision towards P2P has several dimensions from the conceptual aspect to the spatial and time scale aspects [10]. Each of these aspects has various components affecting the implementation of P2P trading when it is used in the energy trading framework.

To implement P2P energy trading, various components are needed. These include being connected to the electricity infrastructure (to physically deliver/receive the traded electricity), ICT infrastructure for supporting information exchange and measurements, trading platforms for participants to negotiate and trade with each other, market design to set the trading rules, and laws and policies to regulate and guide the trading. However, there is a distinction between the **physical layer** and the **virtual layer** of the trade as shown in Figure 1. The physical layer deals with the tangible electricity delivery infrastructure aspect while the rest of the above-mentioned components and financial trade mechanism fall into the virtual layer. The initial nature of P2P trading is based on the fact that it is a form of financial trade giving the trade parties more autonomy and negotiation powers in setting the price and financial attributes of the trade. Therefore, most of the elements that are mentioned above and fall in the virtual layer of the trade are common between P2P trades despite what the traded commodity is. However, when this concept is applied to the electricity sector, the complications of the physical layer are added, hence, the formation of the physical layer. Although many P2P energy trade settings keep the trades still as a financial only trade without considering the physical (i.e., the network) aspect, it cannot be neglected that the outcome of these trades can have an impact on the operational planning of the network operator as well as the flows in the grid. Therefore, recently more studies started to look at the P2P trading problem, with both virtual and physical layers points of view.

On a spatial scale, P2P trading can occur at different levels. On the lowest level, the P2P energy trading can happen on a local level, within a microgrid or a community. Depending on the status of production/consumption matching in the community/microgrid, trading between different communities/microgrids may be set. On the next level, P2P trading can happen with the upstream network.

Similar to traditional energy trading in the electricity wholesale market, P2P energy trading can span a wide range of time scales as well. The trading contracts can be made well in advance (i.e., long-term/mid-term trading, such as year/month ahead), day-ahead, intraday, to real-time. After the delivery time, settlement needs to be conducted to examine whether and to what extent the participants in P2P energy trading have followed the pre-made contracts, and then execute the financial payment accordingly.

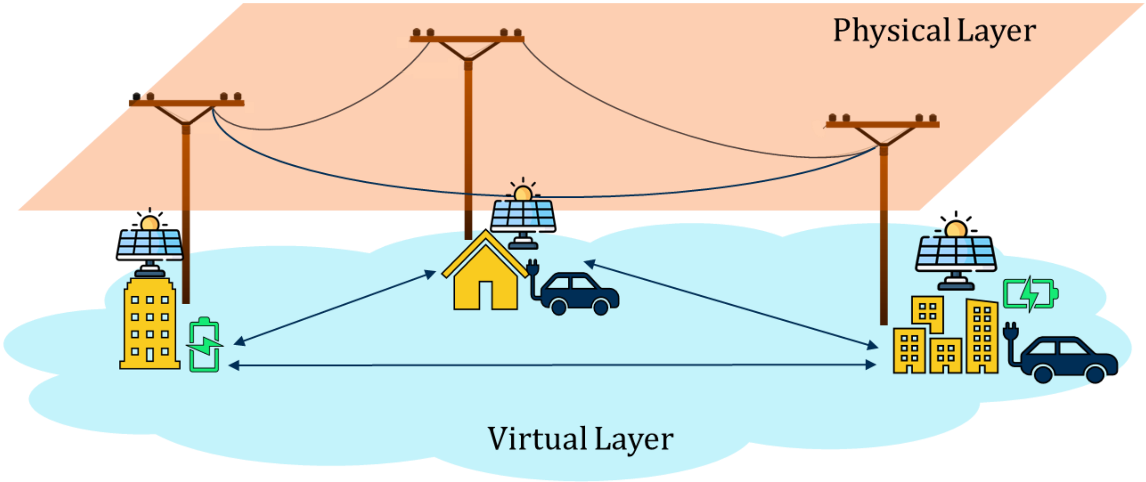


*Figure 1. Layers of P2P Trading*

One of the key aspects of the P2P trade is its market design. The market design specifies the rules that the participants must follow to conduct the trade. In the context of P2P, these rules include the required information to be provided by the peers (e.g., the quantity of the bid and price), the rules to match the bids, the pricing model, and the market settlement mechanism. Considering how the trading process is performed and how information communication takes place among the participants, different market design approaches are used for P2P trading. In the following paragraphs, the models as suggested in the literature on P2P are explained.

Literature on P2P trading has provided three categories: the centralized model, the decentralized model, and the hybrid model.

The first market design model is a **centralized** or **coordinated** model as shown in Figure 2 where the trading process and the communication of information are done in a centralized manner. That is, a centralized mediator communicates with each peer within the network and manages the selling and purchasing of energy that the prosumers share among themselves through P2P trading. Once the trading is complete, the revenue of the participating peers is distributed among the prosumers by the mediator according to pre-set rules. In this setting, each peer does not directly communicate and negotiate the energy transaction with other peers because it is done by the mediator; however, they influence the final decision on the matched trades by independently deciding their trade quantity (i.e., production or consumption values) and price before sharing that information with the mediator. A key advantage of the centralized market is that in such a market setting social welfare maximization could potentially be realized [11].

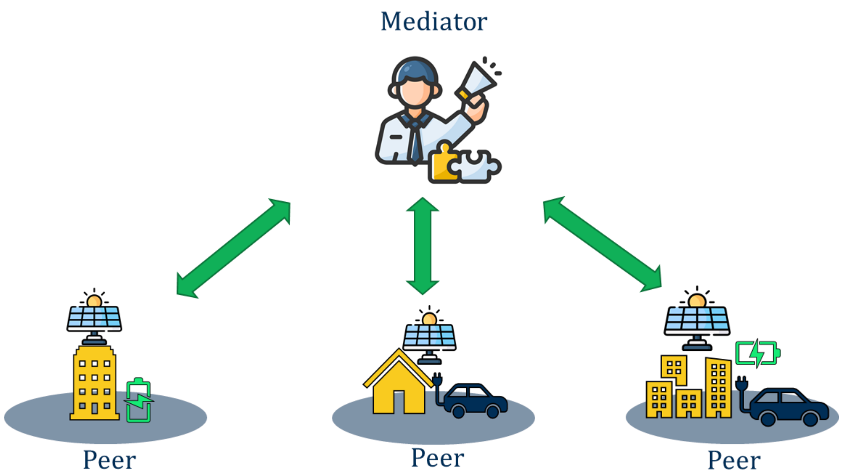


*Figure 2. Centralized P2P Trading*

Another market design model for P2P trading is the **decentralized model**, where peers can directly communicate with each other and decide on their energy trading parameters (i.e., quantity and price) without the involvement of any centralized mediator [12] as shown in Figure 3. Thus, in a decentralized market, both the trading process and the communication of information are done in a decentralized manner. The main advantage of a decentralized market is that prosumers are in full control of their decision-making process, e.g., they can easily decide whether to participate in energy trading or not with a specific peer or at any given time slot and their privacy is well protected [13]. Furthermore, the scalability of the decentralized market is better compared to the centralized model as mainly with the centralized mediator, the area that can be covered by a single mediator is limited and if the number of participants increases too much, there would be a problem with reaching the results. However, in a decentralized model, the peers can choose each other regardless of their location as long as there exists a physical connection [11]. As the overall energy that is traded in a decentralized market is not known to third parties such as network operators, retailers, and transmission system operators, managing the impacts of decentralized trades could be more difficult for system operators due to the challenge of maintaining network constraints and improving the operational efficiency of the power system. To be able to have such a market model in the system while maintaining the reliability of the grid, sometimes network operators need to take drastic measures such as load curtailment and blocking peers from the network [14] to maintain the reliability of the grid.

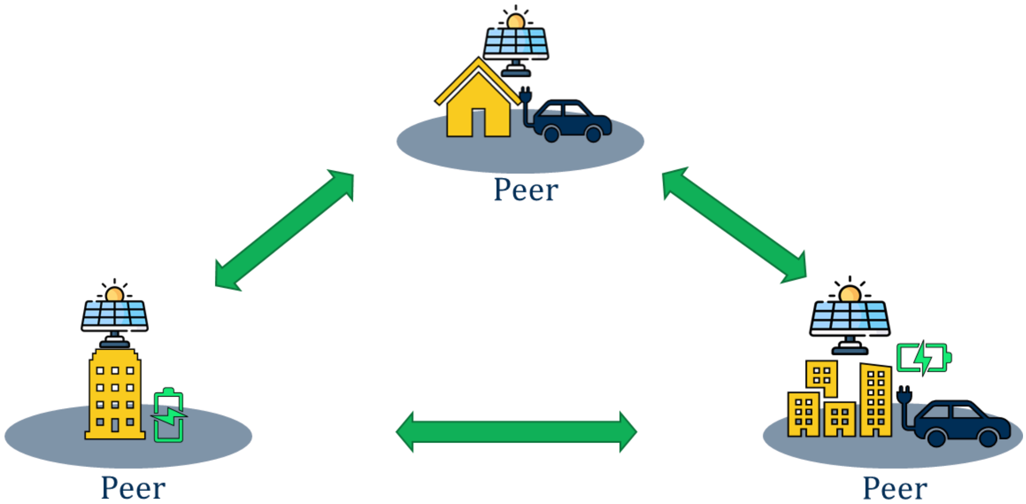


*Figure 3. Decentralized P2P Trading*

Considering the pros and cons of each of the above-mentioned models and the fact that many prosumer-centric studies evolved around energy communities, another approach for the P2P trade has also emerged. This approach is known as the **community** [15] or **hybrid model** [16]. In this case, the trading process is decentralized although the communication between the participating prosumers is done in a centralized manner. In this market, the role of a mediator still exists, and it is usually taken up by the community manager to coordinate the P2P energy trading among the prosumers. Rather, the community manager influences the prosumers to participate in P2P trading indirectly via suitable pricing signals. Thus, in a hybrid market model, prosumers need to share limited information with the mediator while, simultaneously, maintaining a higher level of privacy.

Once the proper design of a P2P energy market is set, the market participants (i.e., depending on the market model could be peers and/or mediators) need an environment such as a platform to exchange information and negotiate with each other, make deals and transactions, and conduct other relevant activities such as problem reporting and dispute resolution. Considering that trading frequencies are usually high in P2P energy trading, trading platforms are set up to provide such services to the participants. A P2P trade platform is a virtual marketplace that allows parties to buy or sell energy, managing price and volume risk themselves, optimizing the traditional role of the Energy Retailer optimizing the traditional role of the Energy Retailer who acted as the provider of energy for the peers by being able to set their preferences (e.g., green energy, location of the seller, etc.), and gaining access to additional financial and non-financial benefits [17].

### 2.1.3 Flexibility services

The flexibility services required by the DSOs according to their needs were fully studied in Deliverable 2.1 [1]. Here, a summary of these services is presented as input to this deliverable. As can be seen in Table 1, each of the identified DSO needs can be fulfilled with one or multiple flexibility services. As can be seen, there are a variety of flexibility services that can address the DSO needs in the system. However, in the context of the EUniversal project, the focus is on corrective and predictive congestion management and voltage control which are flexibility services that can address multiple DSO needs as can be seen in the table.

*Table 1 Summary of DSO needs and flexibility services*

| DSO Needs | Flexibility Service |
|---|---|
| Physical congestion | Corrective and Predictive Congestion Management |
| Control of voltage violation | Corrective and Predictive Voltage Control |
| Support to network planning | Support to Network Planning |
| Phase balancing | Corrective and Predictive Voltage Control |
| Support to planned and unplanned operations | Corrective and Predictive Congestion Management, ~Voltage Control, Islanding, Emergency Load Control and Mobile Generation Capacity |
| Support to extreme events | Corrective and Predictive Congestion Management, ~ Voltage Control, Islanding, Black Start, Emergency Load Control and Mobile Generation Capacity |
| Support to islanding | Islanding |

### 2.1.4 Flexibility mechanisms

DSOs can use a wide range of mechanisms to acquire flexibility from resources owned by other actors (e.g., distributed generators, prosumers, customers, and aggregators). The main considered mechanisms according to [2] are the following:

- **Flexible access and connection agreements:** Flexible access and connection agreements are agreements between the system operator and the FSPs in which the latter agrees to have the connection curtailed for some periods. Demand could be temporarily reduced during the periods of load peak demand, whereas generation could be curtailed to avoid network contingencies such as congestion or voltage issues.
- **Dynamic network tariffs:** Dynamic tariffs concern devising time (and locational) differentiated network tariffs which can be adjusted to reflect the necessary temporal and spatial cost variations. The grid users are incentivised to change their consumption and/or production according to the grid operation and future network needs.
- **Local flexibility market:** Local flexibility markets include long-term and short-term pools in which offers are received from FSPs. A long-term mechanism could be used in planning activities to procure flexibility by contracting long in advance the potential service providers. The local market extension depends on the grid characteristics, i.e., the market area can encompass only a portion of the distribution network. The size of the local market is site-specific. The DSO will utilise flexibility based on its willingness to pay for it, the available fallback solutions and the type of flexibility product required. A local flexibility market seeks to promote competition among flexibility providers.

- **Bilateral contract:** A bilateral contract is a binding agreement between two parties. In the context of grid services, one side is represented by the system operator while the other is the FSP. A bilateral contract requires a negotiation process between the two parties. Differently from the flexible connection mechanism, the bilateral contract mechanism is in general exploited for existing connected resources and constrained situations.
- **Cost-based mechanism:** A cost-based mechanism deals with the remuneration of the flexibility provided by the FSP based on the actual costs of providing the service. To illustrate, the cost-based mechanism for flexibility can determine the price of the service provided according to the opportunity cost of active power generation curtailment. The cost-based mechanism requires an acknowledged audit process of the provider's costs and financial margin that allows providers a return.
- **Obligation:** The obligation mechanism for flexibility provision defines a mandatory service provision from the FSPs. The service requested by the system operator to the FSPs is not remunerated, but instead, the FSPs who are asked to participate in service provision are obliged to contribute with their flexibility.

## 2.2 Motivation & Methodology

With the emergence of distributed energy resources and increased levels of renewable generation, centralised mechanisms that were the conventional method in the electricity grid were gradually changed to accommodate the integration of these resources and meet the system requirements. The decentralized approaches have also gained more importance with the recent focus on consumer-centric solutions in the system. Many studies have addressed the pros and cons of each model (i.e., centralised or decentralised) by evaluating different operational criteria in the electricity system, thus providing insight into the extent that the decentralised model can be used without compromising the system's operation.

Another critical aspect of the distribution system operation is flexibility provision. Flexibility services can be provided by various types of flexible resources in the distribution grid. With the empowerment of consumers and prosumers with higher degrees of flexible equipment, new business models for acquiring their flexibility are being increasingly studied.

One of the user-centric mechanisms that have been introduced for prosumers, as explained in section 2.1.2, is P2P trading. The P2P trade concept did not initially stem from the energy sector, but several studies and projects tried to adapt it to the energy world. Therefore, the initial vision of P2P trade was a pure financial trade to benefit the peers (i.e., prosumers) by having more options for price negotiation and trade selection. However, allowing P2P trading in the system can have dual effects on the grid operation. They can lead to either the exacerbation or the resolution of network issues such as congestion. Therefore, P2P trading can impact the required flexibility in the system and how the flexibility services would be provided. In that regard, flexibility services provision for the DSOs in grids where P2P trading also exists is a challenge that needs to be addressed.

Most of the literature on the P2P topic has addressed market design, market clearing mechanisms, market settlements, and how to implement different mathematical models and communication infrastructure with the P2P setting in the electric systems. Being a financial setting, most of the early-stage literature would address the business aspect of P2P energy trading; hence, later studies also built on it. However, one of the recent trends in the literature was to consider the network constraints in P2P energy trading. Given the importance of the DSO's role and the benefits that can be potentially obtained from the P2P energy trades, some recent studies investigated the network status concerning P2P trading and how the trade process would change if the network constraints were considered in it. Therefore, to accomplish the objectives of this task, a literature review was conducted.

For this purpose, a database of recent literature (i.e., 2018 onwards) was created by consulting certain keywords in web-based journal databases. The research databases that were used in this study are Web of Science[1], IEEE Xplore[2], and ScienceDirect[3]. The keywords included 'peer-to-peer', and 'P2P trading' and their variations. It should be noted that the search for literature was limited to peer-reviewed journals related to the electricity system studies, such as IEEE Transactions on Power Systems and IEEE Transactions on Smart Grid as well as journals from Elsevier publications, namely Applied Energy, Energy, and International Journal of Electrical Power & Energy Systems. The reason for taking this measure was to avoid the literature on P2P trading that involves P2P computing, control, communication, and ICT aspects. The initial search results were then refined by searching for further keywords in the content of collected papers related to flexibility services, such as 'network constraints', 'congestion management', 'voltage control', 'loss allocation', etc. as well as market design aspects including, 'market design', 'market clearing mechanism', 'flexibility trade', etc. Another round of refining occurred by limiting the number of papers to the ones that consider the grid and the DSO-related problems rather than energy management-related problems in energy communities or neighbourhoods. Moreover, other electric system aspects such as system resiliency that were not a focus point in the EUniversal project were also disregarded.

With all the refining, a total number of 270 papers were selected for the next round of review. At this step, a general check on the assumptions, objectives, and model used in the collected paper was performed. The result of this round was to further reduce the number of papers to be reviewed by the partners involved in this task to a total number of 120.

To further study the prospect of each flexibility service in the P2P literature, the created paper database was categorized based on the principal flexibility services that are under study in this task (i.e., congestion management and voltage control). However, it was seen in the literature that the loss factor is also another aspect that is considered in many studies that have included the physical network besides P2P trading. Therefore, the network loss was also added as a specific category. The remaining papers were mainly "review papers" and papers focusing on market design that were kept for general consultation on the fundamental aspects of the topic. To collect information from the literature, an excel-based form was created and filled out by the partners who reviewed the papers. These forms can be found in Annex I. The takeaways from this literature review are summarised in section 3.1.

After a careful literature search, it was clear that the number of existing studies that have simultaneously considered the P2P energy trading problem and the physical network is limited. In this task, the number of papers that were found to directly address this issue was 29. Other than that, the published papers that explicitly consider flexibility services in combination with P2P trading, are even more scarce. It highlighted the void in this topic's literature and the importance of our analysis in this deliverable as part of the EUniversal project.

With the knowledge from the literature survey, it was clear that the next step was to define the concepts that cover both P2P trading and flexibility services areas. For this purpose, a set of design elements were defined that could affect the market design models, interactions with the DSO and addressing the network constraints, interactions with other flexibility mechanisms, specific service provisions, and geographical scope. Based on the comprehensive design elements and to have a more focused study, certain assumptions were made to narrow down the number of conceptual models. These models consider a setting in which P2P trading exists in the distribution system where some network violations may occur and need to be resolved by the DSO. The developed conceptual models aim at showing potential variations of such settings, i.e. show the linkages between the considered market mechanisms - the P2P market and the local flexibility market (LFM) - and discuss the high-level interactions between the involved roles. Five different conceptual models are introduced and described and the main advantages and disadvantages of each of them are highlighted.

[1] https://mjl.clarivate.com/home

[2] https://ieeexplore.ieee.org/Xplore/home.jsp

[3] https://www.sciencedirect.com/

As a next step, a quantitative assessment of potential implementations of some of the proposed conceptual models is given, focusing on the models with bilateral P2P energy trading in combination with an LFM. As P2P trading leads to changes in net injections and withdrawals at various nodes in the grid, it has a direct impact on the power flows, voltages, and different operational aspects of the system. As such, when the P2P mechanism does not consider network limitations, it can lead to violations of operational constraints (such as, causing congestions or exacerbating existing ones). Quantifying this effect and proposing grid-aware P2P trading mechanisms are of paramount importance to enable the safe integration of P2P markets within distribution systems. These aspects are the core goal of the quantitative analysis. It is noted that in the quantitative analysis, the LFM is considered to be in place to resolve original congestion problems, as well as congestion caused by P2P trading. Therefore, this considers a sequential setting in which the P2P market runs first, followed by a subsequent LFM market run.

The goal of LFMs is to enable DSOs to procure flexibility from distributed resources to meet their needs (with primary application to congestion management). As P2P trades can have a direct impact on the grid, they will also directly influence the operation, feasibility, and costs of LFMs. In fact, the effects of P2P markets on the grid and LFMs can span a wide range of negative and positive possibilities.

On the positive side, the P2P trading, by enabling localized trades between generation and load resources, may decrease the cumulative loading on the grid (e.g., at higher levels in the feeder), and through this redistribution, may serve to decrease the anticipated grid congestions.

On the negative side, the non-controlled exchange of energy between peers, which does not consider network limitations, can lead to congestions in the grid (e. g., violation of line flow or nodal voltage magnitude limits), especially when the grid is in a relatively high loading condition. In the extreme sense, the P2P mechanism may lead to large volumes of P2P trades that exacerbate congestions to a critical level, which cannot be resolved using flexibility procurement mechanisms at the disposal of the DSO (e.g., the LFM).

Due to those imposed risks, the DSO would be incentivized to implement safety measures to allow P2P trading while ensuring the safe operation of the grid. This stems from the goals of the DSO to manage the use of its grid and ensure its efficiency and secure operation. In this respect, in the quantitative analysis in Chapter 5, we introduce, analyse, and numerically assess different cases in which the P2P and LFM markets can coexist including different ways in which the DSO can impact the LFM trading. We namely propose and investigate three distinct scenarios (while multiple settings within each scenario are also considered):

1. Scenario 1: the setting in which the P2P market runs unchecked without any inputs from the DSO and without imposing any grid limitations.
2. Scenario 2: the setting in which the DSO pre-emptively prohibit possible trades which are deemed to be harmful to the grid.
3. Scenario 3: the setting in which the DSO provides incentives and disincentives to the peers to incentivize P2P trades that are deemed beneficial to the grid (i.e., leading to a reduction in the grid congestions) and discourage P2P trades that are deemed harmful to the grid.

To quantitatively analyse and compare those scenarios, we develop a simulation environment composed of a local flexibility market (based on the model proposed in [18]–[20]) and a game-theoretic based P2P market (based on the model proposed in [21]), whose coexistence is governed by the three different proposed scenarios. In addition, we consider a base case in which no P2P market is present (to which we refer as scenario 0) and is considered as the reference scenario to which the outcomes of the other scenarios are compared. The simulation environment enables tracing the effects that the P2P market can have on the grid's operation state (i.e., power flows, congestion levels), and on the local flexibility market that is subsequently run to alleviate any original congestions and any additional congestions created through the P2P trading process. The comparison between the scenarios is based on a set of KPIs including:

1. The total cost of the local flexibility market, which allows capturing the change in cost due to the preceding P2P market (computed before the P2P market – in scenario 0 – and after the P2P and subsequent LFM market in scenarios 1-3).
2. The number of congestions, which constitute the number of lines in the grid with flows larger than their capacity limits (computed before and after the P2P market and before running the LFM for all scenarios)
3. The summation of the overflows (i.e., the expected amount of flow above the line capacity limit) over all the lines that are anticipated to be congested (computed before and after the P2P market and before running the LFM for all scenarios)
4. The weighted average of the overflows over the set of congested lines, which is weighted based on the capacity of the different lines (computed before and after the P2P market and before running the LFM for all scenarios)
5. The cumulative volume of energy traded between peers in the P2P market (computed after the run of the P2P market for scenarios 1-3).

This structured comparison among the scenarios enables the derivation of key insights and recommendations, regarding the integration of P2P markets in distribution systems, their potential impacts on the operation of the grid, and adjusting measures that can be implemented by the DSO.

# 3 P2P trades and flexibility Services

## 3.1 Overview of the literature

The literature on the topic of P2P energy trading is relatively wide, introducing the peer-to-peer trading concept to the energy sector while accommodating the specific characteristics of the electric system as well as the communication requirements, ICT infrastructure, and control aspects. There are various studies and implementation projects that have P2P as their core concept. As described in the methodology section (section 2.2), the literature screening process was narrowed to focus on the studies that could provide insights relevant to the scope and aim of this task which is to analyse the applicability and the impact of the flexibility services and market mechanisms that are considered in the EUniversal project in a peer-to-peer market context. Although several existing literature surveys have categorized the existing publications from different perspectives [22]–[29], in this chapter, a high-level categorization of the surveyed papers and reports is presented. In this regard, three key aspects of the P2P trade that are aligned with the objective of this task are identified below and further discussed.

- ***P2P market design and clearing mechanisms,*** which address the related aspects of market *designs suitable for P2P trading*, different clearing mechanisms, trade specifications, and settlements.
- ***Network constraints in P2P trading,*** which address the physical layer aspect of P2P trading and how they can become grid-aware trades.
- ***P2P with Flexibility and ancillary services***, which address the flexibility services and P2P mechanisms together.

### 3.1.1 P2P Market Design and Clearing Mechanism

In Section 2.1.2, the main market design models for P2P trading were introduced. However, another important aspect that has been widely studied in the context of P2P is the market clearing mechanism which refers to the procedure through which the matching between peers as well as the (optimal) trading volumes are performed. There are several attributes to the market design and its clearing mechanism some of which are shown in Table 2. Most of the existing literature in P2P energy trading has focused on this aspect providing insights into the differentiation of the attributes and how different attributes would have an impact on the energy system operation.

***Table 2 P2P Market Attributes***

| Attribute | Description |
|---|---|
| **Market operator** | *Who runs the P2P market? e.g., an independent operator; community manager; aggregator/utility; (distribution) system operator, no market operator, etc.* |
| **Type of participants** | *Who can participate in the P2P trade? e.g., no restrictions; residential; small industrial, business park; multiple participant type; etc.* |
| **Trade mechanism** | *What is the P2P trade mechanism? e.g. direct bilateral trade; p2p via a third party; centralized forms of trade; etc.* |
| **Trade type** | *Which trade type is used? e.g., continuous trade, discrete trade, etc.* |
| **Trade frequency** | *How often does the trade happen? e.g., irregular - when there is a match; yearly; monthly; daily; hourly; etc.* |
| **Trade commodity** | *What is the traded product? e.g., capacity; energy;* |
| **Product duration** | *What is the duration of the traded product? e.g., 5'; 15'; 30'; 1h; 4h; 1 day; 1 week; longer than 1 week; other* |
| **Pricing scheme** | *How is the price defined, i.e., how are the bids settled? e.g., negotiated price; pay-as-bid; etc.* |

Given the complexity of the decentralized market model and its complicated impacts on the system especially from the system operation point of view, many studies tried to provide innovative solutions by designing a decentralized market model, defining specific characteristics and attributes of bilateral P2P trading [30]–[33]. Moreover, several market clearing approaches have been proposed in the literature to define the market clearing objective function (in case such a function exists) or the peer's objective functions. If the market is structured in a fully decentralized manner, then the objective function definition depends on each peer's decision variables and market participation options. However, in hybrid and centralized approaches, where a mediator exists, the objective function of the mediator needs to consider the competition between peers [34]–[37].

Another line of study in the literature regarding the market design and market clearing mechanism is related to the algorithms that are used to match the peers' bids. Depending on the market design model (i.e., centralised, decentralised, or hybrid), different approaches have been suggested in the literature to be used in the mathematical model. However, these approaches can be categorised into two most common groups 1) **Auction-based** and 2) **Game theory** approaches.

An **auction** process is a well-specified negotiation mechanism mediated by an intermediary (i.e., the mediator as defined in 2.1.1) that can be considered as an automated set of rules " [38]. There are different types of auctions depending on the number of sellers and buyers. Auctions that involve one seller and multiple buyers or one buyer and multiple sellers are called single-sided auctions. On the other hand, auctions that are composed of multiple sellers and multiple buyers are called double auctions. From the energy trading perspective, double auctions help in providing a two-sided market in which both sellers and buyers can switch their roles from offering their surplus power for the energy trading auction to buying it and vice versa. This process has been widely used in the P2P literature. The study in [39] has provided a single and multi-unit auction framework for the P2P transactions while [40] discusses the multi-round auction mechanism. Moreover, [41] provided a comparison of the different auction mechanisms and their impact on the bidding strategies of the peers.

The other widely used approach in the P2P literature is game theory approaches [42]–[44]. **Game theory** is defined as a mathematical tool used to analyse the behaviour of different participants in a competitive environment and give the proper result. This model is used to provide a solution based on understanding the behaviour of the other agents. There are two main classes in game theory approaches: 1) **Non-cooperative game:** This type of game theory is used to model participants with conflicting interests and make decisions without coordination or communication; and 2) **Cooperative games:** This concept refers to a game in which players cooperate to gain more profits from taking part. Examples of both of these methods can be found in the literature on P2P, however, the examples of non-cooperative games are more due to the competitive nature of P2P trading.

### 3.1.2 P2P with Network Constraints

Although the initial definition of peers covered individual prosumers trading with each other, the range of P2P trading in the energy sector has grown beyond the trade between two closely located prosumers. When considering the flexibility services with the P2P trade, (part of) the distribution network where the peer is connected can be considered the domain of the service provision. In fact, this scope may differ from providing a service from an individual peer to another fellow peer considering the network status or providing a service from an individual peer to the upstream grid. Moreover, this flexibility can be provided by a group of peers (in a community or located within a microgrid) to another microgrid or the upstream network. However, each of these settings may consider different needs for which flexibility is provided. For example, many of the existing scientific literature [15], [45]–[51] have addressed the concept of flexible power usage by each peer in the context of an energy community and the P2P trade among the peers is set up with the objective of increasing self-consumption within the community. Although some of these works considered network-related aspects such as network losses as in [47], the main objective was promoting self-consumption in a microgrid which ultimately allowed for the reduction of the total network energy loss. It is clear that local trade can potentially bring benefits to the operation of the distribution system, such as minimization of losses, however, it cannot be considered as a specific provision of flexibility services as envisaged in the EUniversal project. Such studies have used P2P trading as a mechanism for enabling local trading and subsequently improving the community or microgrid operation.

From the flexibility services' perspective, peer-to-peer trading can be similar to the conventional prosumer-to-grid concept by substituting the prosumer with peer in the definition of the concept leading to peer-to-grid, redefining the responsibilities of the flexibility service provider (i.e., the peer) and the boundaries for the operation and acquiring of those services .It is already an implemented procedure in some of the distribution networks that the prosumers with the availability of flexible resources such as Electric Vehicles (EVs) and batteries would provide their available flexibility as a support service to the DSOs when and where they needed it using a different kind of mechanism as mentioned in 2.1.4. However, with the emerging concept of P2P trading in the distribution system, the flexibility service topic has also become the subject of studies in the P2P trading field. Examples of considering P2P energy trading as well as peer-to-grid service delivery are few. In [52] and [53], the trading of available flexibility from peers equipped with EV batteries in a community-based microgrid is considered. In both of these studies, the interaction with the grid operator was through the community manager and the peers would trade with each other for the purpose of their energy management, promoting community self-sufficiency. Other examples of the same approach are given in [54] and [55] where local generation from PV panels was considered in the flexibility portfolio. From these studies and further look in the literature, one sees that there can be several options of p2p trading for flexibility provision with different scopes and objectives of the trade. This observation is summarized in Table 3. It should be noted that in this table, the aggregated peers are the peers that provide their flexibility in a collective/cooperative manner managed by a community manager or an aggregator. Aggregated peers are treated separately to highlight the difference in scope and possible objectives compared to individual peers.

***Table 3 Overall flexibility provision from peers***

| Service Provider | Service Requester | Scope | Objective |
|---|---|---|---|
| Individual peer | Individual peer | Within an energy community | Energy management and self-consumption |
| Individual peer | Grid | Within an energy community or microgrid | Resolving network-related issues of the community or microgrid |
| Individual peer | Grid | The portion of the distribution grid with grid issues | Resolving distribution grid issues |
| Aggregated peers | Aggregated peers | The portion of the distribution grid with grid issues | Resolving distribution grid issues |
| Aggregated peers | Grid | The portion of the distribution grid with grid issues | Resolving distribution grid issues |

One of the objectives of the literature review was to investigate how the literature on P2P market design and mechanisms has considered or included the role of and impact on the DSO. The first step was to check whether the P2P mechanism considered the physical network and its constraints in the P2P trading process or not. The results of the literature survey showed that there is increased interest in the modelling of distribution network constraints where P2P trading happens [56], [57]. By doing so, the studies analysed the magnitude of the impact that P2P trading may have on the network and how adding network constraints to P2P energy trading would change different aspects of P2P trading such as the peers' behaviour, social welfare, and trade volume. For example, the study in [58] has co-simulated P2P energy trading and network constraints and demonstrated the results using data from an existing low-voltage network in the UK. The conclusions of this study showed that the impact of P2P trade on the network under study was not significant and the grid constraints remained within the expected margins.

Some studies further focused on specific network constraints such as congestion and voltage values and proposed methods and algorithms for including the related constraints with the P2P trades. An example of this type of study is [59] where the voltage variations and congestion values of the network are evaluated after each round of P2P matching. Some studies focused on methods of including the impact of the network constraints in P2P trading. These studies have provided trading frameworks [56], [60], reassessing the attributes of P2P market designs [61] and how to change the matched trades in case they are violating the constraints.

The methods and approaches that were used in the above-mentioned literature are categorized with details and described in 3.2.4.

### 3.1.3 P2P with Flexibility and Ancillary Services

The concept of flexibility in P2P trading has been the subject of many studies, but the main goal has been to see to what extent energy management and self-consumption can be achieved in a community setting or for each peer. There are very few examples in the literature that have considered the possibility of ancillary service provision for DSOs through P2P trading.

In [62] an iterative and coordinated market design for P2P energy trading and ancillary services is proposed. In their model, both the P2P market and ancillary service market (i.e., congestion, voltage support, loss balancing, peak shaving) is operated by the DSO. First, the P2P negotiation for energy trade is initialized in a fully distributed manner. Second, the proposed updated grid usage prices (i.e., an incentivizing mechanism in P2P trading ref. 3.2.4) are calculated by the DSO and communicated to peers. The negotiation steps are repeated until a consensus is reached between peers regarding the trading price and quantity. The ancillary service market that complements the P2P market is centrally operated by the DSO to remove any existing violation of grid constraints during negotiations. Moreover, in [63] a framework is proposed to enable ancillary service provision from a P2P energy trading community. The model provides a sequential interaction of a P2P market and ancillary services market. Through this approach additional value is created for both the customers in the community and the power system.

## 3.2 Design elements of P2P Trading for Flexibility services

In this section, the factors that would affect the process of providing flexibility services while there is peer-to-peer trading in the system or when these services are provided through this type of trade are discussed. It should be noted that these elements cover the main aspects of the subject: first, the P2P trading; second, the flexibility services and their acquisition mechanisms. Finally, some general attributes such as the involved parties and the geographical scope are considered in a separate aspect. Figure 4 shows a summary of the design elements according to these different aspects. In the following, each of these design elements is described.

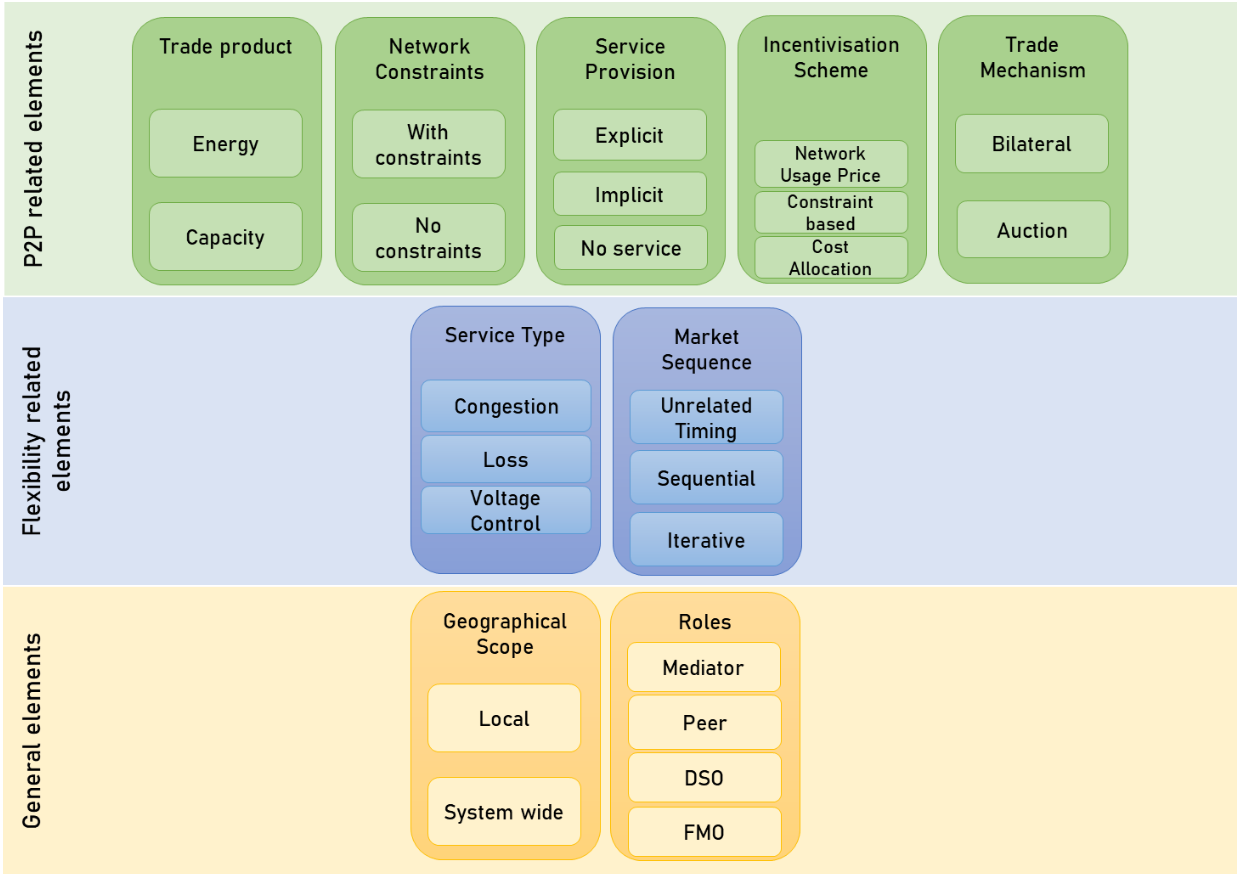


*Figure 4. Design Elements*

### 3.2.1 Trade Product

Electrical energy can be referred to as a commodity that can be traded and used by end-consumers for operating electric devices. In contrast, flexibility is defined as the possibility of adjusting patterns of generation and consumption in reaction to a signal (price or activation signal) to contribute to different services. From a technical perspective, flexibility can be seen as a power modification and is described by the following 5 attributes [64]:

1. Direction (up or down)
2. Power capacity (kW)
3. Starting time and trigger
4. Duration
5. Location

According to the literature, , the most common commodity that is traded between peers is **energy**. However, flexibility can also be the traded between the peers. Whenever the traded commodity is mentioned as flexibility it is in fact referring to the kWs of **capacity**. However, most of the studies that considered flexibility trading in the context of P2P had energy management within a community as their main objective as explained before. Regarding the implications of P2P trading on flexibility services to the DSO, both energy and capacity trading between the peers can affect the DSO's needs and its required flexibility. Therefore, both energy and capacity are considered as options of trade products in this study. However, it is assumed that the common trade product between peers is energy and the DSO's needs affected by the change of energy flows in the grid due to these trades. On the other hand, the peers would trade capacity only if the P2P trade mechanism is set-up specifically for the delivery of flexibility services to the DSO

### 3.2.2 Network Constraints

It is obvious that, while dealing with DSO requirements and flexibility services, an important aspect is the consideration of network constraints. On the other hand, P2P trading is a financial trade that typically does not consider the physical network. Therefore, when in the context of P2P trading and flexibility services, the physical layer of the trade is added to the financial layer further complexities are added to the problem. If in the P2P trade matching process, the network constraints are not considered, the selected match could violate network constraints causing further operational costs for the DSO to solve this issue and/or make the peers prone to penalties or curtailments. Therefore, this aspect of considering network constraints as part of the P2P trade has an impact on the evaluation of the flexibility requirements in a system as well as the efficiency of P2P trading. We, therefore, distinguish between **P2P markets which consider network constraints and those that do not** consider constraints.

### 3.2.3 Service Provision method

Providing flexibility services is not considered a common feature of P2P trading. However, for the objective of this task (i.e., to assess the impact of P2P on flexibility services), a new concept of service delivery through P2P trading is defined. This concept considers that P2P energy trading can be considered a new decentralised market mechanism for flexibility service delivery. In other words, the idea is to have the network problems, such as congestion, solved by the transactions between the peers instead of foreseeing extra flexible capacity to solve those issues. In that sense, three options for the service provision are considered:

1. **No services:** This means there are no flexibility services provided to the DSO through P2P trading. The P2P market is thus run without any interference from the DSO, and without any limits imposed by the grid. This means that the peers decide to trade together to optimize their objective function based on their preferences and there is no supervision by the DSO.
2. **Implicit services:** In this concept, the implicit service delivery entails that network constraints are included in the P2P energy trading so that the trades would not cause further problems for the system, hence, implicitly providing services to the grid. In this type of service, the product that is being traded between the peers is energy and the peers trade for their own energy requirements. However, by adding the network constraints to the peer matching process, they are becoming network-conscious traders and eventually support the system.
3. **Explicit services:** An explicit service delivery refers to a situation where the P2P trade is set up for providing specific flexibility services to the DSO. This type of service refers to the situation that P2P trading is used to meet a total quantity of flexibility based on a request of the DSO to alleviate system problems. In this type of service, the peers trade capacity between each other and although the individual matches are not specified by the DSO, the overall capacity requirement for solving the forecasted problem is communicated to the P2P market.

### 3.2.4 Incentivisation Schemes

The incentivisation scheme as a design element in this task refers to the situation where the network constraints are included in the P2P matching process; thus, the P2P trades can provide implicit services as defined in section 3.2.3. It has been mentioned that in the case of implicit service provision, the network constraints are added to the P2P matching process and therefore the impact of the potential trades on the network can be assessed. To deal with these trades in a way to support the DSO, the P2P matching intentionally tries to redirect the trades towards a set of matched bids that improve the network status. This redirection happens through incentivising/penalizing specific trades that are the source of constraint violations. If a set of matched bids create an issue in the network, this approach adds additional costs to that trade prices to penalize those specific peers. This penalization pushes the matched peers towards changing their trade quantities to not cause network problems anymore. In other case, if matched bids are solving an issue from the network, then they are incentivized for that specific trade.. Some of the common approaches for incentivization in the P2P literature are described in the following.

1. **Trade blocking:** One straightforward approach to penalize the trades that are violating the network constraints is to block those trades. In this approach, all those trades that are violating the constraints or aggravating the network status are prohibited from getting cleared in the P2P market.
2. **Network Usage Price:** One of the most common approaches for redirecting P2P trades when considering network constraints is the network usage price. The network usage price or the network usage charge is a term introduced by [65] to the P2P concept to encourage those P2P transactions that improve the distribution system performance and generate an additional revenue stream intended to offset the drop in the revenue caused by the roll-out of customer-end DERs. The Network Usage Price is calculated based on the distribution local marginal price (DLMPs) and intends to incentivize those P2P transactions that facilitate distribution network operations and penalize those P2P transactions that are unfavourable from the network operation perspective. This price is applied to the P2P transactions and the revenue or the cost (depending if the transaction is favourable to the distribution system operation or not) would be shared or covered by both parties of a trade.
3. **Constraint-based approach:** This approach uses network constraints as the main factor for calculating the incentive/penalty values. Bilateral trade willingness is affected by the coefficients calculated based on the network constraint values (i.e., congestion and voltage) and reflected in the energy pricing of the match [66].
4. **Cost allocation approach:** The cost-allocation approach calculates the cost that is imposed by the specific trade to the system and applies it to the trade price. The difference between this approach and the network Usage Price approach is that here the costs are calculated exogenously with the cost values associated with different network prospects (i.e., congestion, voltage, loss) and applied as per unit values to the trade before the matching process so that the peers would behave better concerning the network operation costs. This approach also requires less interaction of information or iteration between the P2P market and the system operator. An example of this method is in [67] where the cost of network loss was calculated.

All of the above-mentioned approaches are used in the implicit service provision model of P2P trading, therefore, all of them need to check the network constraints and make the transactions accountable for the effects that they have on the system. However, the difference between these approaches is in the modelling of the incentive and when they are being applied to the transactions. Trade blocking and network usage price are the two approaches that check the network constraints after the quantities of the matched bids are clear. If they are for example violating the constraints in the trade blocking approach they are blocked and in the network usage price approach they are penalized. In the constraint-based approach, the constraints are added in the form of weighted coefficients to the bids matching objective of the P2P market. In other words, this approach is used during P2P matching. Finally, the cost allocation approach is applied to the P2P trading before the peer matching because the model uses a unit-based value that does not need the quantity of the trade for its calculation. Instead, this value is added to the peers objective, thus changing their behaviours towards better trades for the network.

### 3.2.5 Trade Mechanism

As described in section 2.1.2, in a peer-to-peer trading concept, different market design models can be considered. The selected market design (i.e., centralised, decentralised, or hybrid) defines the level of centralization of the trades and communication. Each of the models aspires different trade mechanism which is an attribute of the P2P market (ref. Table 2). The most common approaches for trade mechanisms are 1**) Bilateral P2P trading** and 2) **Auction-based P2P trading**.

Bilateral trading is mainly used in a decentralised market model and is a form of trade that does not require a mediator so that the peers directly negotiate, start a contract, and trade with each other as shown in Figure 5.

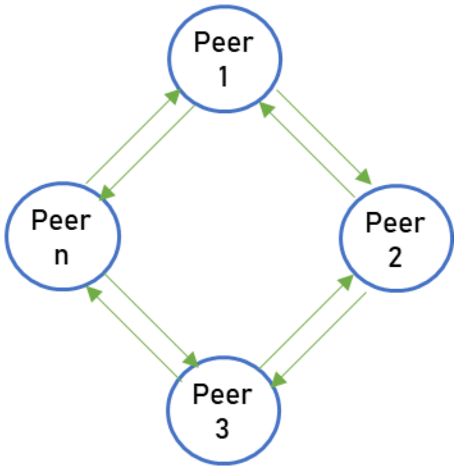


*Figure 5. Bilateral Trading*

An auction-based process is a market procedure based on negotiation techniques of the available bids to specify the buyer of the item according to specific bidding rules. The centralised market models use auctions to match the collected bids of the peers. A representation of this type of trading is shown in Figure 6.

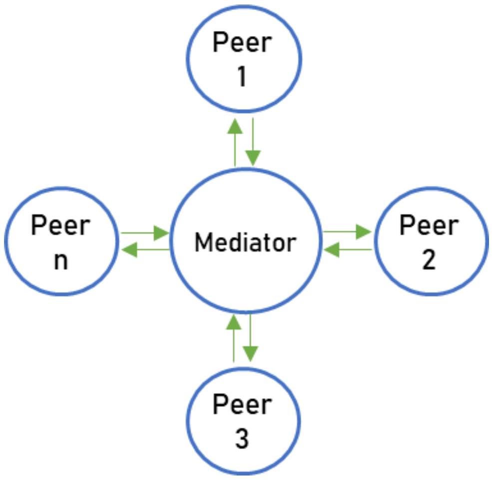


*Figure 6. Auction-based trading*

As mentioned in 2.1.1, the hybrid model has elements of both centralised and decentralised models. Consequently, both auction-based and bilateral trades can happen in a hybrid model. For example, if the hybrid model consists of two energy communities, then an auction can be run within each energy community by its community manager while the two communities trade bilaterally with each other.

Depending on the type of P2P trade mechanism, different layers of interactions and data sharing are required for the provision of flexibility to the DSO. Therefore, it is considered an important design element in the context of this task.

### 3.2.6 Addressed flexibility services

As mentioned before, providing flexibility services is not necessarily a feature for P2P trading; however, in this task, this feature is further analysed. As mentioned in section 2.2, the addressed flexibility services in the EUniversal project were screened in the existing literature on P2P trading. Referring to 3.1, the current literature does not consider the specific provision of flexibility services from P2P trading or by peers as a specific service to the DSO, rather they have included network constraints to study the impact of P2P trading on network issues such as congestion. According to the literature, the most common flexibility services that are considered are **congestion management** and **voltage control** while some literature has also considered the impact of P2P trades on **network losses** thereby providing solutions for reducing the total loss during peers' matching. This shows an alignment between the service needs identified in the EUniversal project as well as the trend in the P2P literature. In this regard, analysis in this deliverable also prioritizes congestion management and voltage control as the main services to be analysed alongside P2P trading.

### 3.2.7 Sequence with other flexibility mechanisms

Depending on which flexibility mechanisms are considered in the system and used for flexibility service provision, these mechanisms and their interaction with P2P trades are different. Most of the mechanisms that are described in section 2.1.4, other than the LFM, are implemented in the system through agreements between the DSO and the FSPs. The only mechanism that follows a market-based approach is the LFM, therefore, the sequence based on which the LFM market and the P2P market run may have an impact on their results. In this regard, the critical element to consider is the sequence of P2P markets with LFM.

As mentioned before, the peers can trade two main products, i.e., energy and capacity. For the flexibility service, when they trade capacity, they are an independent mechanism for the provision of flexibility to the DSO, therefore, it can co-exist with other flexibility mechanisms. However, when the P2P market exists in the system with energy being the main product the sequence of occurrence of P2P energy trade and the LFM needs to be considered as the energy trade among peers can affect the total amount of required flexibility. Another important aspect is whether the peers are allowed to participate in the LFM as well or not. If they have the option of both markets, then the sequence of these two markets are needed to be taken into account as it affects the commitment of peers in each market. There are three main possibilities:

1. **Unrelated timing**: in this case, the two market mechanisms can happen simultaneously or they are overlapping markets, therefore their timeframe remains unrelated.
2. **Sequential markets**: in this case, the LFM and the P2P market run in sequence. This means that either first the peers clear their bids and match their trades and then the status of the network is analysed for the required amount of flexibility that will be traded in the LFM or first the LFM runs and then the peers would go for the matching session. In the latter situation, if any issues are caused by the peers trading, then the DSO needs to resolve them by other mechanisms rather than the LFM. However, this order of sequence is important when the peers participate in the LFM market as well as the P2P trade which can affect their capacity commitment to solving network issues and can have further implications for the quantity that they can trade in the P2P market.
3. **Iterative markets:** in this case, there is an iteration between the LFM and P2P markets until they reach a point of convergence. In this case, the converging point is where there are no issues caused by the peers for the network as and the peers have met their objectives.

### 3.2.8 Geographical scope/Locality of the market

It was mentioned in section 3.1.2 that the flexibility services from the peers can cover a broad scope in terms of the grid coverage, however, depending on the trade process the P2P trade can cover a different geographical area. As P2P trading has been considered one of the main mechanisms for empowering local trading and consumer-centric approaches, many of the P2P trades happen within an energy community or a microgrid. In this case, a geographical boundary is considered for the P2P market. In other cases, the peers have the freedom to select the fellow peer they wish to trade with, who may not be located in the same area or a short distance from the initial peer. A distinction is therefore made between **local and system-wide geographical scopes**.

The LFMs can also cover different geographical areas in a distribution network. Where the two mechanisms - LFM and P2P market - co-exist, they may not necessarily cover the same geographical area which has an impact on the cross-participation of peers in these markets, i.e., participation of peers in P2P markets and/or (aggregated) peers in LFM. However, when the areas covered by these two mechanisms collide, the impact of the two mechanisms can be more intertwined. The energy trade of the P2P market can in this case increase or decrease the flexibility requirements that should be resolved by the LFM as will be studied in this deliverable.

### 3.2.9 Roles

The roles that are involved in the P2P energy trade and the EUniversal project have already been introduced in section 2.1.2. For the concept of P2P trading including flexibility services, these roles can be categorized into three main groups:

- Network-related roles
- Flexibility provision roles
- P2P trading roles

In this study, the only actor who can and plays the network-related role is the **DSO**. The DSO is the entity acquiring the services in the system as well as imposing/communicating network-related constraints.

The flexibility service provision roles are 1) the flexibility market operator (**FMO**) who runs the local flexibility market for providing the flexibility requirements of the system, and 2) the FSPs who provide the flexibility services and participate in the LFM. In this study, the DSO is the entity that needs flexibility services to resolve the network issues while the FSPs can be all prosumers in the system or their representatives.

The final group regards the P2P trading roles where other than the **peers** who play a fundamental role in the P2P trade process, the **mediator** is an important role, especially in a centralised or hybrid market model where many of the responsibilities are assumed by it. Depending on the setting and design of the P2P market (e.g., in a community or a microgrid) different entities can become the mediator. In community-based P2P trading, in addition to the responsibilities of its role, the community manager can act as a mediator. The same applies to an aggregator, a microgrid operator, or an Energy Service Company (ESCO) depending on the specific settings of the P2P trade. However, what is important for the role of the mediator is that wherever a mediator exists, it acts as an intermediary between the P2P trade and other mechanisms, such as LFM, and would be responsible for the required communications.

The design elements that are identified based on the screening of the models and methods in the literature of P2P trading and flexibility service provision, are used to design the conceptual models for the mechanisms of P2P trading and flexibility service provision described in Chapter 4. In the following chapter, it is described how each design elements contribute to the formation of conceptual models.

# 4 Proposed concepts on P2P trading for flexibility services

## 4.1 Concept definition assumptions

The design elements that were explained in the previous chapter are the factors that can lead to different conceptual models (CM) for running a P2P market considering flexibility service provision. The conceptual models in this task represent the setting in which P2P trading exists in the distribution system and interacts with the DSO or other flexibility service resources to provide services. The developed conceptual models aim at showing potential variations of such settings, i.e. show the linkages between the considered market mechanisms - the P2P market and the LFM - and discuss the high-level interactions between the involved roles.

Given that the main purpose of this work is to analyse the implications of P2P trading on the flexibility requirements of the DSO, the definition of the proposed concepts prioritizes the elements that have a more significant impact on the flexibility requirements of the DSO when considering the existence of P2P trading in the distribution system. In this regard, certain assumptions are made before conceptualizing the P2P trade and DSO flexibility service provision:

1. It was assumed that the only flexibility mechanism for the DSO to obtain its required services is the local flexibility market (LFM). Other flexibility mechanisms mentioned in section 2.1.4 are not considered;
2. The flexibility services that are needed in the system are assumed to be congestion management and voltage control;
3. It is assumed that whenever the P2P energy trade process considers the network constraints, the P2P trade is providing an implicit service to the DSO by not violating the operational constraints of the network.
4. It is assumed that the area where the peers are located and trade with each other overlaps with the market area of the LFM.

With these assumptions, the remaining design elements that would make a difference in the setting of the P2P market and flexibility service provision are shown in Table 4. This means Table 4 shows the elements from section 3.2 that have an impact on the interactions between the P2P market involved parties (i.e., the peers and the mediator) and other entities in the system responsible for other mechanisms such as FMO and DSO. Based on these elements the following conceptual models are defined and will be further discussed in the following sections.

- **CM1** – Auction-based P2P energy trade with no service: where the peers trade energy through a mediator and as no network constraints is considered, no DSO service is provided by the peers. The option of co-existing LFM is possible.
- **CM2** – Bilateral P2P energy trade with no service: where the peers bilaterally trade energy and as no network constraints are considered, no DSO service is provided by the peers. The option of co-existing LFM is possible.
- **CM3** - Auction-based P2P energy trade with implicit service: where the peers trade energy through a mediator and the network constraints are considered as part of P2P trading, hence, implicit services to the DSO are provided. The option of co-existing LFM can cause a variation in the interaction in this CM.
- **CM4** - Bilateral P2P energy trade with implicit service: where peers bilaterally trade energy and the network constraints are considered as part of P2P trading, hence, implicit services to the DSO are provided. The option of co-existing LFM is possible.
- **CM5** – Bilateral P2P capacity trade with explicit service: where the P2P trading is specifically set up to provide flexibility services to the DSO and the peers' trade capacity with each other to provide the total required flexibility of the DSO.

The rest of the design elements that are not shown in the table or not mentioned as a specific assumption above are the roles and the sequence with other flexibility mechanisms. The role element is an indicative aspect of the chosen trade mechanism as well as the option of participating in the LFM which necessitates the role of the FMO. What remains is the sequence of the P2P and LFM market that is described as part of the conceptual model itself.

*Table 4 Design elements and conceptual model variations*

| | Trade Product | | Service Provision Method | | | Trade Mechanism | | Participation in LFM | |
|---|---|---|---|---|---|---|---|---|---|
| | Energy | Capacity | No Service | Implicit | Explicit | Auction | Bilateral | Yes | No |
| **CM1** | ✓ | | ✓ | | | ✓ | | ✓ | |
| **CM2** | ✓ | | ✓ | | | | ✓ | ✓ | |
| **CM3 - V1** | ✓ | | | ✓ | | ✓ | | | ✓ |
| **CM3 - V2** | ✓ | | | ✓ | | ✓ | | ✓ | |
| **CM4** | ✓ | | | ✓ | | | ✓ | ✓ | ✓ |
| **CM5** | | ✓ | | | ✓ | | | | ✓ |

It should also be noted that when the following conceptual models are explained, the focus is to highlight how the P2P market set-up can provide services to the grid, and how it interacts with other flexibility service mechanisms in the system (i.e., LFM) and the DSO. Therefore, the representative figures are not depicting the whole energy business in the grid but rather what is most relevant to the purpose of this task. This means that, although the figures or the description of the conceptual models may not indicate the LFM and other FSPs in the system, it does not necessarily mean that they cannot operate beside or in parallel with the presented model. The reason that they are not included is that they are not considered to be directly affecting the set of interactions that are highlighted in the conceptual model (i.e., the interactions between peers, the interactions between the P2P mechanism and LFM, and the interactions with the DSO).

### 4.1.1 Conceptual Model 1- Auction-based P2P trade with no service

The first model considers the existence of P2P trading where the peers trade with each other using an auction-based approach. The network constraints are not included in the peer matching process, therefore, according to our assumptions, no service from the P2P trading is offered to the system. One potential implementation process for operating this model is shown in Figure 7. As can be seen, the mediator runs the auction and matches the bids of the peers participating in the P2P trade. As no network constraints are considered, the mediator does not have any knowledge of the network status as a result of the selected trades, and, therefore, the main objective of the mediator, in this case, is to maximize the collective objective taking into account the peers' preferences.

Considering the other flexibility provision mechanism to be the LFM according to our assumptions, the interactions of the mediator and the DSO with LFM are also shown in Figure 7. The mediator has the option of participating as well in the LFM using the aggregated flexibility of the peers. Therefore, another revenue stream possibility exists for the peers. In this case, as the peers' matching is done without the knowledge of the network constraints, the final results will have a twofold impact: either they unintentionally improve the network situation, therefore, reducing the amount of flexibility that is needed from the LFM; or they worsen the network situation which needs to be solved by the LFM. In the latter case, the mediator who has the option of participating in the LFM may abuse the situation by intentionally violating the constraints and then offering its alleviation in the LFM.

This model is most suited for settings where peers would prefer the centralised P2P market model and are located within a community or microgrid. The role of the mediator has been highlighted for the interactions between other flexibility service mechanisms such as the LFM and the P2P market. As this model does not provide a specific service to the DSO or consider network constraints, no specific interaction between the P2P market and DSO is required.

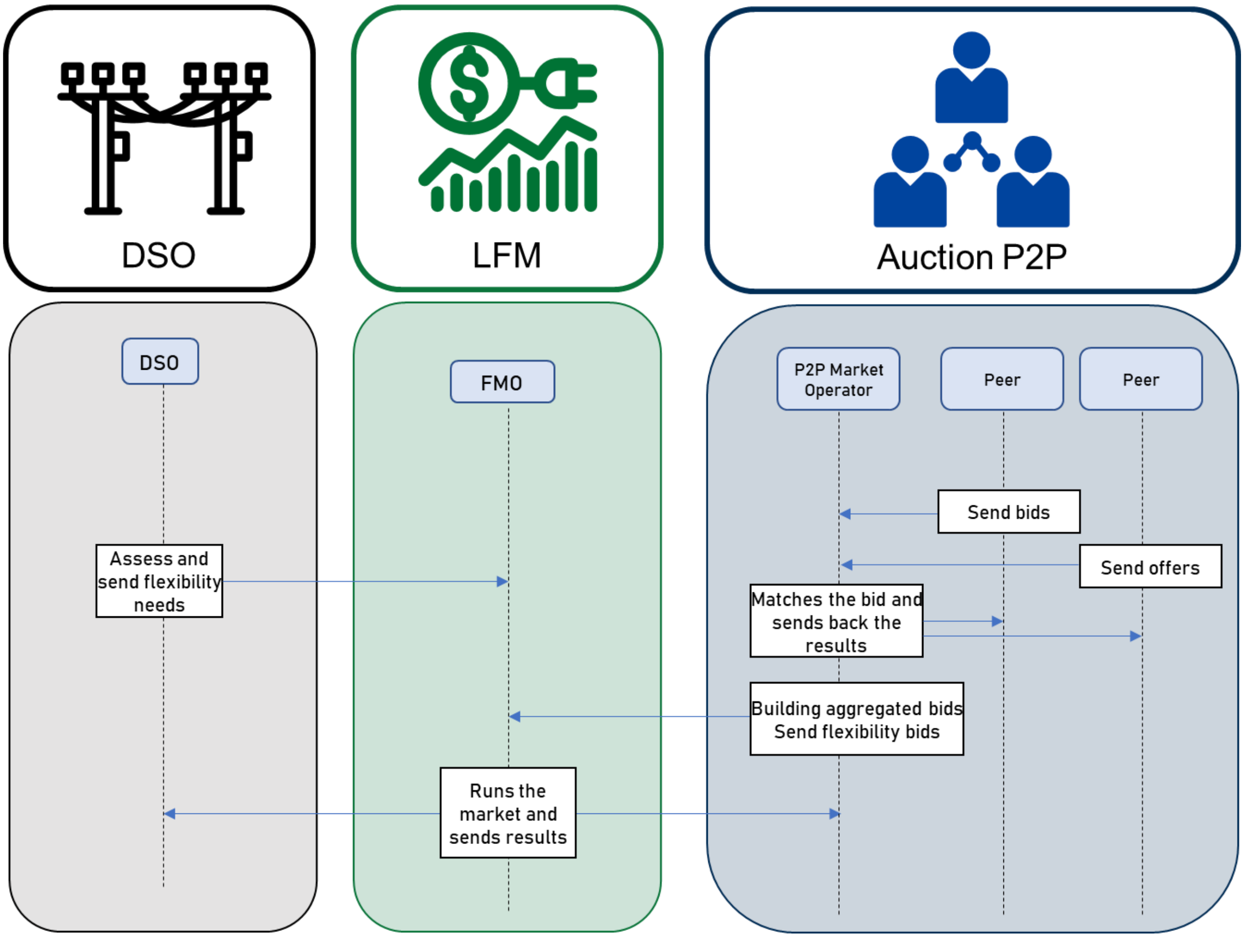


*Figure 7. CM1 – Auction-based P2P and no service with LFM*

### 4.1.2 Conceptual Model 2 - Bilateral P2P trade with no service

This model considers P2P energy trading in the system with a bilateral trade mechanism between the peers. The peers in the model have no knowledge of the network and they trade with each other only to satisfy their energy needs and without consideration of the impact that their trade may have on the network. Therefore, this model is also considered a 'no-service' model as no flexibility services are provided to the DSO through P2P trading. Whenever such a model exists in the network, other flexibility mechanisms (i.e., LFM) should be used in the system to support the flexibility requirements. Figure 8 shows one potential implementation of the interaction process between the involved parties in this conceptual model. In chapter 5, a specific sequential setting of this conceptual model will be further analysed, namely a case with a sequential P2P and LFM, where the P2P market runs first followed by the LFM. Parts of the peers would in this case participate in the LFM with their remaining flexibility.

As can be seen, the peers trade bilaterally to meet their energy needs. The LFM market is the environment where the existing FSPs in the system would offer their flexibility. The flexibility market operator runs the market, and the results of this market would meet the flexibility needs of the system. The LFM participants are the FSPs in the system. However, a peer can also be an FSP and participate in the LFM. This means that in this setting the decision-making of each peer on how to bid to other peers as well as how to bid in the LFM would have an impact on the total cost of providing flexibility in the system. When the peers have both options of P2P trading and the LFM, the decision of peers on how they would bid in these markets is affected by their provisional revenues from each market. The amount of energy that is provided through P2P trading affects the amount of energy that is needed from the upstream network. On the other hand, the commitment of peers to the P2P trade affects their availability to be offered to the LFM. Nonetheless, the P2P energy trading itself can also create further network problems that should be addressed by the LFM.

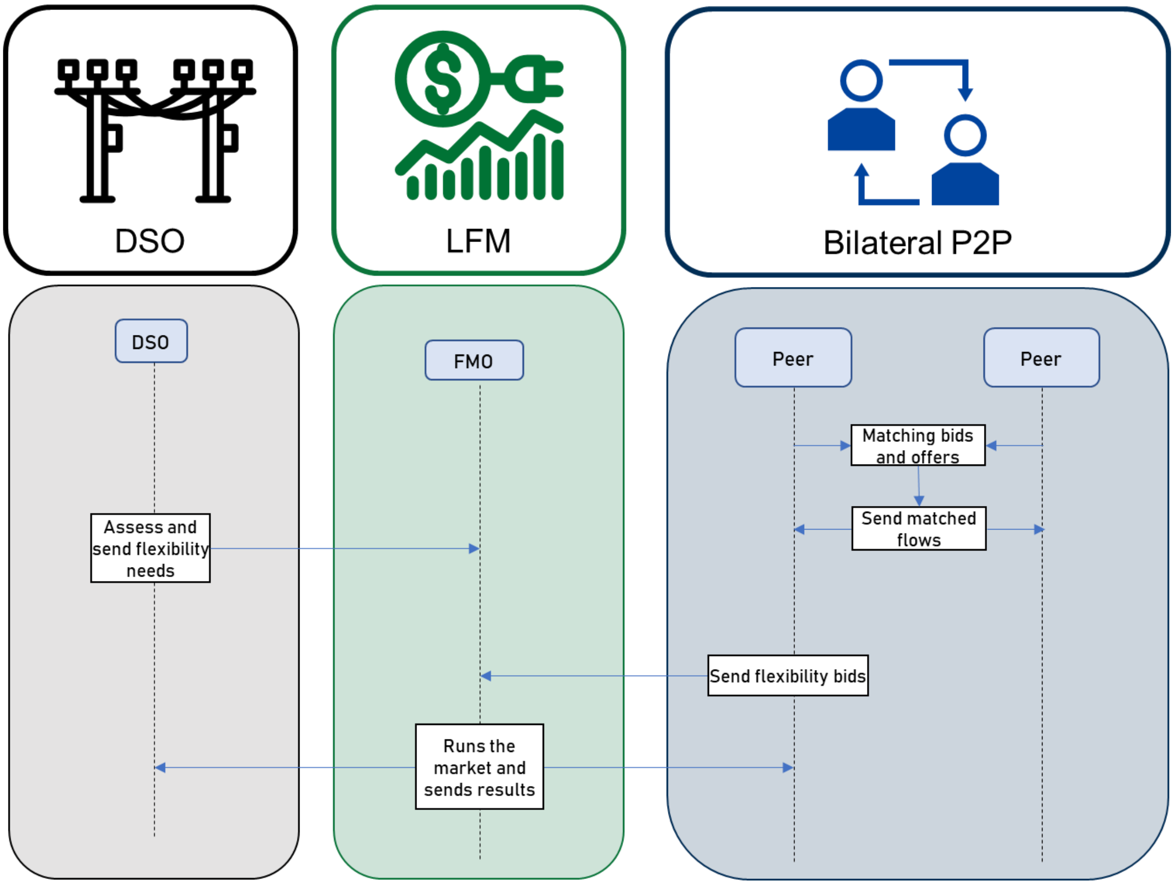


*Figure 8. CM2 – Bilateral P2P and no service with LFM*

### 4.1.3 Conceptual Model 3 - Auction-based P2P trade with implicit service

In order to have a P2P trading process aligned with the system requirements and thus not cause further network problems, this model is considered. It is an extended model from CM1, but in this case, implicit service provision for the DSO is considered. In this model, the status of the network (i.e., network constraints) is considered as part of the P2P energy trading. For this purpose, an additional layer of communication between the DSO and the mediator is considered so that the P2P trade matching process performed by the mediator is network conscious. Depending on the scope of the P2P trades, the role of the mediator can be assumed by a community manager, an aggregator or other entities that would act as an intermediary both for running the P2P market and facilitating the data sharing between the peers and the DSO.

The specific aspect of this model is that when a trade violates the network constraints, there are two options on how to deal with this issue. The first approach is to block the trade that is aggravating the network status and the peers involved in this trade need to find other alternatives for their energy requirements. In this case, the problematic trade would be prohibited so that no constraint violation would be imposed on the system, hence, implicitly the procedure of P2P trading is supporting the network operation. The second approach is to redirect the P2P trading in a way that the final results of the matched bids would not violate any constraints in the system. The approach of redirecting is done by incentivizing the trades that improve the status of the network and/or penalizing the trades that are violating constraints. The methods of implementing these pricing schemes have been introduced in the design elements in section 3.2.4. Regardless of which specific method is going to be used, what is important is the interaction between the DSO and the mediator on the network constraints and the status of the network as a result of the P2P trades.

The process of this model can have two variations which are shown in Figure 9 and Figure 10. In variation 1 (i.e., Figure 9), it is assumed that the P2P matching considers the network constraints and implicitly provides the service to the DSO, but no other flexibility service mechanism exists in the system. In the second variation (i.e., Figure 10), it is assumed that the LFM also exists in the system and the mediator has the option of participating in the LFM with the aggregated flexibility of the peers; thus, offering flexibility to the DSO through LFM.

The implementation of this model and how the pricing scheme would be imposed depends a lot on who would take up the role of the mediator and what would be its level of control over the peers. An example of this model in the literature is [68] which provides implicit services through centralized P2P trading with a focus on the trades between two neighbouring communities. The model considers various network constraints such as flow constraints, network losses, and voltage regulation. The flows are redirected to support the DSO by applying a constraint-based pricing scheme.

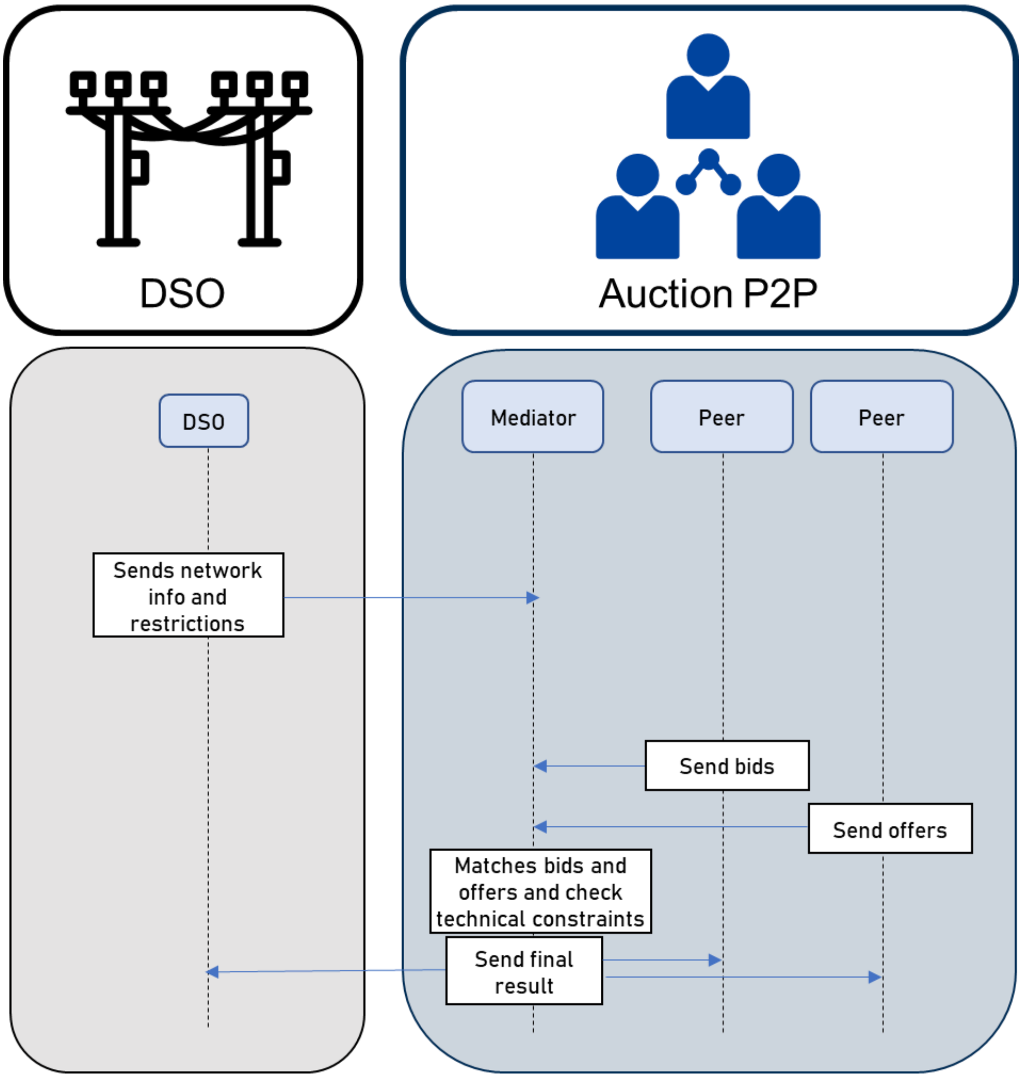


*Figure 9. CM3 -Variation1 – Auction-based P2P with implicit service and no LFM*

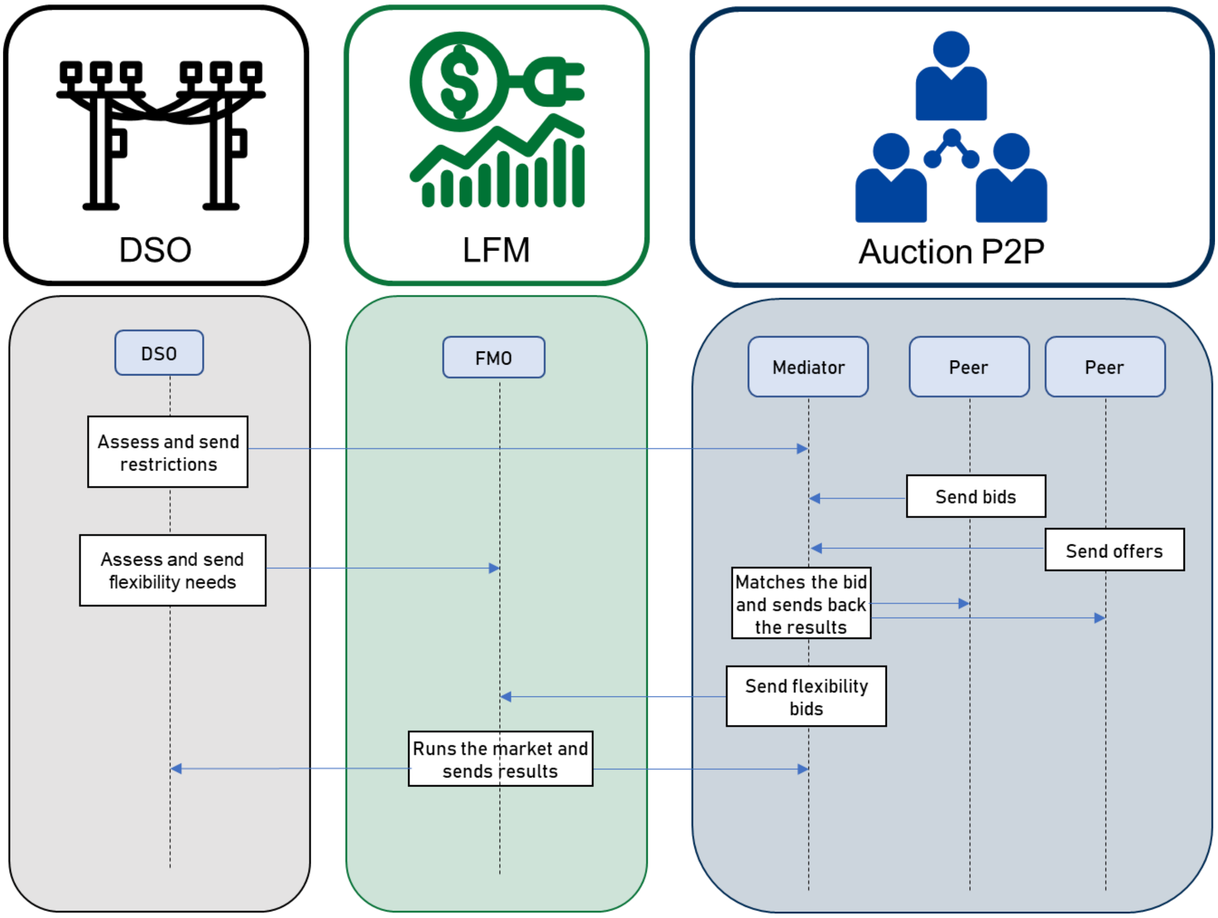


*Figure 10. CM3 – Variation 2 – Auction-based P2P with implicit service and LFM*

### 4.1.4 Conceptual Model 4 – Bilateral P2P trade with implicit service

In this model, a decentralized P2P market structure is considered with bilateral trading. The main actors in this model are the peers and the DSO. In the first round, the peers trade bilaterally without considering the network constraints. The bilateral negotiations are based on the peers' objectives and preferences. The energy quantity of the negotiated bids is communicated to the DSO while the price quantity remains confidential to the involved peers. Then, the DSO analyses the system state and network constraints considering the possible trades from the peers. This analysis checks the feasibility of the P2P trades in terms of network constraint violations. If the trades violate the network constraints, then the two options of dealing with the problematic trade mentioned in the previous conceptual model also apply here which are either blocking the trade or redirecting it through incentives. The procedure in this CM is shown in Figure 11.

Being a bilateral trade, the individual peers are not informed of the network constraints on their own. Therefore, a network-related role, which in this model is considered to be the DSO, is needed to check the effects of the trade. The decision-making on changing the violating trades is on the peers which means that if a possible trade has been detected as violating constraints, the peers need to renegotiate. The process is an iterative process which needs to converge to a point where all the bids are matched, and no constraint is being violated. The process that is shown in Figure 11 is an example of the interaction between the peers in a bilateral trade and the DSO when the P2P trading provides implicit services.

Like in CM3, in this model peers can unintentionally make the network status better which reduces the required amount of flexibility by the DSO. However, as in previous models, other flexibility mechanisms such as an LFM can also exist besides the P2P mechanism. In fact, these mechanisms can run in parallel and there is no interference with the process of this CM. An example is [59] where a methodology based on sensitivity analysis is proposed to assess the impact of P2P transactions on the network and to guarantee an exchange of energy that does not violate network constraints. In order to achieve this, the matched bids are checked by the DSO and the feedback on violating trades is done by affecting the price through the cost allocation method (ref. 3.2.4). Their methodology considers various factors such as the voltage sensitivity coefficient, power transfer distribution factor, and loss sensitivity factor that are defined as a function of the power injected in the network, hence, correlated with P2P trade options. The results compare the system costs and users' revenues to evaluate the effectiveness of the model. On the other hand, in [69], a game-theory-based model for multi-bilateral trading with network constraints provides a pricing signal to consider voltage violation in the P2P pricing scheme. Another example of this conceptual model with multi-bilateral trading is [70] where a joint transmission and distribution P2P market is studied with loss allocation policies.

In chapter 5, two potential implementations of this conceptual model are analysed. Both cases consider a sequential setting of a P2P market followed by an LFM, which aims at resolving the updated network congestions after the P2P market. In the first implementation, the DSO can block any two peers from trading, if this would increase the congestion of the grid, while in the second implementation, the DSO redirects the P2P trades to resolve resulting grid issues.

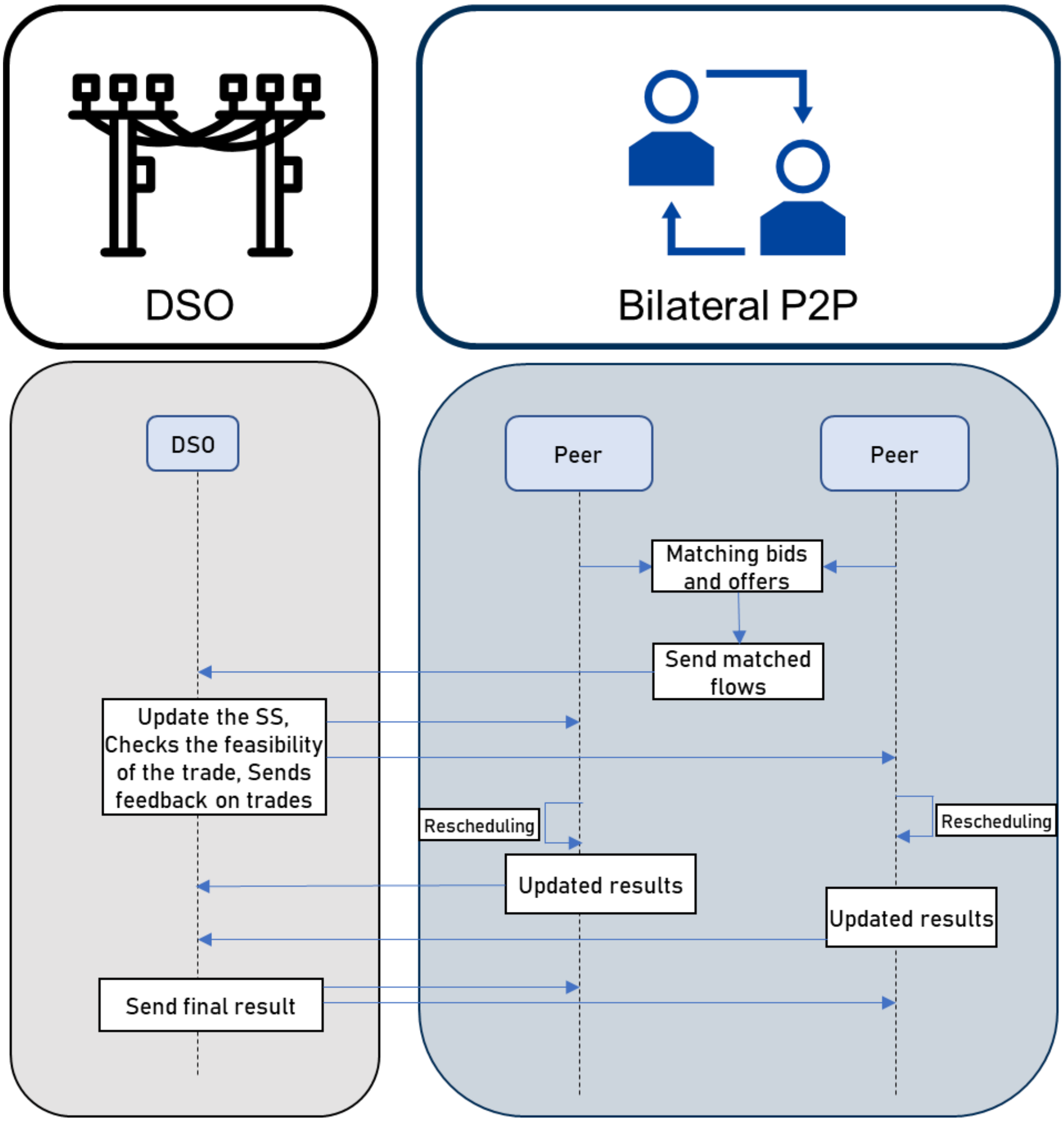


*Figure 11. CM4 – Bilateral P2P with implicit service*

### 4.1.5 Conceptual Model 5 – Bilateral P2P trade with explicit service

The final conceptual model is the only one that considers the trade product to be capacity, unlike the other CMs where the traded product between the peers was energy. Moreover, in this concept, the P2P market is set up to provide explicit flexibility service to the DSO, meaning that they are trading to relieve a specific requirement of the network (hence it is an explicit service provision). In this model, the DSO checks the status of the network and estimates the total amount of flexibility (in kW) that is needed for a specific area. The required quantity is communicated to the P2P market. Therefore, the objective function of the P2P market is to meet the estimated flexibility requirement of the DSO and the total trade quantity should provide that value. The process of this concept is shown in Figure 12.

It can be seen that the requirement of the DSO on the total capacity is communicated to the participants of the P2P market. The peers trade bilaterally, however, as mentioned, the total traded volume should meet the expected flexibility quantity of the DSO. The final results are then communicated to the DSO. This conceptual model is an alternate mechanism to provide flexibility services to the DSOs instead of a conventional LFM where the results of the local flexibility market should resolve the flexibility needs of the DSO. It provides a distributed market model to the prosumers with the benefits of a decentralized market model which is on the other side of the spectrum compared to the LFM which has a central model.

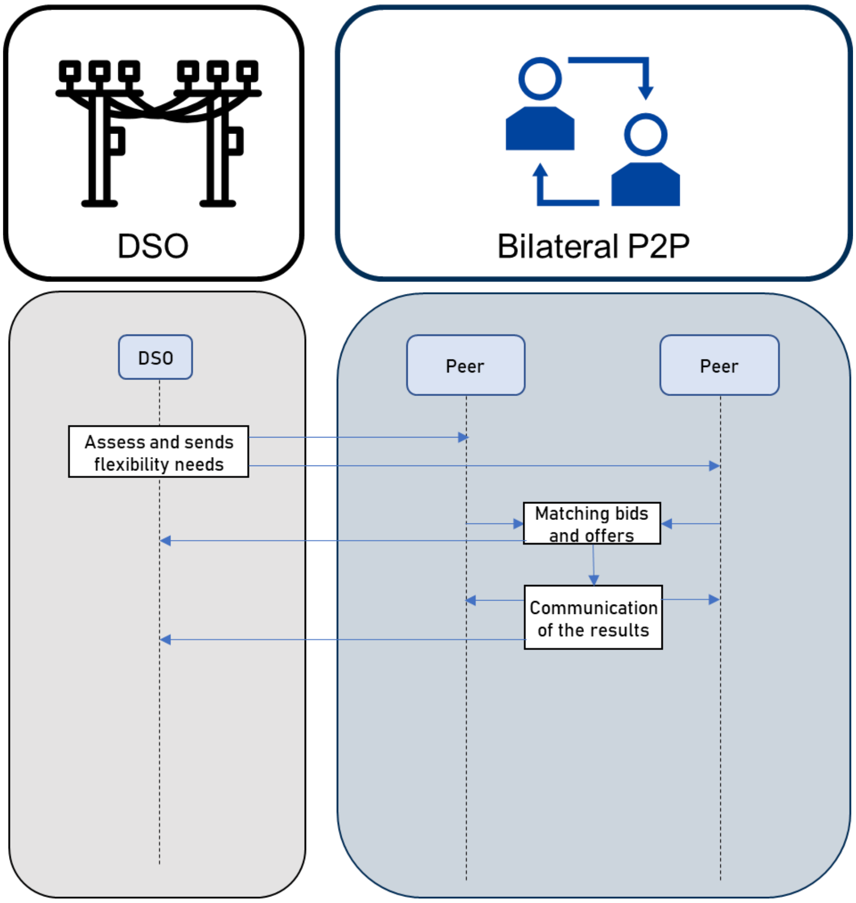


*Figure 12. CM5 – Bilateral P2P with explicit service*

### 4.1.6 Comparison of the different conceptual models

To conclude this chapter, the table below describes some of the high-level advantages and disadvantages of the different conceptual models. It should be noted that the advantages and disadvantages are dependent on the actual design choices and effective implementations of the different models. Conceptual model 5 is not considered in this table as it is the only model that considers explicit service delivery, so cannot be easily compared with the other models. In the next chapter, a quantitative assessment of potential implementations of some of the proposed conceptual models (i.e., CM1 to CM4) will be made, focusing on the models with bilateral P2P energy trading in combination with an LFM.

*Table 5: Advantages and disadvantages of the different conceptual models*

| | Advantages | Disadvantages |
|---|---|---|
| **Conceptual Model 1- Auction-based P2P trade with no service** | - Peers can trade with each other through a mediator.<br>- Social welfare maximization of P2P trading can be realized.<br>- Aggregated flexibility of the peers can be offered to the LFM by the mediator. | - Privacy concerns of the peers.<br>- Uncertainty for the DSO on the impact of P2P market trades on the network.<br>- P2P trading can create further network constraints that should be addressed by the LFM. |
| **Conceptual Model 2 - Bilateral P2P trade with no service** | - Peers are in full control of their decision-making process.<br>- Peers can freely trade with each other based on their own objectives<br>- Peers have the option to offer their flexibility to the LFM.<br>- The privacy of peers can be assured. | - Potentially lower overall efficiency of the P2P market.<br>- Uncertainty for the DSO on the impact of P2P market trades on the network.<br>- P2P trading can create further network constraints that should be addressed by the LFM. |
| **Conceptual Model 3 - Auction-based P2P trade with implicit service** | - Peers can trade with each other through a mediator.<br>- Aggregated flexibility of the peers can be offered to the LFM by the mediator.<br>- P2P trading considers network constraints to avoid violations. | - Privacy concerns of the peers.<br>- The revenue of the peers can be affected by the interventions of the DSO.<br>- The overall cost of the DSO interventions can be more expensive.<br>- Need for more complex P2P market clearing.<br>- Additional layer of communication is needed between the DSO and the P2P market.<br>- Interference by the DSO in the P2P market which can create market distortions. |
| **Conceptual Model 4 – Bilateral P2P trade with implicit service** | - Peers can trade with each other based on their own objectives<br>- Peers have the option to offer their flexibility to the LFM.<br>- P2P trading considers network constraints to avoid violations. | - Privacy concerns of the peers (information to be shared with DSO)<br>- The revenue of the peers can be affected by the interventions of the DSO.<br>- The overall cost of the DSO interventions can be more expensive.<br>- Need for more complex P2P market clearing<br>- Additional layer of communication is needed between the DSO and the P2P market<br>- Interference by the DSO in the P2P market which can create market distortions. |

# 5 Quantitative evaluation of selected cases

## 5.1 Introduction and Motivation

In emerging distribution-grid settings, there is an increasing need for local flexibility markets (LFMs), through which the DSO can procure flexibility to meet its system services need, such as congestion management (including management of line flows, and voltage magnitudes, making sure they are restricted to their predefined limits). However, the emerging concepts of P2P trading, through which consumers bilaterally trade energy, can naturally also have a direct effect on the grid operation, especially when P2P trading does not take into account grid limitations and operational constraints. As explained before, the coexistence of P2P trading and LFMs ought to be analysed to determine the dimensions along which the two market mechanisms can be complementary or opposed and the effects thereof on the grid operation.

Indeed, when considering the coexistence of LFMs and P2P mechanisms, one can identify two theoretical extremes and a spectrum of possibilities that lie in between:

1) On the positive extreme, the P2P trading can result in energy traded between peers that are completely in line with the needs of the DSO, hence, resolving the existing congestions, thus, avoiding the need to run an LFM for a particular period.
2) On the negative extreme, the P2P mechanism may result in P2P trades that exacerbate the congestions previously available in the grid (while also creating new ones), rendering the LFM not able to resolve all caused congestions.
3) Between those two extremes, the P2P trading can be advantageous to the LFM, partly resolving (or attenuating some congestions) and leading to a reduction of the total cost of procuring flexibility by the DSO, while in other cases, the P2P can worsen the congestions available in the grid, rendering the procurement of flexibility by the DSO through the LFM more costly. These instances can also coexist, in the sense that the P2P trading may resolve some congestions while causing others.

As such, the goal of this chapter is to analyse the effects of P2P markets on the grid operation and procurement of flexibility for some of the proposed conceptual models in chapter 4, by providing detailed examples that highlight the possible negative and positive coexistence between LFMs and P2P mechanisms. In this chapter, we will specifically focus on the conceptual models which consider bilateral P2P energy trading, respectively without the consideration of DSO needs (conceptual model 2) and with implicit DSO services (conceptual model 4). For the cases corresponding to conceptual model 4, different incentivisation schemes (as introduced in section 3.2.4) will be considered.

In this respect, we propose and explore different ways (referred to hereafter as scenarios) in which P2P trading can take place. Each of these scenarios reflects a different level or method in which the DSO can impact the P2P trading mechanism, while all are compared to a reference scenario 0 in which no P2P trading takes place. The effects of those scenarios on the grid are analysed and compared, resulting in a set of insights and recommendations.

The local flexibility market and P2P market models used in this analysis are introduced next. Then, the different scenarios are described in detail, followed by the quantitative analysis, and derived conclusions.

## 5.2 Local Flexibility Markets and Peer-to-Peer Market Models

### 5.2.1 Local Flexibility Market Model

The local flexibility market is a market setting in which the market operator receives upward and downward flexibility bids, along with submitted bid prices, from FSPs, where the market clearing chooses the optimal set of bids to (partially) meet the flexibility needs of the DSO (e.g., congestion management) at the least possible cost. The needs of the DSO are based on its network topology, grid operational limits (e.g., line capacity limits), and forecasted base load and generation profiles, which based on power flow calculations would result in the expected flows over the lines [18]–[20].

The local flexibility market would, hence, output the set of bids to be purchased, the quantities purchased from each bid, and the updated state of the network considering the effect of the accepted bids. A summary diagram of the LFM is shown in Figure 13.

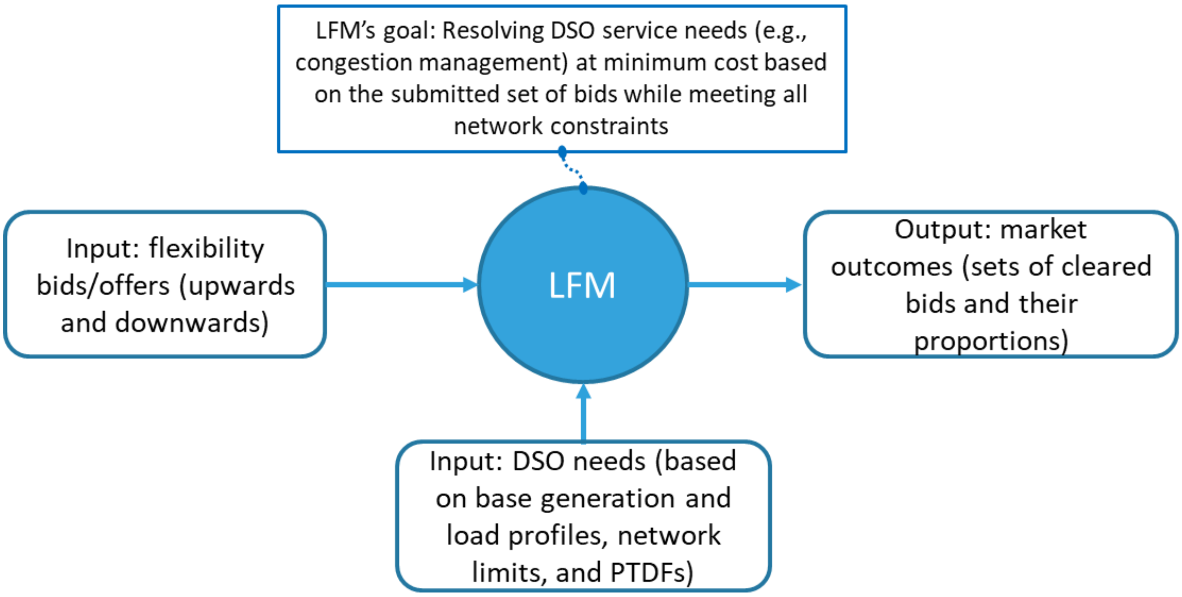


*Figure 13. Local flexibility market model*

The local flexibility market mechanism used in this case study is the one originally presented in [19], [20]. This market mechanism is a disjoint (i.e., not common or shared with other system operators) market mechanism which makes use of power transfer distribution factors (PTDF) – equally known as generation shift factors (GSF) – to quantity the changes in nodal power injections and withdrawals on the flows over the different lines. This enables the market clearing to compute, for each possible set of purchased bids, their effects on the flows/congestions within the network, which enables the market clearing to be constrained accordingly to make sure not only that the initial congestions – for which the market was set up – are optimally solved, but also that no additional congestions arise due to the market clearing. The mathematical details of this market clearing are provided in [19], [20].

An additional mechanism is also implemented, to which we refer as "grid check", which, for any set of injections and load profiles, computes the expected network flows. This enables the calculation of the expected flows over the lines, and hence, the identification of possible congestions. Based on this calculation, a key element is computed for each line, referred to as the "overflow", which – when positive – reflects the amount by which the expected flow over a line exceeds its line capacity limit. The grid check is, hence, also a key functionality that identifies the effects of the P2P trading on the network state (flows, and expected congestions).

### 5.2.2 P2PMarket Model

The P2P market model is modelled using game theory in which each peer attempts to optimize their own objective given the objectives of other peers and subject to the presence of constraints. Each peer's objective consists of a production cost of generation, a usage (i.e., consumption) benefit utility, and the cost of trading with other peers.

Each peer presents a bid or set of bids, in which they indicate their local consumption needs or generation provisions, and the cost of trading with other peers. This cost reflects the peer's preference to trade with any other peer.

The peer-to-peer matching algorithm then pairs the peers according to the collection of their objectives. The outcome of the model consists of a list of realized (equilibrium) bilateral trades between established pairs of peers. Figure 14 provides a summary description of the P2P market model.

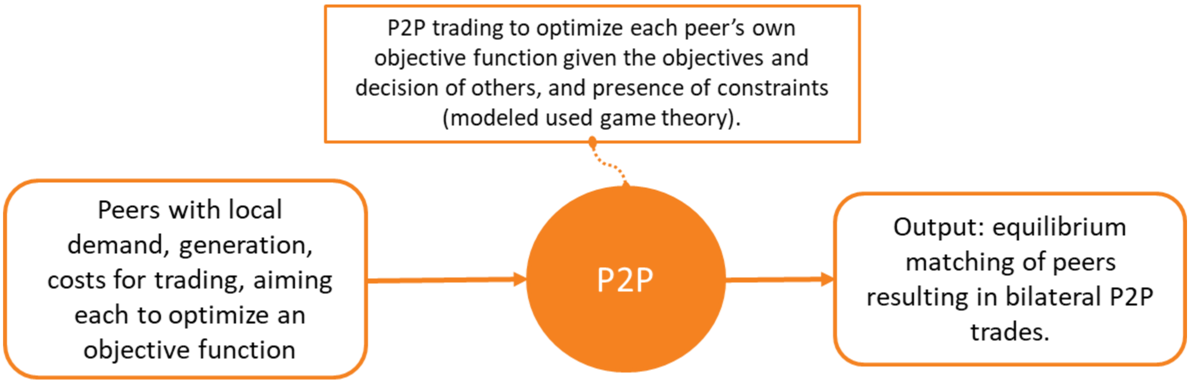


*Figure 14. Peer-to-Peer market model*

As, in this case study, the LFM and P2P market interaction is sequential meaning that after P2P runs, its outcomes are then communicated to the LFM in the form of updated base generation and consumption in the nodes where the peers are located. Then, the LFM runs to resolve all initial congestions as well as congestions arising from the P2P trading Additionally, flexibility bids are also updated, where volumes realized in the peer-to-peer market model are cleared from the original orderbook.

## 5.3 Description of Use Cases

The different scenarios capture different ways in which the DSO may impact the P2P trading mechanism. Scenario 0 is introduced as a reference case including solely an LFM (no P2P mechanism is in place).

In all the studied scenarios, the grid initially is in a congested state, where the LFM is in place so that the DSO can purchase flexibility to resolve those congestions. In each of the scenarios (except scenario 0), the P2P trading takes place before the LFM mechanism. This P2P energy trading will result in an updated state of the grid (i.e., updated generation and load profiles, flows, and hence, congestions). The LFM would, then, take that updated state as input to try to resolve all arising congestions. Scenario 1 corresponds to a potential implementation of conceptual model 2 "Bilateral P2P trade with no service", while scenarios 2 and 3 are potential implementations of conceptual model 4 "Bilateral P2P trade with implicit service" with different incentivisation schemes. Table 6 shows the link between the conceptual models from chapter 4 and the scenarios studied in this chapter. In the quantitative studies, only the conceptual models with bilateral trading option is selected to be analysed to showcase a more decentralised approach and compare it to the centralised approach of LFM. The scenarios will be further explained in the remainder of this section.

*Table 6 Overview of the conceptual models studies in the scenarios*

| | **Conceptual Model** | **Incentivisation scheme** |
|---|---|---|
| **Scenario 1** | CM2 - Bilateral P2P trade with no service | NA |
| **Scenario 2** | CM4 - Bilateral P2P trade with implicit service | Blocking of trades |
| **Scenario 3** | CM4 - Bilateral P2P trade with implicit service | Redirecting (incentivizing/disincentivizing) trades |

### 5.3.1 Scenario 0

In scenario 0, only an LFM market is in place to resolve the existing congestions. In other words, in scenario 0, the DSO – based on available forecasts on generation and load profiles – aims to purchase flexibility through the LFM to resolve those congestions (the LFM mechanism is introduced in Section 5.2.1) without P2P trading market. This mechanism is highlighted in Figure 15.

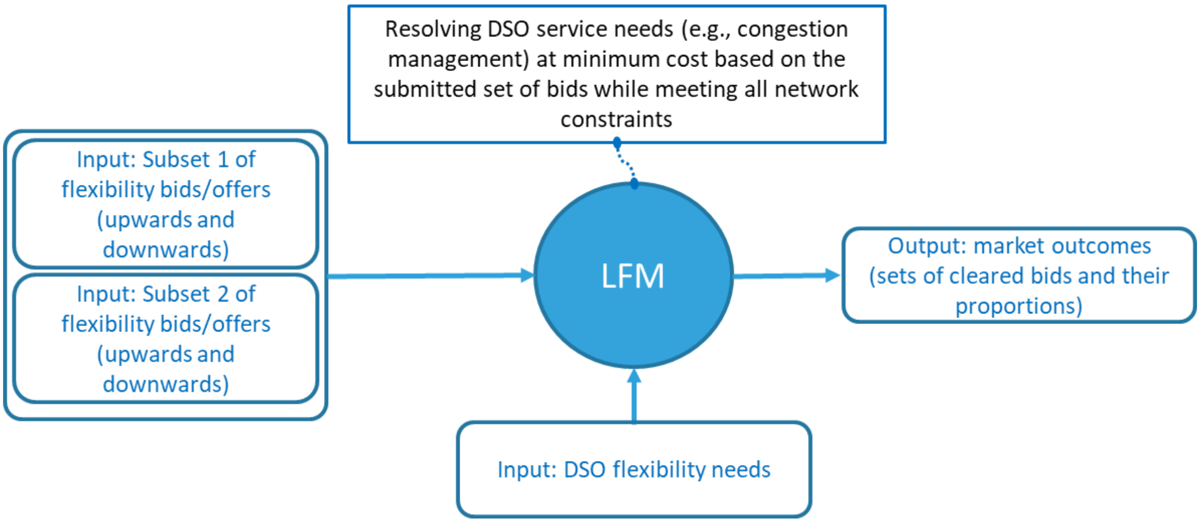


*Figure 15. Scenario 0 - Local flexibility market with no peer-to-peer mechanism (reference scenario)*

The sets of input bids in Figure 15 are split in two (where both are still submitted to the LFM), as this split will be used in the following scenarios. In this respect, in the following scenarios, we consider that some agents acting as FSPs in the LFM – i.e., which would otherwise participate in the local flexibility market (i.e., subset 2), would choose to rather participate in the P2P trading mechanism, and hence act as peers. This is further highlighted in scenarios 1 to 3.

Scenario 0 is used as a reference scenario, as this highlights the setting of no P2P mechanism, and hence, captures the costs that would be paid by the DSO to resolve its congestions during a certain market time unit.

The next scenarios add the existence of the P2P market and capture its effects on the grid (through the grid-check) and its consequence on the functionality and total cost of the LFM (for each market session in which the LFM is run):

a) If the cost of the LFM decreases after the P2P trading session, this highlights that the P2P trading – for that period – has helped the grid; while
b) if the cost of the LFM increases, this reflects the setting in which the P2P trading – for this period – has worsened the state of congestions in the system (either exacerbating existing congestions or creating new ones).

These aspects are further detailed next where the three different scenarios of coexistence between the LFM and P2P market mechanism are introduced, where each scenario presents a different level and type of inputs that the DSO can use to impact the P2P trading, aiming to lead its outcome to a situation less harmful to the grid. Scenario 1 presents a completely unchecked P2P mechanism, while scenarios 2 and 3 provide two different alternatives through which the DSO can provide inputs to the P2P trading scheme.

### 5.3.2 Scenario 1

In scenario 1, the P2P market is run first, resulting in energy trades between the peers, which would then affect the base injection and load profiles at all the nodes. Through the grid check, the effect of the P2P trading on the grid can be quantified, generating the updated network state. After the P2P trading, an LFM is run, through which the DSO can resolve any (remaining or exacerbated) congestions and any newly created ones. This process is highlighted in Figure 16.

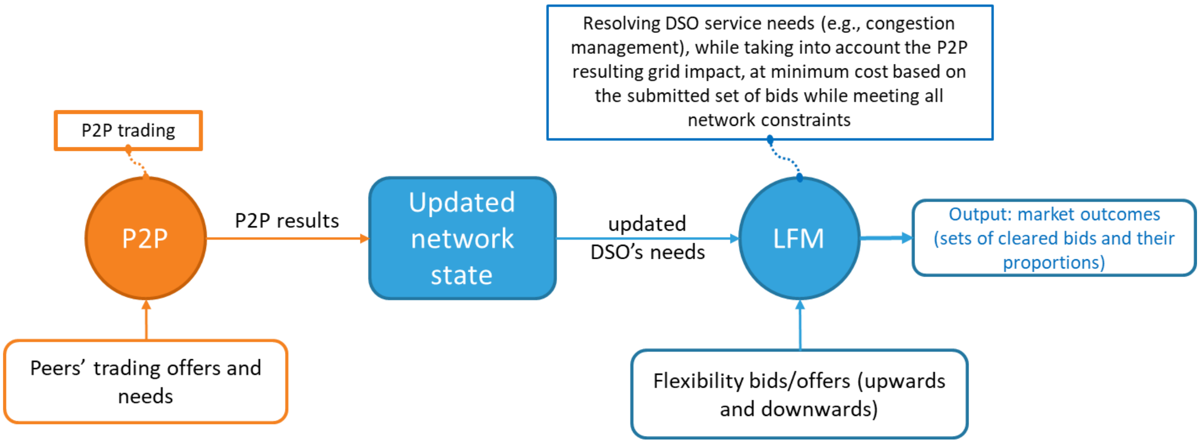


*Figure 16. Scenario 1 - P2P followed by an LFM (the P2P trading is unsupervised – i.e., no inputs from the DSO are considered)*

Scenario 1 captures a sequential P2P and LFM, where the P2P market runs first followed by the LFM. In addition, in this case, the original two subsets of LFM bids (as shown in Figure 15) are now considered to split the participation of the bidders either in the LFM (as FSPs) or the P2P market (as peers). In this respect, subset 2 is considered to primarily participate in P2P trading instead of the LFM. As such, their trading costs in the P2P are chosen to reflect their original bid prices submitted to the LFM (in scenario 0) to have a balanced comparison between the scenarios. In addition, any remaining parts of the generation offers or demand needs that are not met in the P2P are then considered to be submitted as, respectively, upward or downward flexibility bids in the subsequent LFM. This sequential process as well as the bid selection and handling will also be similarly applied in scenario 2 and scenario 3 introduced next.

In scenario 1, the P2P is run completely freely, without any inputs from the DSO, and without any limits imposed by the grid. In other words, the peers – based on their preferences, costs, and utilities – decide to trade together to optimize their objective function, i.e., maximize their value functions / minimize their costs (the P2P process is explained in Section5.2.2). As such, by comparing the results of scenario 1 to scenario 0 – in terms of the updated network state, the creation/exacerbation/resolution of congestions, and effects on the costs of the subsequent LFM[1] - the effects of allowing the P2P to run independently on the grid can be quantified. In other words, this process investigates whether (and in which instances) an interference of the DSO would be needed for the grid, and in which instances the P2P trading can either run safely or even (unintentionally) help the grid. The spectrum of such possibilities is highlighted through detailed examples in Section 5.4.

### 5.3.3 Scenario 2

Scenario 2 proceeds similarly to scenario 1, with a subset of FSPs considered to be primarily taking part in the P2P market (i.e., acting as peers in the P2P market), followed by an LFM, which aims at resolving the updated network congestions and, hence, captures the incurred cost to the system. However, in this scenario, rather than allowing the P2P trading to be completely unchecked, the DSO reserves the right to block any two peers from trading, if it is determined that they will contribute towards increasing the congestion of the grid (this process is presented in detail in Section 5.4.2.3).

[1] All of the elements are considered as key performance indicators (KPIs) in this comparative analysis

This is done by selecting a subset of lines in the network determined to be at risk of congestion (i.e., lines that are either already congested or at a certain level of capacity usage – defined through a capacity usage limit), and by considering the position of any pair of two peers on the grid. The location of the peers allows determining the impact of increasing their load or generation on the power flows over the lines. If trades from the pair of peers contribute towards increasing the flows on any of the lines at risk of congestion, these trades are pre-emptively blocked by the DSO. The peers receive this information beforehand so that they know not to attempt to trade with one another. This process is highlighted in Figure 17. This scenario is expected to reduce the volume traded on the P2P market, but it is also expected to prevent further congestions from taking place as a result of the P2P trades, thereby safeguarding the operation of the grid and keeping the cost of the LFM from increasing significantly.

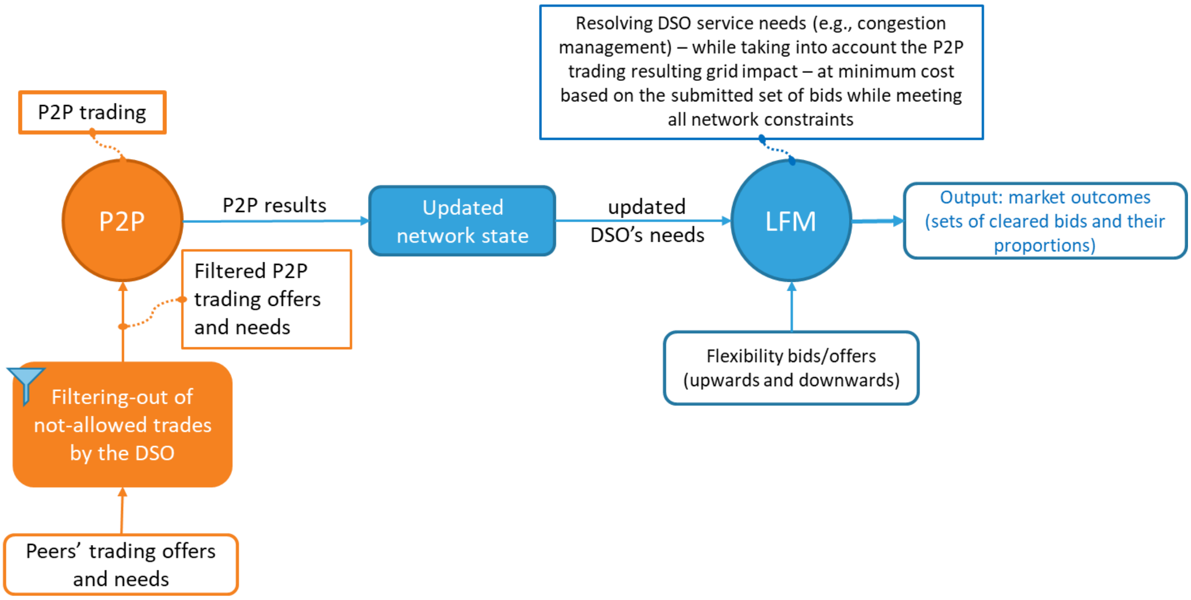


*Figure 17. Scenario 2 - P2P with DSO-disallowed trades, followed by the LFM*

### 5.3.4 Scenario 3

In scenario 3, the DSO attempts to steer P2P trades towards outcomes that are beneficial for grid operation, but without actively preventing peers from trading with one another. This can be achieved using incentivises and penalties for certain trades, specified by the DSO as explained in section 3.2.4. Indeed, the main concept in scenario 3 consists of incentivizing trades that help the system, i.e. that contribute towards reducing grid congestion, and disincentivizing trades that harm the grid (i.e., worsening existing congestions, and possibly creating new ones). Faced with attractive incentives to trade in a way that leads to a positive outcome for the grid (and, conversely, partially avoiding trades that lead to a negative outcome for the grid), the peers will naturally define their own preferences regarding with whom to trade. They are no longer prevented from trading but are encouraged to trade in ways that are beneficial to the grid. These incentives can constitute subsidies or adders to peers acting, respectively, as consumers or producers, while disincentives are captured through applied penalties to the selected trades (the details of the inclusion of those incentives and disincentives are provided in Section 5.4.2.4).

The same criterion used in scenario 2 to determine which set of lines are at risk of congestion is used in scenario 3 as well. The set of lines that are at risk of congestion, and by considering any two pairs of peers (seller and buyer) along with their location and impact on the grid, the DSO then applies incentives or disincentives to the trades that would impact the flows over those lines. The other possible trades are then left unaffected. The peers are then informed about those incentives and disincentives, and take them into account in their optimal decisions regarding with whom to trade, which would then impact the result of the peer-to-peer trading. This process is highlighted in Figure 18.

The incentives and disincentives are financial mechanisms that the DSO can apply which would incur costs to the DSO to implement and settle them. Therefore, the benefit of applying them by the DSO should outweigh the costs for this option to be practically attractive. It is here also noted that this process may also face regulatory limitations due to direct interference by the DSO in the market (creating possible discrimination between peers, market distortions, and possible strategic trades capitalizing on the given incentives in ways unintended by the system operator), which is a subject that is out of the scope of the current quantitative analysis, but is nonetheless a topic requiring a dedicated investigation.

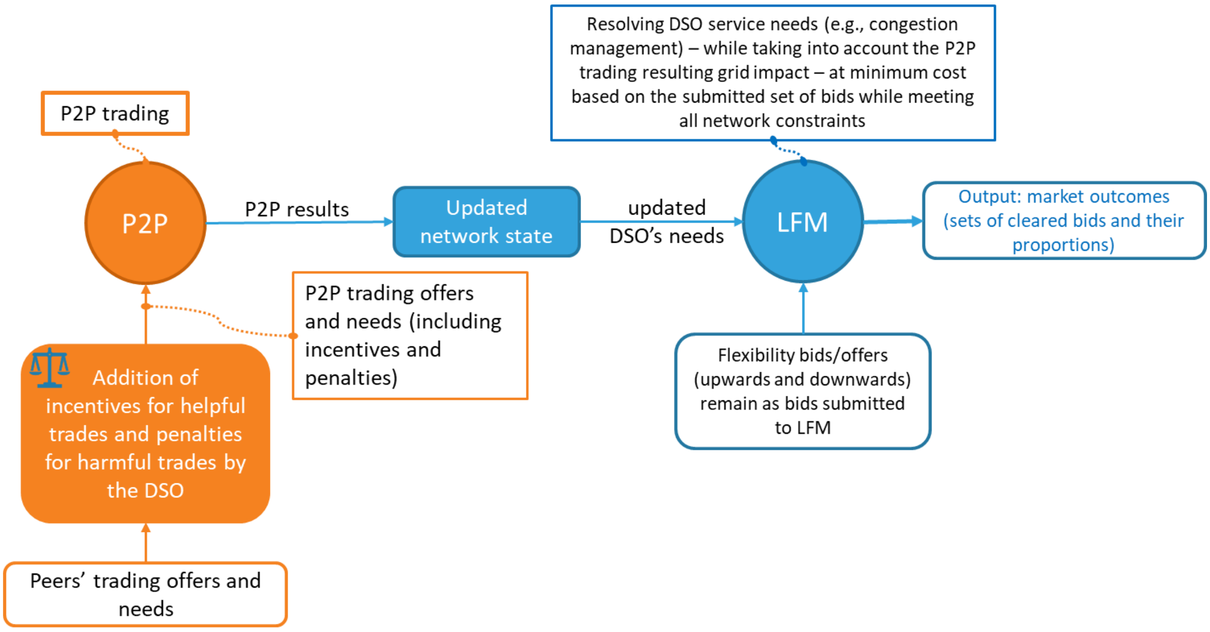


*Figure 18. Scenario 3 - P2P with DSO-incentivized and disincentivized trades, followed by the LFM*

## 5.4 Quantitative analyses and numerical results

### 5.4.1 Description of the simulation environment

For our simulation of a distribution grid environment, we use the Matpower 69-bus system [71], adjusted by including line limits that were chosen based on initial power flow calculations. The network topology of the 69-bus system is shown in Figure 19. In the case study, we start from a setting in which two lines are expected to be congested (that applies in most cases, while the exceptions will be duly highlighted in Section 5.4.25.4.2 when those apply), where the initial congested lines are marked in red.

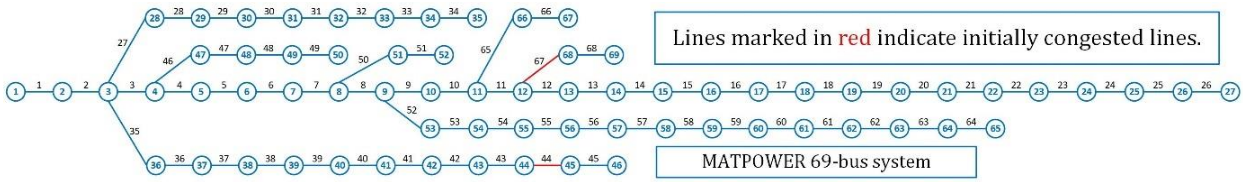


*Figure 19. Matpower 69-bus system (original congested lines marked in red)*

The LFM consists of the linear optimization problem described in [19], [20] as detailed in Section 5.2.1**Error! Reference source not found.**, where peers are located at pre-determined nodes of the network. Each node is characterized by a base generation and base consumption. The P2P market consists of quadratic optimization peer objectives subject to coupled linear constraints leading to the formation of a game, the details of which can be found in [21], as introduced in Section 5.2.2.

Additionally, there is a set of flexibility bids, characterized by a price and volume pair, and an indication of whether they are for supply or demand. The set consists of 172 bids, located on 46 nodes of the 69-bus system. The flexibility bids' prices are randomly generated, to avoid including biases. In this regard, the bids' prices are drawn from a uniform distribution in the range [5, 15] €/MWh for downward flexibility bids, and in the range [45, 55] €/MWh for upward flexibility bids. The submitted bid quantities are chosen as an arbitrary proportion of the base load or generation (where, from each, an upward or downward flexibility bid can be generated) at the node from which the bids are submitted.

All of the numerical exercises that follow start with a selection of a subset of flexibility bids, chosen to take part in the P2P market. This subset is randomly selected and consists of 70 out of all 172 bids in the original list of bids (or 40% of all bids). This subset is used in nearly all scenarios to facilitate a comparison between them. The sole exception where a different subset of P2P bids was used will be explicitly mentioned and detailed in the Numerical Results detailed in Section 5.4.2.

The comparison between the scenarios is performed based on a set of KPIs defined in Table 7.

*Table 7 Definition of KPIs for the quantitative analysis*

| KPI | Description |
|---|---|
| **Cost of LFM** | The total cost for solving the local flexibility market |
| **Number of congested lines** | The number of lines in the grid whose flows surpass their capacity limits (computed before running the LFM) |
| **Overflow sum** | The summation of overflows over the congested lines (computed before the LFM run) |
| **Overflow weighted average** | The average overflow over the congested lines weighted based on the capacity of the lines (computed before the LFM run) |
| **P2P traded volume** | The cumulative volume of traded energy among peers in the P2P market |

### 5.4.2 Numerical results

The numerical study has two objects of interest. The first consists of evaluating the general impact of an independent P2P trading mechanism on a local grid. In other words, two primary questions are addressed:

1. Does a P2P market in this setting necessarily contribute towards increasing grid congestion?
2. When do P2P trades contribute positively to the system with the effect of decreasing congestion, and when do they contribute negatively? Can both effects concurrently take place?

To answer these questions, three cases are studied, namely, scenario 1 is considered under different settings.

The second object of interest consists in evaluating the performance of measures the DSO can have at its disposal to condition and influence the P2P market trades. In this exercise, the performance of scenarios 1, 2 and 3 are compared when faced with a common initial state (scenario 0).

#### 5.4.2.1 Scenario 0

The initial grid state used in scenario 0 has two congested lines (as shown in Figure 19). With the full set of bids, this congestion is resolved in an LFM with a cost of 1.33 units to the system. In other words, this cost reflects the cost of the LFM for resolving all congestions. Note that these units of cost are indicative and only have meaning when compared relative to the costs of other scenarios.

With two congested lines out of 67, the grid is mildly congested, in the sense of the number of lines that surpass their capacity. The overflow observed in the congested lines is 0.02 MW on average. However, the grid lines have an average 65% occupancy ratio (with 60.29% of the lines loaded above 60% of their capacity), which reflects a relatively high loading of the grid. Figure 20 shows the occupancy ratio of each line. As can be seen in Figure 20, two lines have an occupancy ratio higher than 100%, and are, hence, congested. Figure 21 showcases the distribution of occupancy of the different lines under scenario 0 (before running the LFM). This figure highlights the relatively high loading of the grid.

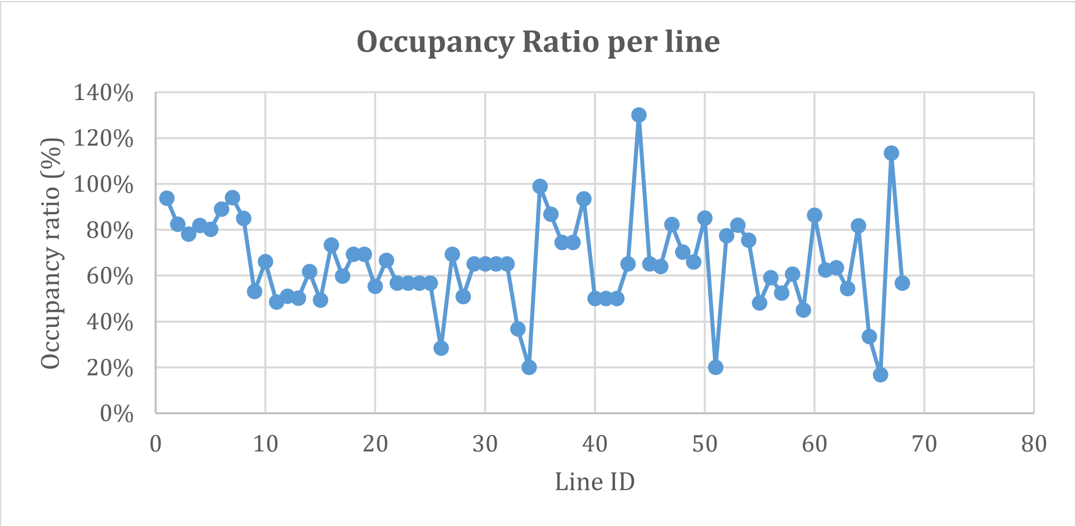


*Figure 20. Occupancy Ratio of all lines before running the LFM - Scenario 0*

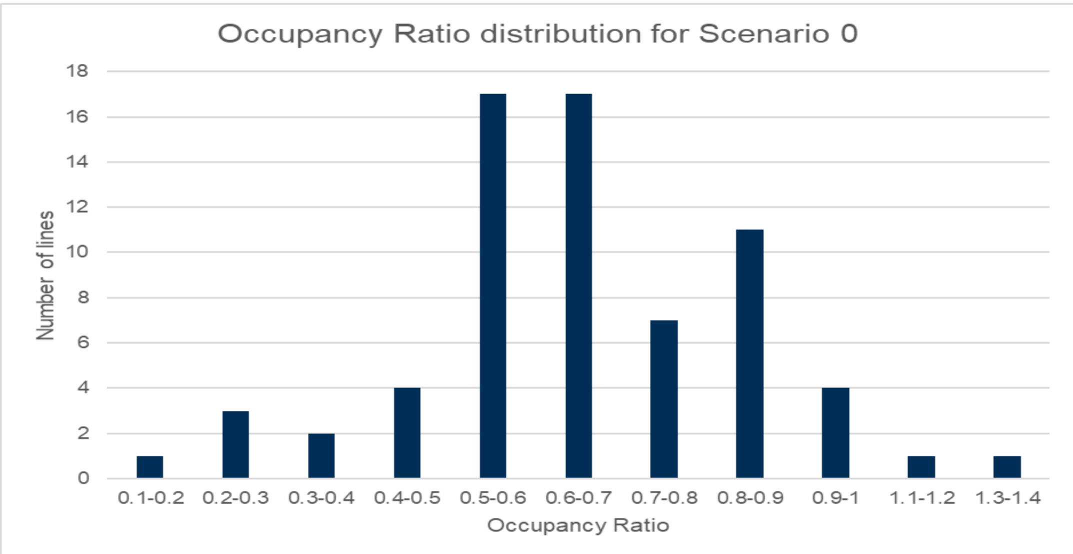


*Figure 21. Distribution of the occupancy ratios of the lines before the LFM - scenario 0*

This grid state is the starting point for all subsequent scenarios (1, 2 and 3). These will all be compared to this reference based on the set of KPIs defined in Table 7.

***Remark***: as part of the KPIs computed in the following scenarios, the summation of overflows and the weighted average of overflows (weighted based on the line capacities) over the congested lines are calculated to indicate the loading of the congested lines in the different scenarios (i.e., the degree of congestion). However, it is noted here, that this is not an indication of the amount of flexibility needed, since a 1 MW flexibility activated at a certain node can resolve concurrently multiple congestions (hence, concurrently reducing multiple overflows in a non-additive manner).

### 5.4.2.2 Scenario 1

Scenario 1 is the case with the least restrictions for peers. Peers trade among themselves with no network constraint considerations. As a result, after the P2P market, the grid is more heavily congested than in scenario 0. This is apparent in all metrics: the number of congested lines grew from 2 to 12, the average overflow volume increased from 0.02 MW to 0.26 MW (these two measures, we note, are before running the LFM) and the cost to resolve the LFM after the P2P market increased nearly 20-fold from 1.33 units to 25.78. Similarly to scenario 0, the LFM in scenario 1 is still capable of successfully resolving all existing congestions. Figure 22 shows the relative change to occupancy ratios of all lines from scenario 0 to scenario 1. As can be seen in Figure 22, even though the total number of congestions grew from 2 to 12 (as compared to scenario 0), the P2P mechanism unintentionally resolved the original two congestions that had existed in scenario 0, while 12 new congestions created. Hence, the P2P mechanism, even though unchecked, can in instances help or harm the grid (and the two aspects can concurrently take place), while the occurrence of those aspects is primarily dependent on the practical operational case. However, this uncertainty could provide a driving reason for the DSO to provide grid-safety inputs to the P2P mechanism to ensure that the secure operation of the grid is maintained (these aspects are further explored in scenario 2 and scenario 3).

The amount of traded volume in the P2P market in this scenario is 2.59 MW. This quantity indicates the highest volume that can be traded among peers in this P2P market where peers are free to trade with no network considerations.

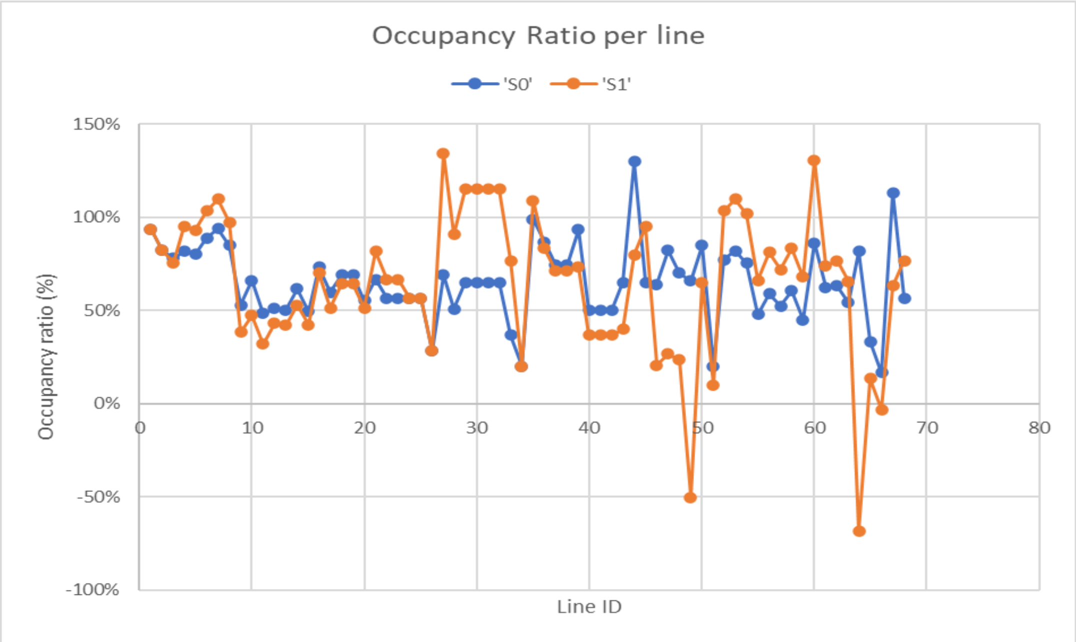


*Figure 22. Occupancy Ratio of all lines before running the LFM - Scenario 1*

With a randomly selected subset of bids taking part in the P2P market, this scenario indicates a relatively expected case, showing when a P2P market runs without network constraints being checked, it will most likely harm the grid especially when the grid is heavily loaded.

To further demonstrate the effect of P2P on the grid under scenario 1, two instances representing extremes are highlighted, one in which the P2P market renders the LFM effectively unsolvable, and one in which the P2P market resolves all congestions by itself, requiring no need for an LFM and therefore no cost to the DSO.

- ***Scenario 1 alternate conditions – Infeasibility***

Scenario 1 has highlighted a setting in which the P2P leads to concurrently solving congestions but also creating new ones. In total, the results of scenario 1 have led to a general worsening of the grid operational state, as shown by the significant increase in the number of congested lines and the distinctly higher LFM cost. Therefore, this variation of scenario 1 aims to highlight an extreme case in which the P2P significantly exacerbates the number and volume of congestions in the grid, to a point that it may even cause the LFM not to contain enough flexibility to resolve those congestions (i.e., leading the LFM to be infeasible). This can be shown by starting from a heavily congested initial case, which shall be denominated thereafter as scenario 0'.

In scenario 0', there are 34 congested lines (out of 68), and the cost to resolve the LFM corresponds to 451.80 units, exceedingly more than the 1.33 unit cost of the original scenario 0. The orderbook of bids remains the same as in scenario 0. Figure 23 displays the occupancy ratio of all lines before the LFM in scenario 0'. As can be seen in Figure 23, the network is markedly more loaded and congested as compared to the initial scenario 0.

Under these circumstances, the P2P market consisting of the same set of bids that took part in the original scenario 1 will cause the LFM to be infeasible. This is denominated scenario 1'.

In scenario 1', the traded volume between peers is identical to the one in scenario 1, with 2.59 MW being traded. However, the number of congested lines before the LFM increased to 37 (compared to 34 in scenario 0'). The aggregated and average overflows also increase compared to the ones in scenario 0', but most importantly, the LFM is no longer feasible (i.e., the offered flexibility through the bids is no longer enough to resolve all congestions seen in the grid). As peers were able to freely trade among themselves, the volume of available flexibility to the LFM decreased, while the number of congestions in the grid increased to a point where the LFM was no longer feasible.

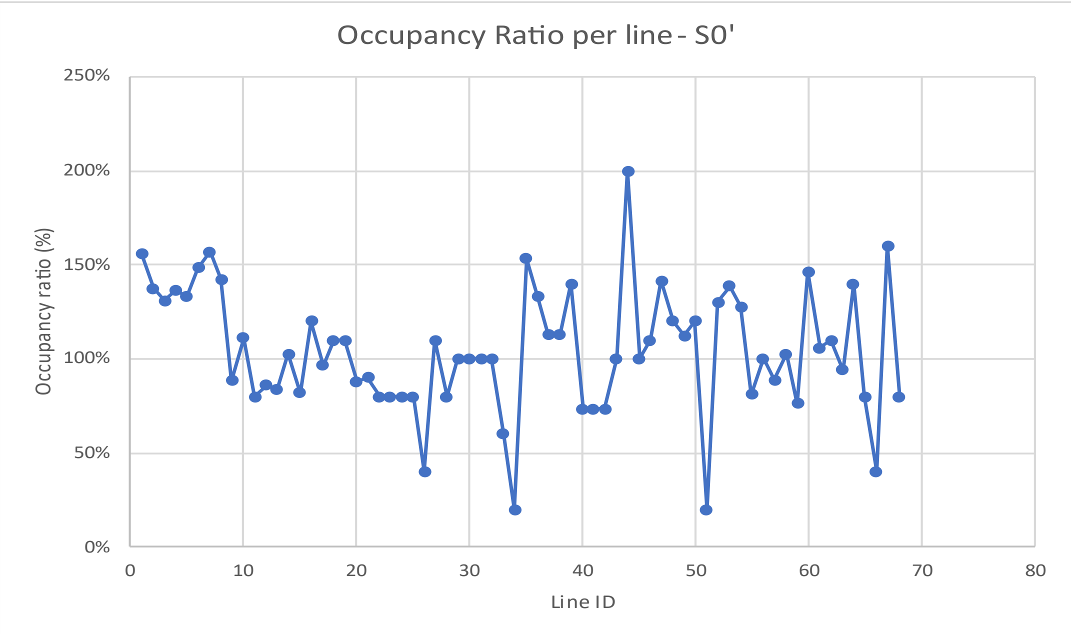


*Figure 23. Occupancy Ratio of all lines before running the LFM - scenario 0'*

- ***Scenario 1 alternate conditions – P2P market resolves congestion on its own***

This last scenario 1 instance explores the other extreme situation: one in which the free P2P trades are coincidentally in line with the grid's congestion needs so that all initial congestions in the grid (i.e., in scenario 0) are resolved through the P2P market. This is the best possible outcome for a DSO and one that illustrates that P2P markets are not necessarily harmful to the grid.

The initial circumstances are the ones from scenario 0. However, the main difference lies in the set of bids that take part in the P2P market. For this instance, only a small set of bids are considered to be part of the P2P market and are bids that – coincidentally – have a positive impact on resolving the congestions over line 44 (connecting nodes 44 and 45) and line 67 (connecting nodes 12 and 68), which are originally congested, as highlighted in Figure 19. As such, in this stylized example, rather than having 70 bids participating in the P2P (as in the original scenario 1), only 7 bids (i.e., 7 peers) take part in the P2P trading, while those bids are from peers that are located in positions on the grid that make them able to resolve the congested lines from scenario 0.

As a result of this selection of P2P trades, the grid is no longer congested after the P2P market, which means there is no need for an LFM and therefore represents no cost to the DSO.

This is, indeed, a stylized example, but the aim is to show through such a specific example the mechanism in which P2P trading can end up being helpful to the grid, even without external guidance. In fact, the goal of the analysis in scenario 1 has been to show, through three different examples, the spectrum of possibilities regarding the impacts that a P2P market can have on the grid. Indeed,

1) Scenario 1 highlighted a standard case where the P2P trading concurrently resolves some congestions but also leads to creating further, which in the numerical case, were larger and more numerous than the original congestions, leading to an overall significantly negative impact on the grid.
2) Scenario 1' presented a negative extreme where the P2P mechanism resulted in P2P trades that exacerbate the original congestions and cause new ones, thus, rendering the LFM incapable of resolving all caused congestions.
3) Scenario 1'' presented the positive extreme in which the P2P trading results in P2P trades that are fully in line with the needs of the grid, hence, resolving the existing congestions and avoiding the DSO's need to run an LFM for a particular period.

Due to this uncertainty regarding the impact of the P2P market on the grid, the DSO can opt to introduce and apply inputs to guide the functionality of the P2P market, aiming at allowing P2P trades while also safeguarding the reliable operation of the distribution grid. These aspects are explored in the introduced scenario 2 and scenario 3, next.

***Remark:*** It is noted here that the results in scenario 1 start from a grid that is relatively highly loaded (as highlighted in scenario 0), and consider the availability of a significant volume of P2P offers and needs. This setting is the same starting point that will also be considered in scenarios 2 and 3. Had the grid been lightly loaded, or had the volumes of energy trades between peers been less-significant, the gravity of the impacts of the P2P market on the grid would have been significantly reduced. However, this case study aims at capturing the settings in which the P2P market can markedly impact the local grid.

### 5.4.2.3 Scenario 2

In scenario 2, trades from peer pairs that harm the system are blocked. This scenario successfully prevents peers from causing additional congestions to the grid, at the cost of a lower volume of P2P trades. The criterion that defines whether a line is at risk of congestion is the occupancy ratio of that line. If a line is at or above 80% of its capacity, any pair of peers that by trading with one another will increase the power flow on that line will be prevented from doing so. Through this process, the goal of the DSO is to still allow almost free P2P trading, but while safeguarding the grid.

Indeed, as observed in the results of scenario 2, the number of congested lines before the LFM (i.e., 2) remains the same as in scenario 0, the average overflow over congested lines before the LFM remains at 0.02 MW, and the cost of the LFM is marginally higher at 1.336 units compared to 1.330, the cost of scenario 0. It is noted here, that – similarly to scenario 0 – the LFM is capable in scenario 2 to resolve all existing congestions. Figure 24 compares the occupancy ratio of all lines for scenario 2 with scenario 0. Figure 24 showcases that the two lines originally congested are still congested, while the loading of the other lines has slightly changed, but without causing any new congestions.

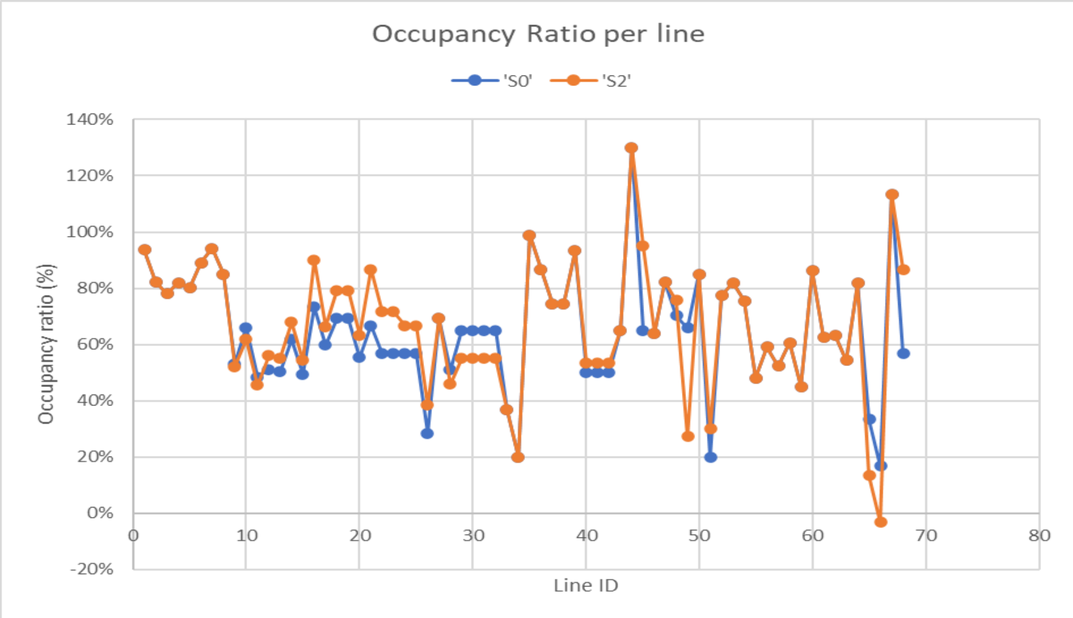


*Figure 24. Occupancy Ratio of all lines before running the LFM - scenario 2*

The traded volume in the P2P market was 1.17 MW, which corresponds to 45% of the volume in scenario 1. This is unsurprising, as harmful trades are blocked.

However, with minimal increases to the cost of the LFM and no congestion increases to the grid, scenario 2 shows how a well-regulated P2P market can take place without harming the state of the grid, and while allowing the opportunity for peers to (almost freely) trade. Indeed, at periods in which the grid is not heavily loaded (e.g., when the capacity usage of each line is below 80%), none of the trades would be pre-emptively blocked, allowing the peers to trade completely freely.

#### 5.4.2.4 Scenario 3

In scenario 3, peers are incentivized to trade if their trades reduce the power flow of lines at risk of congestion, and conversely are disincentivized from trading if these trades increase the power flow on those lines. Unlike scenario 2, this approach does not prevent peers from trading but seeks to guide them towards an outcome that is better for the grid. This, however, means that the incentives must be finely tuned, as the method is less controllable and the effect of the incentives less direct. To illustrate this, two instances of scenario 3 are presented. The difference between these instances lies in the set of lines considered to be at risk of congestion. Where the first instance considers only lines that are at 100% occupancy rate or above in scenario 0, while the second instance considers a larger set of lines, including all lines with an occupancy ratio of 80% or higher (such as in scenario 2).

Incentives are promoted by updating a cost preference matrix of coefficients. This is an N-by-N matrix, where N is the number of peers, and the element $(i,j)$ indicates how willing peer $i$ is to sell to peer $j$. Conversely, element $(j,i)$ indicates how willing peer $j$ is to sell to peer $i$. If a sale trade from peer $i$ to peer $j$ is determined to improve the congestion on a line from the set at risk of congestion, then element $(i,j)$ is increased, indicating a greater willingness to sell from $i$ to $j$, and element $(j,i)$ is reduced, indicating a disincentive for $i$ to buy from $j$. Cost preference coefficients are updated by applying a multiplicative factor $W$, which in this numerical exercise was arbitrarily chosen to be 0.2.

Note that the set of lines determined to be at risk of congestion plays a key role in the effectiveness of this method, as is showcased in the two instances of scenario 3 presented next.

- ***Scenario 3 – Incentives considering 100% congested lines only***

Scenario 0 has two congested lines, which are considered in the updating of the cost preference matrix elements (i.e., elements corresponding to the peers whose trades influence the congestion of these lines). For each line, the multiplicative factor $W$ is applied. This means that trade pairs that influence both lines will see their cost preference coefficient updated twice. It should be noted that in the initial state of the cost preference matrix the elements of each row have to be equal, reflecting no preference on the part of each peer with respect to with which other peers to trade (i.e., equal preference). This is the state used in scenarios 1 and 2, and it is updated in scenario 3.

The impact of these incentives can be gauged by comparing the KPI values with scenario 1. The cost of the LFM after the P2P market is marginally lower than in scenario 1, namely 25.51 and 25.78 respectively, meaning little to no change. This is further corroborated by no change in the number of congested lines (12) and the same volume of traded volume on the P2P market (2.59 MW). However, while the aggregated nominal overflow of all congested lines is larger than in scenario 1, 2.02 MW compared to 1.92 MW, the overflow average of 0.17 MW, weighted by the capacity of each congested line, is less than in scenario 1 (0.26 MW). It is re-iterated here that the nominal overflow, average, and weighted average overflows give only an indication of the severity of the congestions over the lines. However, they do not reflect the volume of flexibility needed, as in cases where the flexibility needs within the grid are aligned, a procured flexibility can concurrently meet several congestion management needs. This is highlighted by the fact that even though scenario 3 leads to a larger aggregated nominal overflow of all congested lines than scenario 1 (2.02 MW compared to 1.92 MW), the LFM under scenario 3 is less costly (25.51 vs. 25.78), which indicates that a lower flexibility purchasing volume was required to resolve congestions under scenario 3 than under scenario 1, hence, indicating that scenario 3 resulted in an improved outcome over scenario 1. This improvement is albeit small in this specific setting and will be more pronounced in the following subsection, in which the class of lines considered when providing incentives/disincentives is larger.

This scenario is included in this analysis as an illustration of how these incentives, by exerting less control over peers compared to scenario 2, must be subjected to parameter fine-tuning and a carefully chosen set of lines deemed at risk of congestion. In the next instance, we see that by expanding the set of lines at risk of congestion, the effect on the grid is larger.

- ***Scenario 3 – Incentives considering 80% congested lines and above***

In this instance, we use the same criterion used in scenario 2 to determine the set of lines at risk of congestion. All lines in scenario 0 are at least 80% occupied are considered. This corresponds to 17 lines out of 68. Incentives are applied as previously described in this section, which means the cost preference of a trading pair may be updated up to 17 times, should this pair be found to be harmful or beneficial to every line in the set. Under those updated incentives and disincentives, P2P trading takes place. Figure 25 displays the resulting line occupancy ratio after the P2P trading at all lines for scenario 3, as compared to scenario 0 (both of which were before the run of the LFM).

The outcome reveals that these incentives had a much larger and more positive effect on the grid than in the previous instance. The cost of the LFM was reduced by half of what it is in scenario 1 to equal 13.03 units. The traded volume in the P2P market is 1.22 MW, which corresponds to 47% of the traded volume in scenario 1. The aggregate and average overflow quantities across all congested lines (0.85 MW and 0.13 MW, respectively) decreased by half when compared to their scenario 1 counterparts. Despite these positive outcomes, the number of congested lines did not reduce, counting 12, the same as in scenario 1. Moreover, the cost of the LFM, although half of that of scenario 3, is still ten times higher than the costs seen in scenario 0 and scenario 2.

Indeed, among scenarios 2 and 3 treading in this case study, scenario 2 is objectively the one performing the best, sacrificing 0.05 MW of traded volume over scenario 3 to do so (recall 1.17 MW for scenario 2). However, it can be stated that scenario 3 can still potentially provide improved outcomes, provided the incentives and disincentives are fine-tuned and carefully chosen (which can be a challenging task). This is clear from the improvement seen over the previous scenario 3 instance.

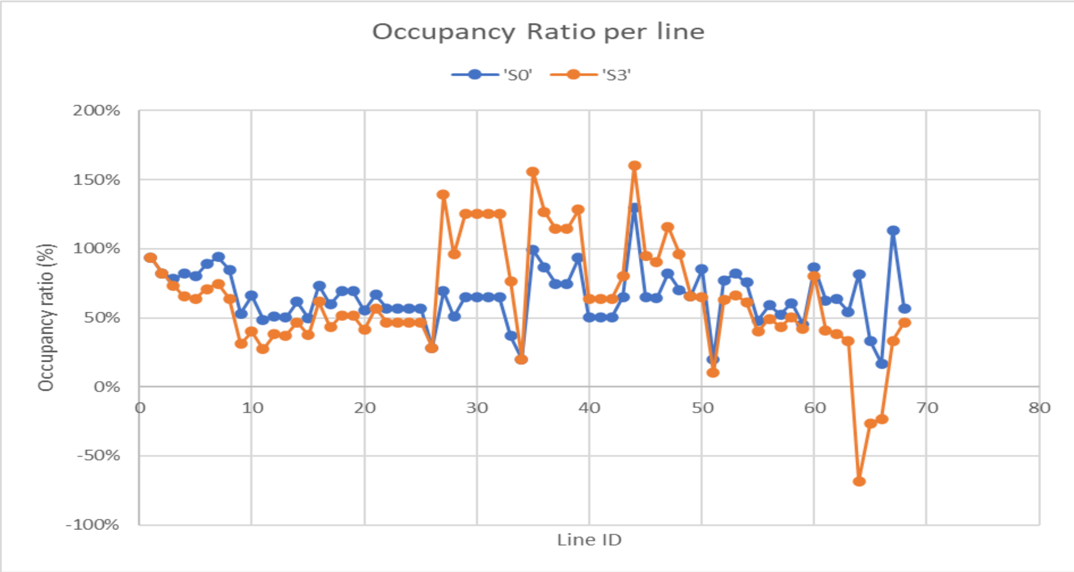


*Figure 25. Occupancy Ratio of all lines before running the LFM - scenario 3*

### 5.4.2.5 Summary of KPIs

For convenience and ease of comparison, a summary of the different calculated KPIs for the different scenarios presented so far are presented in Table 8. Note that the values in this table are presented in per unit.

*Table 8 Main Summary of scenarios and KPIs*

| Scenario | Number of congested lines | Overflow sum | Overflow weighted average | Cost of LFM | P2P Traded Volume |
|---|---|---|---|---|---|
| **Scenario 0' (extremely high loading)** | 34 | 23.64 | 1.50 | 451.80 | - |
| **Scenario 1' (extremely high loading)** | 37 | 31.14 | 1.87 | Infeasible | 2.59 |
| **Scenario 0 (initial)** | 2 | 0.04 | 0.02 | 1.330 | - |
| **Scenario 1** | 12 | 1.92 | 0.26 | 25.78 | 2.59 |
| **Scenario 2** | 2 | 0.04 | 0.02 | 1.336 | 1.17 |
| **Scenario 3 (80% or higher)** | 12 | 0.85 | 0.13 | 13.03 | 1.22 |
| **Scenario 3 (100% or higher)** | 12 | 2.02 | 0.17 | 25.51 | 2.59 |
| **Scenario 1''** | 0 | 0 | 0 | 0 | 0.04 |

## 5.5 Evaluation and Conclusions

As has been detailed in this chapter, the P2P market can in some cases serve to help to reduce the congestions in the grid, while in some cases leading to the exacerbation of congestions. As such, measures can be taken by the DSO to supervise or provide inputs to the P2P market, to ensure the safe operation of the grid under its existence. In this respect, this chapter investigated 3 proposed scenarios in which the P2P market can take place:

1. Scenario 1: the P2P runs independently, without any inputs from the DSO and with no consideration of the impact of the P2P trades on the grid.
2. Scenario 2: under critical grid loading conditions, the DSO blocks selected peer-to-peer trades beforehand to ensure no harmful effects of the P2P trades are implied to the grid, while all other potential trades are left unaffected.
3. Scenario 3: under critical loading conditions, the DSO provides incentives and disincentives to peers, to incentivize trades that serve to reduce congestions and penalize trades that worsen the congestions, while leaving all other potential trades unaffected.

Different variations were also explored under each of those scenarios. The analysis served to highlight several key insights summarized next.

The results of Scenario 1 showcase – through specifically derived examples – how the P2P mechanism, even if left completely unchecked, can actually result in unintentionally resolving congestions available in the grid. While, on the other extreme end, the analysis of scenario 1 has also shown how this unchecked P2P trading – by not taking into account the impact of the trades on the grid – can extremely congest the grid to a point that the LFM may not possess enough flexibility to alleviate those congestions. In between those two extremes, the results of scenario 1 have also illustrated how the P2P trades can concurrently solve some congestions while causing others, which depends on the initial loading levels of the lines within the grid. Given this uncertainty, and given the case-dependence of those results, the DSO would likely be incentivized to provide inputs guiding the functionality of the P2P market, especially under heavy loading conditions, aiming at limiting its possible harmful effect on the grid.

The guidance by the DSO of the P2P mechanism can be provided through incentives and penalties, as shown in scenario 3. The results of scenario 3 have shown that this method can result in a better setting than those under scenario 1. However, this process is not guaranteed to generate results approaching the nominal results of scenario 0 (i.e., limiting the risk of the P2P market of causing additional congestions, or even driving the P2P market to resolve existing congestions). The results of scenario 3 showed that some congestions were resolved, while other congestions were created, but the results were markedly worse than the original case under scenario 0. Even though this is a case-dependent result, it is an appropriate case in point, which highlights the associated risks. The proposed method under scenario 3 is faced with a number of challenges, which must be overcome to improve its effectiveness and implementation potential:

i. The incentives and disincentives may not be appropriately calculated to significantly favour good P2P trades (as measured by their impact on reducing congestions) and effectively disincentivize bad trades. As can be seen in the numerical results of scenario 3, congestions increased in number and volume as compared to scenario 0.
ii. The costs of the given incentives may outweigh the benefits, in terms of the reduction to the LFM costs (as compared, e.g., to scenario 1).
iii. This option may face legal barriers as it may induce market distortions, which can also lead to strategic behaviour capitalizing on the provided incentives and penalties in a manner that can be harmful to the grid. This risk necessitates a dedicated analysis.

Scenario 2 provides a more hands-off, and easily implementable approach by the DSO, in which the DSO exercises restrictions on the usage of its grid to safeguard its operation. The obtained results for scenario 2 showed how the DSO can still allow P2P (largely free) trading while limiting its effects on the grid, especially in heavy-loaded conditions. As the DSO may exercise checks and limits on the usage of its grid, and pursue its goal and duty of securing the safe operation of the distribution system, this method may constitute the most practical and effective solution. The numerical results within scenario 2 are indeed specific to the case study considered. However, as the derived preliminary results are favourable (markedly outperforming scenario 1 and scenario 2, allowing P2P trading while safeguarding the grid resulting in no variation to its original congestion state, hence, outperforming scenario 0), this paves the way for additional investigation of this method, to further study its merit and applicability potential.

# 6 Conclusions

This deliverable has provided background on P2P trading as a decentralised market model and how it may impact the flexibility services provision in the system. Through the studies conducted in this task, various aspects of the P2P as well as providing services to the DSO were analysed, and the common points were discussed in the form of design elements. These design elements are the critical factors that need to be taken into account whenever the P2P mechanism and flexibility mechanism would want to meet. Using the defined design elements, the conceptual models showed the possible variations of how the P2P market setting could provide flexibility services to the DSO by including the network constraints in their peer matching mechanisms. They also showed that for doing so, how the P2P setting should interact with the DSO and what information needs to be exchanged.

Other than this, the conceptual models showed how the P2P setting would interact with other flexibility mechanisms, specifically the LFM. They showed the extra required communication layers to make the P2P market compatible with network-aware trading behaviour. The comparison between the conceptual models showed that the very nature of P2P trading contradicts the concept of providing a service to another party, such as DSO. The intention of the peers for participating in a P2P trade is to maximise their own objective (namely, minimising the cost or maximising the profit) while providing the service to the DSO means a compromise in this objective. The analysis showed that the DSO may need to interfere in the process of P2P trading by imposing certain constraints or redirecting the trades towards a set of trades that would not cause network problems. This process would change the results of the P2P matching, affecting the individual or collective objectives of the peers compared to a case where no support to the DSO is considered.

Although service provision from P2P trading can provide a relatively more decentralized option compared to more centralized flexibility service approaches, the study showed that in order to make that practical a stepwise transition may be required. Given that the P2P market setting itself has a degree of centralization (centralized market model vs. decentralized vs. hybrid), the inclusion of network-related attributes to the P2P trading mechanism can benefit from this degree of centralization.

The quantitative analysis showcased the conceptual models in different scenarios and how they would impact the network status, the flexibility requirement, and the traded volume in P2P trading. The results show that the behaviour of the peers in supporting the DSO and improving the network status depends a lot on the specific case that is being analysed. The network where the peers are connected, the loading of the system and overflow of the lines, the percentage of peers in the system compared to FSPs, the rules of the peer matching, incentives and penalties applied to a set of bids could change the results of the peer matching, affect the flexibility requirements of the system, and subsequently, the total cost compelled to the system. One can conclude that the design of the P2P trade setting needs to take into account all these aspects before agreeing to contribute to the grid services.

In final words, the P2P context opens new horizons of distributed mechanisms for flexibility service provision to the DSOs, however, these new options come with their own complexities and challenges. The acceptance of the compromise in the trade process in return for supporting the DSO by different peers requires another line of studies which is an important factor in the effectiveness of the P2P mechanism for flexibility services. Moreover, the results from the P2P and LFM and their mutual impact are so case-dependent that a general statement on the efficiency of each of these approaches may not be reached. However, it is clear that depending on the network at hand, the available resources, and the peers' preferences, the DSO can benefit from various options in both centralised and decentralised mechanisms.

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## Annex I – Excel based literature Survey

| Category | Detail | |
|---|---|---|
| **general info** | **Title** | Coordinated Market Design for Peer-to-Peer Energy Trade and Ancillary Services in Distribution Grids |
| | **Authors** | Kai Zhang, Sebastian Troitzsch, Sarmad Hanif, Thomas Hamacher |
| | **document type** | journal publication |
| | **Year** | 2020 |
| | **web link (doi)** | 10.1109/TSG.2020.2966216 |
| **consumer-centric market design** | **market operator** | there are two markets, run iteratively: an independent P2P market for energy and a centralized market for AS ran by DSO. The two markets are cleared iteratively (see Fig 4 in the paper) |
| | **trade mechanism** | pure p2p (direct bilateral trade) for energy, solved iteratively (needed for inclusion of the grid constraints), and a centralized market for reserves |
| | **market type** | discrete/call market |
| | **trade frequency** | Daily |
| | **traded commodity** | Electricity |
| | **product duration** | not specified |
| | **how are network operator's needs considered?** | *yes, during the p2p matching (congestion prevention)* |
| | **is there trade/physical exchange with the rest of the network** | Yes |
| | **pricing scheme** | DLMP, the bids are settled using Grid Usage Pricing algorithm using ADMM |
| | **can peers trade in other markets? If yes, please specify how** | Yes |
| **participants** | **type of participants** | no restrictions |
| | **locality of participants** | within the same local distribution system |
| | **role of the DSO** | DSO is a market operator that operates the integrated local market for energy, ASs,<br>and transport services for P2P trade. It operates markets in multiple time scales. It also manages the energy exchange to alternative markets, which requires coordination with upstream transmission system operator (TSO) markets |
| | **who are the other considered players and their tasks?** | interactions with a TSO mentioned in a remark but not explicitly considered |
| | **aggregation possible within the market** | not specified |
| | **can participants indicate specific preferences?** | yes - renewable production |
| **algorithms** | **peers bidding algorithm** | economically rational, seeking the maximization of their individual economic surplus. Each can decide to participate in energy P2P market or also in centralised AS market |
| | **market matching/clearing algorithm** | DLMP, the bids are settled using Grid Usage Pricing algorithm using ADMM |
| | **problem class** | It uses ADMM so the central problem is decomposed to individual problems for seller and buyer |
| | **additional relevant properties** | network constraints are included in the clearing |
| **other information** | **info provided by** | VITO (Nilufar Neyestani) |
| | **additional comments** | None |
| | **applications in the real world?** | theoretical case study |
| | | |

| Category | Detail | |
|---|---|---|
| **general info** | **title** | Bilateral Contract Networks for Peer-to-Peer Energy Trading |
| | **authors** | Thomas Morstyn, Alexander Teytelboym, Malcolm D. Mcculloch |
| | **document type** | journal publication |
| | **year** | 2019 |
| | **web link (doi)** | https://ieeexplore.ieee.org/document/8279516/ |
| **consumer-centric market design** | **market operator** | |
| | **trade mechanism** | pure p2p (direct bilateral trade) |
| | **market type** | discrete/call market |
| | **trade frequency** | other |
| | **traded commodity** | electricity |
| | **product duration** | 1h |
| | **how are network operators' needs considered?** | *yes* |
| | **is there trade/physical exchange with the rest of the network** | yes |
| | **pricing scheme** | a price adjustment process is proposed for both real-time and forward markets |
| | **can peers trade in other markets? If yes, please specify how** | yes |
| **participants** | **type of participants** | Three type of participants are considered, prosumers, suppliers, generators |
| | **locality of participants** | multiple connections accross the public grid |
| | **role of the DSO** | not specified |
| | **who are the other considered players and their tasks?** | Three type of participants are considered, prosumers, suppliers (aggregators), generators |
| | **aggregation possible within the market** | not specified |
| | **can participants indicate specific preferences?** | yes - wide range of preferences are possible to consider including sustainability, price, economic, etc. |
| **algorithms** | **peers bidding algorithm** | NA/ bilateral agreement |
| | **market matching/clearing algorithm** | NA/ bilateral agreement |
| | **problem class** | |
| | **additional relevant properties** | The algorithm to select the set of trades |
| **other information** | **info provided by** | VITO (Nilufar Neyestani) |
| | **additional comments** | It proposes both future and real-time markets for an hourly resolution<br>The product is being traded for different time intervals according to the real-time requirements |
| | **applications in the real world?** | Theoretical |
| | | |

| Category | Detail | |
|---|---|---|
| **general info** | **Title** | Optimizing rooftop photovoltaic distributed generation with battery storage for peer-to-peer energy trading. |
| | **Authors** | Su Nguyena, Wei Penga, Peter Sokolowskib, Damminda Alahakoona, Xinghuo Yub |
| | **document type** | journal publication |
| | **Year** | 2018 |
| | **web link (doi)** | https://doi.org/10.1016/j.apenergy.2018.07.042 |
| **consumer-centric market design** | **market operator** | community manager |
| | **trade mechanism** | Dispatch optimization problem. P2P transaction result from centralized optimization. |
| | **market type** | discrete/call market |
| | **trade frequency** | Hourly |
| | **traded commodity** | Electricity |
| | **product duration** | 1h |
| | **how are network operator's needs considered?** | *No* |
| | **is there trade/physical exchange with the rest of the network** | Yes |
| | **pricing scheme** | Price defined after dispatch optimization. It seems to be a pool-based pricing mechanism and it does not appear to be a P2P trading. |
| | **can peers trade in other markets? If yes, please specify how** | No |
| **participants** | **type of participants** | households with and without pv and storage systems |
| | **locality of participants** | within the same local distribution system |
| | **role of the DSO** | none. |
| | **who are the other considered players and their tasks?** | Retailers (aggregators) supply(buy) any amount of energy not traded in the LM for each agent. |
| | **aggregation possible within the market** | n/a |
| | **can participants indicate specific preferences?** | No |
| **algorithms** | **peers bidding algorithm** | MILP determinated |
| | **market matching/clearing algorithm** | MILP determinated |
| | **problem class** | central optimization |
| | **additional relevant properties** | Dispatch optimization problem to minimize costs with apparent pool LM |
| **other information** | **info provided by** | INESC TEC (Joao Melo) |
| | **additional comments** | The proposed MILP model will take into account all the above inputs to find the optimal (1) trading decisions such as how much energy generated by PV systems will be traded will be traded in the P2P market and (2) operational decisions such as when the energy storage will start charging or discharging. |
| | **applications in the real world?** | theoretical case study |
| | | |

| Category | Detail | |
|---|---|---|
| **general info** | **title** | Local Energy Markets: Paving the Path Toward Fully Transactive Energy Systems |
| | **authors** | Fernando Lezama , Joao Soares, Pablo Hernandez-Leal, Michael Kaisers, Tiago Pinto , Zita Vale |
| | **document type** | journal publication |
| | **year** | 2019 |
| | **web link (doi)** | https://doi.org/10.1109/TPWRS.2018.2833959 |
| **consumer-centric market design** | **market operator** | aggregator/utility |
| | **trade mechanism** | centralized forms of trade |
| | **market type** | discrete/call market |
| | **trade frequency** | hourly |
| | **traded commodity** | electricity |
| | **product duration** | 1h |
| | **how are network operators' needs considered?** | *no* |
| | **is there trade/physical exchange with the rest of the network** | yes |
| | **pricing scheme** | simultaneous auctions, where clearing happen at a fixed time once at the end of the trading period. Asuply and demand curve indicates the equilibrium prices |
| | **can peers trade in other markets? If yes, please specify how** | yes, via aggregator, or small players |
| **participants** | **type of participants** | not specified. There are DG, Storage, EV, load inside microgrids operated by aggregators |
| | **locality of participants** | multiple connections accross the public grid |
| | **role of the DSO** | There is no DSO. It simulates WS, LM and coupling without considering grid restrictions. Load flexibility and storage is used for balancing commercial flexibilty |
| | **who are the other considered players and their tasks?** | aggregator manages DG, Storage, EV and load flexibility within MG and, together with small players, trade at WS and LM |
| | **aggregation possible within the market** | yes |
| | **can participants indicate specific preferences?** | not defined. Microgrid is managed by aggregators. |
| **algorithms** | **peers bidding algorithm** | Agent based - Zero Inteligence - Constrained for profit |
| | **market matching/clearing algorithm** | two-stage stochastic programming model |
| | **problem class** | Central optimization problem |
| | **additional relevant properties** | Considers uncertainties for price, generation and consumption. |
| **other information** | **info provided by** | INESC TEC  (Joao Melo) |
| | **additional comments** | Coupling of WS and LM, and settling of imbalances. Load Flexibility for imbalance porpuses. |
| | **applications in the real world?** | theoretical |
| | | |

| Category | Detail | |
|---|---|---|
| **general info** | **title** | Electrical-distance driven peer-to-peer energy trading in a low-voltage network |
| | **authors** | Jaysson Guerrero, Bunyim Sok, Archie C. Chapman, Gregor Verbič |
| | **document type** | journal publication |
| | **year** | 2021 |
| | **web link (doi)** | https://10.1016/j.apenergy.2021.116598 |
| **consumer-centric market design** | **market operator** | independent |
| | **trade mechanism** | pure p2p (direct bilateral trade) |
| | **market type** | continuous |
| | **trade frequency** | irregular - when there is a match |
| | **traded commodity** | electricity |
| | **product duration** | not specified. Simulation test uses a 30min database |
| | **how are network operators' needs considered?** | yes, during the p2p matching |
| | **is there trade/physical exchange with the rest of the network** | yes |
| | **pricing scheme** | P2P stable-matching mechanism that matches following a DSO distance list, and (ii) a CDA-based mechanism that matches bids and asks considering first the distance list, and then the price. |
| | **can peers trade in other markets? If yes, please specify how** | no |
| **participants** | **type of participants** | Agents |
| | **locality of participants** | within the same local distribution system |
| | **role of the DSO** | Sends the distance list for each peer. Information is unilateral. Peers a assumed to use this info when trading P2P. |
| | **who are the other considered players and their tasks?** | Retailers supply any amount of energy not traded in the LM for each agent. |
| | **aggregation possible within the market** | n/a |
| | **can participants indicate specific preferences?** | no. They follow the DSO distance preference list. |
| **algorithms** | **peers bidding algorithm** | Agent based - Zero Inteligence profit restriction |
| | **market matching/clearing algorithm** | network restrictions are not considered. Only power flow distances. |
| | **problem class** | Multi agent-based simulation |
| | **additional relevant properties** | |
| **other information** | **info provided by** | INESC TEC (Joao Melo) |
| | **additional comments** | It creates two market designs that makes agents trade preferably with nearby ones. |
| | **applications in the real world?** | theoretical |
| | | |

| Category | Detail | |
|---|---|---|
| **general info** | **title** | Multiclass Energy Management for Peer-to-Peer Energy Trading Driven by Prosumer Preferences |
| | **authors** | Thomas Morstyn, Malcolm D. McCulloch |
| | **document type** | journal publication |
| | **year** | 2019 |
| | **web link (doi)** | https://doi.org/10.1109/TPWRS.2018.2834472 |
| **consumer-centric market design** | **market operator** | community manager |
| | **trade mechanism** | Uber like P2P, where a central entity sets price to maximize social welfare |
| | **market type** | discrete/call market |
| | **trade frequency** | hourly |
| | **traded commodity** | other energy forms - diferentiated electricity types, such as renewable, neighbour, philantropic... |
| | **product duration** | |
| | **how are network operators' needs considered?** | *no* |
| | **is there trade/physical exchange with the rest of the network** | yes |
| | **pricing scheme** | Work as a walrasian model, where the market operator sets prices and peers define how much they will buy or sell. |
| | **can peers trade in other markets? If yes, please specify how** | yes, supply and surplus with the grid |
| **participants** | **type of participants** | prosumers |
| | **locality of participants** | whithin a DSO |
| | **role of the DSO** | There is no DSO, but the market operator coniders losses from the connection to the grid. |
| | **who are the other considered players and their tasks?** | The market operator, who sets prices and maximizes welfare |
| | **aggregation possible within the market** | n/a |
| | **can participants indicate specific preferences?** | generation technology, location in the network and owner's reputation |
| **algorithms** | **peers bidding algorithm** | platform manager adjusts the energy class prices, considering the prosumer energy demands, the wholesale energy price, wholesale price predictions and expected losses. Iteratively, the prosumers and platform agent reach agreement on a schedule of social welfare maximizing power flows. |
| | **market matching/clearing algorithm** | Welfare maximization. Connection losses with the grid are considered |
| | **problem class** | Central optimization problem |
| | **additional relevant properties** | only connection with the grid. DSO has no role |
| **other information** | **info provided by** | INESC TEC (Joao Melo) |
| | **additional comments** | Interesting considerations: prosumers utility function for each type of energy, Walrasian tâtonnement auction type, battery depreciation, grid losses. Could consider restrictions. Limitations: Not really a P2P. Centralized management with single price for each type of energy. |
| | **applications in the real world?** | theoretical |
| | | |

| Category | Detail | |
|---|---|---|
| **general info** | **title** | Distribution Network-Constrained Optimization of Peer-to-Peer Transactive Energy Trading Among Multi-Microgrids |
| | **authors** | Mingyu Yan , Mohammad Shahidehpour , Aleksi Paaso, Liuxi Zhang , Ahmed Alabdulwahab and Abdullah Abusorrah |
| | **document type** | journal publication |
| | **year** | 2021 |
| | **web link (doi)** | https://doi.org/10.1109/TSG.2020.3032889 |
| **consumer-centric market design** | **market operator** | system operator |
| | **trade mechanism** | p2p via third party |
| | **market type** | discrete/call market |
| | **trade frequency** | hourly |
| | **traded commodity** | electricity |
| | **product duration** | 1h |
| | **how are network operators' needs considered?** | yes, after the p2p matching |
| | **is there trade/physical exchange with the rest of the network** | yes |
| | **pricing scheme** | Peers trade bilaterally. Prices converge to na equilibrium. DSO operates power flow to trade flexibility if needed on a later stage |
| | **can peers trade in other markets? If yes, please specify how** | yes, with the DSO if needed |
| **participants** | **type of participants** | Microgrids |
| | **locality of participants** | within the same local distribution system |
| | **role of the DSO** | checks powerflow and hire flexibility |
| | **who are the other considered players and their tasks?** | Basically Microgrids and DSO. Different DER technologies are considered (PV, Wind and microturbine) |
| | **aggregation possible within the market** | The microgrid is in itself na aggregation |
| | **can participants indicate specific preferences?** | no |
| **algorithms** | **peers bidding algorithm** | P2P, optimized with game theory assuming buyers are price takers and sellers set prices to reach na equilibrium beteen supply and demand. |
| | **market matching/clearing algorithm** | DSO runs power flow with the P2P tradings and hire flexibility from microgrids if needed |
| | **problem class** | game theory, multi-leader multi-follower (MLMF) Stackelberg game approach |
| | **additional relevant properties** | yes |
| **other information** | **info provided by** | INESC TEC (Joao Melo) |
| | **additional comments** | Considers flexibility for DSO needs, but it doesn't have storage systems. The mathematical formulations is robust. |
| | **applications in the real world?** | It is good on theoretical approach, but the assumption of buyers as price taker is not practical. |
| | | |

| Category | Detail | |
| --- | --- | --- |
| **general info** | **title** | A Blockchain-Based Load Balancing in Decentralized Hybrid P2P Energy Trading Market in Smart Grid |
| | **authors** | RABIYA KHALID, NADEEM JAVAID, AHMAD ALMOGREN, MUHAMMAD UMAR JAVED, SAKEENA JAVAID, MANSOUR ZUAIR |
| | **document type** | journal publication |
| | **year** | 2020 |
| | **web link (doi)** | |
| **consumer-centric market design** | **market operator** | community manager |
| | **trade mechanism** | centralized forms of trade |
| | **market type** | discrete/call market |
| | **trade frequency** | hourly, with monthly billing |
| | **traded commodity** | electricity |
| | **product duration** | month |
| | **how are network operators' needs considered?** | *no* |
| | **is there trade/physical exchange with the rest of the network** | yes |
| | **pricing scheme** | Peers set pricing bids, and the main contract uses a P2P contract to set prices |
| | **can peers trade in other markets? If yes, please specify how** | yes |
| **participants** | **type of participants** | prosumers and consumers |
| | **locality of participants** | within the same local distribution system |
| | **role of the DSO** | no role |
| | **who are the other considered players and their tasks?** | The main contract acts as a market operator and procures energy from the grid |
| | **aggregation possible within the market** | no |
| | **can participants indicate specific preferences?** | no |
| **algorithms** | **peers bidding algorithm** | Thorugh the main contract. Prosumers and consumers send information and P2P contract set P2P trades. Any excess generation or consumption is procured through the P2G contract. |
| | **market matching/clearing algorithm** | P2P favors proximity. |
| | **problem class** | centralized forms of trade |
| | **additional relevant properties** | no, only peak average rate (PAR) |
| **other information** | **info provided by** | INESC TEC (Joao Melo) |
| | **additional comments** | Valuable due to the practical proposal of a smart contract environment that both geneerates P2P transactions, trade surplus and supply with the grid and bills local market participants montlhy. |
| | **applications in the real world?** | may be applicable in REC and LEM. |
| | | |

| Category | Detail | |
|---|---|---|
| **general info** | **title** | Peer-to-Peer Energy Trading in Smart Grid Considering Power Losses and Network Fees. |
| | **authors** | Paudel, A., Sampath, L. P. M. I., Yang, J., & Gooi, H. B. |
| | **document type** | journal publication |
| | **year** | 2020 |
| | **web link (doi)** | https://doi.org/10.1109/TSG.2020.2997956 |
| **consumer-centric market design** | **market operator** | distribution network operator, decentralized |
| | **trade mechanism** | p2p through iterative process |
| | **market type** | continuous |
| | **trade frequency** | irregular - when there is a match |
| | **traded commodity** | electricity |
| | **product duration** | other |
| | **how are network operators' needs considered?** | *no* |
| | **is there trade/physical exchange with the rest of the network** | no |
| | **pricing scheme** | negotiated iteratively. Considered loss across the line (in producer's utility function) |
| | **can peers trade in other markets? If yes, please specify how** | no |
| **participants** | **type of participants** | no restrictions mentioned |
| | **locality of participants** | no restrictions mentioned, however as the idea is to penalize longer dinstance transctions I believe the line could be drawn at same DS |
| | **role of the DSO** | responsible for giving topological signal |
| | **who are the other considered players and their tasks?** | |
| | **aggregation possible within the market** | assumed |
| | **can participants indicate specific preferences?** | no |
| **algorithms** | **peers bidding algorithm** | |
| | **market matching/clearing algorithm** | MILP |
| | **problem class** | distributed optimization |
| | **additional relevant properties** | losses are considered. further work includes inclusion of grid constraints using OPF |
| **other information** | **info provided by** | Giancarlo Marzano (N-SIDE) |
| | **additional comments** | |
| | **applications in the real world?** | theoretical, software simulation |
| | | |

| Category | Detail | |
|---|---|---|
| **general info** | **title** | Transactive Energy Market Mechanism With Loss Implication |
| | **authors** | Azizi, A., Aminifar, F., Moeini-Aghtaie, M., & Alizadeh, A. |
| | **document type** | journal publication |
| | **year** | 2021 |
| | **web link (doi)** | https://doi.org/10.1109/TSG.2020.3028825 |
| **consumer-centric market design** | **market operator** | system operator |
| | **trade mechanism** | allocation rule/distribution keys |
| | **market type** | continuous |
| | **trade frequency** | irregular - when there is a match |
| | **traded commodity** | electricity |
| | **product duration** | other |
| | **how are network operators' needs considered?** | *yes* |
| | **is there trade/physical exchange with the rest of the network** | no |
| | **pricing scheme** | negotiated |
| | **can peers trade in other markets? If yes, please specify how** | no |
| **participants** | **type of participants** | no restrictions mentioned |
| | **locality of participants** | |
| | **role of the DSO** | DSO collects bid and is responsible for the market |
| | **who are the other considered players and their tasks?** | |
| | **aggregation possible within the market** | assumed |
| | **can participants indicate specific preferences?** | no |
| **algorithms** | **peers bidding algorithm** | |
| | **market matching/clearing algorithm** | |
| | **problem class** | distributed optimization |
| | **additional relevant properties** | loss are considered. Further work includes making it a completely decentralized procedure |
| **other information** | **info provided by** | Giancarlo Marzano (N-SIDE) |
| | **additional comments** | |
| | **applications in the real world?** | theoretical, software simulation |
| | | |

| Category | Detail | |
|---|---|---|
| **general info** | **title** | Transaction-Oriented Dynamic Power Flow Tracing for Distribution Networks—Definition and Implementation in GIS Environment |
| | **authors** | Vega-Fuentes, E., Yang, J., Lou, C., & Meena, N. K. |
| | **document type** | journal publication |
| | **year** | 2021 |
| | **web link (doi)** | https://doi.org/10.1109/TSG.2020.3033625 |
| **consumer-centric market design** | **market operator** | system operator |
| | **trade mechanism** | allocation rule/distribution keys |
| | **market type** | continuous |
| | **trade frequency** | irregular - when there is a match |
| | **traded commodity** | electricity |
| | **product duration** | other |
| | **how are network operators' needs considered?** | *no* |
| | **is there trade/physical exchange with the rest of the network** | yes |
| | **pricing scheme** | negotiated |
| | **can peers trade in other markets? If yes, please specify how** | yes |
| **participants** | **type of participants** | no restrictions mentioned |
| | **locality of participants** | |
| | **role of the DSO** | DSO is the market operator, as he knows the topological configuration of the system and runs consequently the PFT algorithm |
| | **who are the other considered players and their tasks?** | |
| | **aggregation possible within the market** | assumed |
| | **can participants indicate specific preferences?** | not specified |
| **algorithms** | **peers bidding algorithm** | further work |
| | **market matching/clearing algorithm** | assumed MILP |
| | **problem class** | central optimization |
| | **additional relevant properties** | losses are considered |
| **other information** | **info provided by** | Giancarlo Marzano (N-SIDE) |
| | **additional comments** | |
| | **applications in the real world?** | theoretical, software simulation |
| | | |

| Category | Detail | |
|---|---|---|
| **general info** | **title** | Grid Influenced Peer-to-Peer Energy Trading. |
| | **authors** | Tushar, W., Saha, T. K., Yuen, C., Morstyn, T., Nahid-Al-Masood, Poor, H. V., & Bean, R. |
| | **document type** | journal publication |
| | **year** | 2020 |
| | **web link (doi)** | https://doi.org/10.1109/TSG.2019.2937981 |
| **consumer-centric market design** | **market operator** | system operator |
| | **trade mechanism** | P2P trade |
| | **market type** | discrete (not esplicitely specified, but makes sense as bids/asks are aggregated) |
| | **trade frequency** | |
| | **traded commodity** | electricity |
| | **product duration** | other |
| | **how are network operators' needs considered?** | no |
| | **is there trade/physical exchange with the rest of the network** | yes |
| | **pricing scheme** | pay as clear |
| | **can peers trade in other markets? If yes, please specify how** | yes, main grid in case no coalition is made (price higher than P2P including Feed in tariff) |
| **participants** | **type of participants** | no restrictions mentioned |
| | **locality of participants** | within same microgrid/local distribution system for P2P |
| | **role of the DSO** | DSO selects price of supply to incentivize local trade, collects bids and operate the market |
| | **who are the other considered players and their tasks?** | |
| | **aggregation possible within the market** | assumed |
| | **can participants indicate specific preferences?** | not specified |
| **algorithms** | **peers bidding algorithm** | utility function of each agent are considered |
| | **market matching/clearing algorithm** | MILP |
| | **problem class** | game theory - Stackelberg's game |
| | **additional relevant properties** | grid tied network support will be analyzed in further work |
| **other information** | **info provided by** | Giancarlo Marzano (N-SIDE) |
| | **additional comments** | |
| | **applications in the real world?** | theoretical, software simulation |
| | | |

| Category | Detail | |
|---|---|---|
| **general info** | **title** | A Distributed Electricity Trading System in Active Distribution Networks Based on Multi-Agent Coalition and Blockchain |
| | **authors** | Luo, F., Dong, Z. Y., Liang, G., Murata, J., & Xu, Z. |
| | **document type** | journal publication |
| | **year** | 2019 |
| | **web link (doi)** | https://doi.org/10.1109/TPWRS.2018.2876612 |
| **consumer-centric market design** | **market operator** | blockchain based - consensus |
| | **trade mechanism** | P2P via third party ( Coalitions determined by coordination agents) |
| | **market type** | continuous |
| | **trade frequency** | irregular - when there is a match |
| | **traded commodity** | electricity |
| | **product duration** | other |
| | **how are network operators' needs considered?** | yes - a posteriori of the trading before confirming the smart contracts |
| | **is there trade/physical exchange with the rest of the network** | yes |
| | **pricing scheme** | negotiated price - iterative process |
| | **can peers trade in other markets? If yes, please specify how** | not specified |
| **participants** | **type of participants** | no restrictions mentioned |
| | **locality of participants** | multiple microgrids connected to each other via main grid. SCA agent coordinates neighbourhing microgrids |
| | **role of the DSO** | DSO through the two agents (LCA and SCA) collect data and operate the market |
| | **who are the other considered players and their tasks?** | |
| | **aggregation possible within the market** | assumed |
| | **can participants indicate specific preferences?** | not specified |
| **algorithms** | **peers bidding algorithm** | iteratively, sharing offers and counteroffers until convergence |
| | **market matching/clearing algorithm** | |
| | **problem class** | distributed optimization |
| | **additional relevant properties** | coalition and price negotiation algorithms could be revisited to be used in DSO service provision |
| **other information** | **info provided by** | Giancarlo Marzano (N-SIDE) |
| | **additional comments** | |
| | **applications in the real world?** | theoretical, software simulation |
| | | |

| Category | Detail | |
|---|---|---|
| **general info** | **title** | Peer-to-peer energy trading in a microgrid leveraged by smart contracts. |
| | **authors** | Vieira, G., & Zhang, J. |
| | **document type** | journal publication |
| | **year** | 2021 |
| | **web link (doi)** | https://doi.org/10.1016/j.rser.2021.110900 |
| **consumer-centric market design** | **market operator** | blockchain based - auction |
| | **trade mechanism** | auction mechanism (2 proposed) |
| | **market type** | continuous / discrete |
| | **trade frequency** | irregular - when there is a match / hourly |
| | **traded commodity** | electricity |
| | **product duration** | other |
| | **how are network operators' needs considered?** | no - need to account for transmission cost & losses |
| | **is there trade/physical exchange with the rest of the network** | no (as losses and network are neglected) |
| | **pricing scheme** | continuous single price double auction / uniform price double sided auction (discrete) |
| | **can peers trade in other markets? If yes, please specify how** | no |
| **participants** | **type of participants** | no restrictions mentioned |
| | **locality of participants** | within same distribution network |
| | **role of the DSO** | no involvement |
| | **who are the other considered players and their tasks?** | agents submit bids/asks, algorithm matches demand and supply and writes the smart contracts to be executed at expiry date |
| | **aggregation possible within the market** | assumed |
| | **can participants indicate specific preferences?** | not specified |
| **algorithms** | **peers bidding algorithm** | |
| | **market matching/clearing algorithm** | |
| | **problem class** | auction |
| | **additional relevant properties** | the first algorithm is completely decentralized, as any ask price above a bid price is automatically matched. In the second case instead there is the need for an entity generating the aggregated curves and intersect them to obtain a price. Neither of the two cases considers network<br>Possible integration to DSO service procurement? If the agents exchange info from smart meters, and a bidding strategy is designed so that among the inputs we have the DSO service request. Under this scenario, we would be able to automate the process, without overlap as the immediate registration of a smart contract could initialize a mechanism to update the DSO request as different agents accept to provide part of the quantity. |
| **other information** | **info provided by** | Giancarlo Marzano (N-SIDE) |
| | **additional comments** | |
| | **applications in the real world?** | theoretical, software simulation |
| | | |

| Category | Detail | |
|---|---|---|
| **general info** | **title** | A blockchain based peer-to-peer trading framework integrating energy and carbon markets. |
| | **authors** | Hua, W., Jiang, J., Sun, H., & Wu, J. |
| | **document type** | journal publication |
| | **year** | 2020 |
| | **web link (doi)** | https://doi.org/10.1016/j.apenergy.2020.115539 |
| **consumer-centric market design** | **market operator** | blockchain based - auction |
| | **trade mechanism** | auction mechanism |
| | **market type** | discrete - predefined time |
| | **trade frequency** | other - depending on the coalition and the negotiation |
| | **traded commodity** | electricity, carbon allowance |
| | **product duration** | other - depending on the coalition and the negotiation |
| | **how are network operators' needs considered?** | no - Network is neglected assuming exchange within the same microgrid |
| | **is there trade/physical exchange with the rest of the network** | no (as losses and network are neglected) |
| | **pricing scheme** | auction based. Highest ask price in the negotiation is awarded and smart meters + smart contracts automate the settlement |
| | **can peers trade in other markets? If yes, please specify how** | not specified |
| **participants** | **type of participants** | no restrictions mentioned |
| | **locality of participants** | within same microgrid |
| | **role of the DSO** | no involvement |
| | **who are the other considered players and their tasks?** | agents submit bids/asks, algorithm matches demand and supply and writes the smart contracts to be executed at expiry date |
| | **aggregation possible within the market** | assumed |
| | **can participants indicate specific preferences?** | not specified |
| **algorithms** | **peers bidding algorithm** | |
| | **market matching/clearing algorithm** | |
| | **problem class** | auction |
| | **additional relevant properties** | By neglecting the network, auctions won't be optimal and this means that the validity of the solution from the auctions cannot be validated. If the DSO requirements for grid services, as well as the network configurations, could be embedded in the trading platform, then the solution could take these into account and find the optimal schedule |
| **other information** | **info provided by** | Giancarlo Marzano (N-SIDE) |
| | **additional comments** | |
| | **applications in the real world?** | theoretical, software simulation |
| | | |

| Category | Detail | |
|---|---|---|
| general info | title | Approaching Prosumer Social Optimum via Energy Sharing With Proof of Convergence. |
| | authors | Chen, Y., Zhao, C., Low, S. H., & Mei, S. |
| | document type | journal publication |
| | year | 2021 |
| | web link (doi) | https://doi.org/10.1109/TSG.2020.3048402 |
| consumer-centric market design | market operator | blockchain based - optimization |
| | trade mechanism | negotiation + power flow result yields price for the trading, which is then recorded in a smart contract |
| | market type | discrete |
| | trade frequency | other |
| | traded commodity | electricity |
| | product duration | other |
| | how are network operators' needs considered? | no - Network is neglected assuming exchange within the same microgrid |
| | is there trade/physical exchange with the rest of the network | no (as losses and network are neglected) |
| | pricing scheme | the platform designed receives all bids and asks and then solves a power balance to share back the pricing information to all participants |
| | can peers trade in other markets? If yes, please specify how | not specified |
| participants | type of participants | no restrictions mentioned |
| | locality of participants | within same microgrid |
| | role of the DSO | no involvement - could add network data to platform |
| | who are the other considered players and their tasks? | agents submit bids/asks, algorithm matches demand and supply and writes the smart contracts to be executed at expiry date |
| | aggregation possible within the market | assumed |
| | can participants indicate specific preferences? | not specified |
| algorithms | peers bidding algorithm | iteratively, sharing min/max levels for generation and production as well as their utility |
| | market matching/clearing algorithm | |
| | problem class | optimization |
| | additional relevant properties | |
| other information | info provided by | Giancarlo Marzano (N-SIDE) |
| | additional comments | |
| | applications in the real world? | theoretical, software simulation |
| | | |

| Category | Detail | |
|---|---|---|
| **general info** | **title** | Data-driven Distributionally Robust Co-optimization of P2P Energy Trading and Network Operation for Interconnected Microgrids. |
| | **authors** | Li, J., Khodayar, M. E., Wang, J., & Zhou, B. |
| | **document type** | journal publication |
| | **year** | 2021 |
| | **web link (doi)** | https://doi.org/10.1109/TSG.2021.3095509 |
| **consumer-centric market design** | **market operator** | Not clear |
| | **trade mechanism** | P2P |
| | **market type** | continuous |
| | **trade frequency** | other |
| | **traded commodity** | electricity |
| | **product duration** | other |
| | **how are network operators' needs considered?** | yes - network operation and constraints |
| | **is there trade/physical exchange with the rest of the network** | yes - across different microgrids |
| | **pricing scheme** | decentralized, incentive compatible scheme based on distributed robust optimization through ADMM - iterative negotiation |
| | **can peers trade in other markets? If yes, please specify how** | not specified, assumed yes |
| **participants** | **type of participants** | no restrictions mentioned |
| | **locality of participants** | within same distribution network |
| | **role of the DSO** | no involvement (sharing network data with microgrid agents) |
| | **who are the other considered players and their tasks?** | |
| | **aggregation possible within the market** | assumed |
| | **can participants indicate specific preferences?** | not specified |
| **algorithms** | **peers bidding algorithm** | minimize social cost ( transactions è operation) within the entire system. each player in microgrid updates its optimization based on shared variables by other peers and/or other microgrids. This leads to price convergence |
| | **market matching/clearing algorithm** | |
| | **problem class** | distributed optimization |
| | **additional relevant properties** | This is a decentralized approach which takes into account both electricity trading and network operation in a multi microgrid network. It requires further study and analysis but could be promising for DSO Service provision |
| **other information** | **info provided by** | Giancarlo Marzano (N-SIDE) |
| | **additional comments** | |
| | **applications in the real world?** | theoretical, software simulation |
| | | |

| Category | Detail | |
|---|---|---|
| **general info** | **title** | A Decentralized Bilateral Energy Trading System for Peer-to-Peer Electricity Markets. |
| | **authors** | Khorasany, M., Mishra, Y., & Ledwich, G. |
| | **document type** | journal publication |
| | **year** | 2020 |
| | **web link (doi)** | https://doi.org/10.1109/TIE.2019.2931229 |
| **consumer-centric market design** | **market operator** | blockchain based - optimization |
| | **trade mechanism** | P2P |
| | **market type** | discrete |
| | **trade frequency** | hourly |
| | **traded commodity** | electricity |
| | **product duration** | 1h |
| | **how are network operators' needs considered?** | via PTDFs, representing the topology, and by associating line capacity with cost (higher cost if long distance or already high loading on the line) |
| | **is there trade/physical exchange with the rest of the network** | assumed yes |
| | **pricing scheme** | negotiated price + network |
| | **can peers trade in other markets? If yes, please specify how** | not specified, assumed yes |
| **participants** | **type of participants** | no restrictions mentioned |
| | **locality of participants** | within same distribution network |
| | **role of the DSO** | no involvement - could add network data to platform |
| | **who are the other considered players and their tasks?** | |
| | **aggregation possible within the market** | assumed |
| | **can participants indicate specific preferences?** | not specified |
| **algorithms** | **peers bidding algorithm** | iteratively, sharing lagrangian and without need of Coordination as P2P trading scheme using a primal-dual gradient method |
| | **market matching/clearing algorithm** | |
| | **problem class** | |
| | **additional relevant properties** | Market clearing done in a decentralized manner:problem split in local subproblems lagrangian multipliers associated to each constraint are the shared variables for the local optimization Sellers update their prices solving own energy balance. Then "sellable" energy is computed as well buyers consequently adapt the lagrangians associated to their quantity of interest and share the resulting value using PTDFs matrix, it is computed which players utilize which lines. Then, via the lagrangians associated to the line flow constraints, it is computed the loading of each line and a price signal, if necessary, is sent to the players line congestion is prevented, line price incentivize exchange with close neighbours. The reactive power is managed by the local provider while the active power is traded using the algorithm |
| **other information** | **info provided by** | Giancarlo Marzano (N-SIDE) |
| | **additional comments** | |
| | **applications in the real world?** | theoretical, software simulation |
| | | |

| Category | Detail | |
|---|---|---|
| **general info** | **title** | A New Method for Peer Matching and Negotiation of Prosumers in Peer-to-Peer Energy Markets. |
| | **authors** | Khorasany, M., Paudel, A., Razzaghi, R., & Siano, P. |
| | **document type** | journal publication |
| | **year** | 2021 |
| | **web link (doi)** | https://doi.org/10.1109/TSG.2020.3048397 |
| **consumer-centric market design** | **market operator** | not clear, decentralized on platform |
| | **trade mechanism** | P2P |
| | **market type** | discrete |
| | **trade frequency** | hourly |
| | **traded commodity** | electricity |
| | **product duration** | 1h |
| | **how are network operators' needs considered?** | recoverage of network usage through transaction fees |
| | **is there trade/physical exchange with the rest of the network** | assumed yes |
| | **pricing scheme** | negotiated price (through strategy based on greediness factor) + network |
| | **can peers trade in other markets? If yes, please specify how** | yes, trade at less competitive price with the grid |
| **participants** | **type of participants** | no restrictions mentioned |
| | **locality of participants** | within same distribution network |
| | **role of the DSO** | no involvement (not clear whether they are the ones providing PTDFs) |
| | **who are the other considered players and their tasks?** | |
| | **aggregation possible within the market** | assumed yes |
| | **can participants indicate specific preferences?** | not specified |
| **algorithms** | **peers bidding algorithm** | Negotiation Strategy Agents have a greediness factor which they adjust during the negotiation: they start with a high value and decrease to get towards an agreement each agreement is going to be within the zone of agreement. These are different agreement all below the nash equilibrium but meeting all criteria of sellers and buyers (good visualization of agreement Zones in paper) |
| | **market matching/clearing algorithm** | |
| | **problem class** | distributed optimization for peer matching |
| | **additional relevant properties** | The algorithms are part of an iterative design, where participants submit extreme (lowest ask, highest bid) and once matched with a peer progress with a negotiation to find the price. Participants who can't make an agreement or take too long are not able to participate. Participants who have spare energy/demand after negotiation can update positions and look for new partners PRO: computationally efficient, scalable, privacy preserving |
| **other information** | **info provided by** | Giancarlo Marzano (N-SIDE) |
| | **additional comments** | |
| | **applications in the real world?** | theoretical, software simulation |
| | | |

| Category | Detail | |
|---|---|---|
| **general info** | **title** | Optimal Solution Analysis and Decentralized Mechanisms for Peer-to-Peer Energy Markets |
| | **authors** | Nguyen, D. H. |
| | **document type** | journal publication |
| | **year** | 2021 |
| | **web link (doi)** | https://doi.org/10.1109/TPWRS.2020.3021474 |
| **consumer-centric market design** | **market operator** | not clear, most likely decentralized on platform |
| | **trade mechanism** | P2P |
| | **market type** | discrete |
| | **trade frequency** | other |
| | **traded commodity** | electricity |
| | **product duration** | other |
| | **how are network operators' needs considered?** | not considered |
| | **is there trade/physical exchange with the rest of the network** | assumed yes |
| | **pricing scheme** | negotiated price (through strategy based on greediness factor) |
| | **can peers trade in other markets? If yes, please specify how** | not specified |
| **participants** | **type of participants** | no restrictions mentioned |
| | **locality of participants** | within same distribution network |
| | **role of the DSO** | no involvement |
| | **who are the other considered players and their tasks?** | |
| | **aggregation possible within the market** | not specified |
| | **can participants indicate specific preferences?** | not specified |
| **algorithms** | **peers bidding algorithm** | based on a greediness factor |
| | **market matching/clearing algorithm** | |
| | **problem class** | distributed optimization for market clearing, peer matching not clear |
| | **additional relevant properties** | Interesting the ADMM approach. Not much novelty compared to other studies in this literature review. The ADMM approach could be reused for the DSO to have a view on the P2P participants and setup a platform to collect their flexibility needs and match with their needs. |
| **other information** | **info provided by** | Giancarlo Marzano (N-SIDE) |
| | **additional comments** | |
| | **applications in the real world?** | theoretical, software simulation |
| | | |

| Category | Detail | |
|---|---|---|
| **general info** | **title** | Incentivizing distributed energy trading among prosumers: A general Nash bargaining approach |
| | **authors** | Li, G., Li, Q., Song, W., & Wang, L. |
| | **document type** | journal publication |
| | **year** | 2021 |
| | **web link (doi)** | https://doi.org/https://doi.org/10.1016/j.ijepes.2021.107100 |
| **consumer-centric market design** | **market operator** | decentralized platform where agents submit bid |
| | **trade mechanism** | P2P |
| | **market type** | discrete |
| | **trade frequency** | hourly |
| | **traded commodity** | electricity |
| | **product duration** | 1h |
| | **how are network operators' needs considered?** | not considered |
| | **is there trade/physical exchange with the rest of the network** | assumed no |
| | **pricing scheme** | firstly the total welfare for both consumers and producers is obtained, and then allocated among agents proportionally to their contribution |
| | **can peers trade in other markets? If yes, please specify how** | not specified |
| **participants** | **type of participants** | no restrictions mentioned |
| | **locality of participants** | within same distribution network |
| | **role of the DSO** | no involvement |
| | **who are the other considered players and their tasks?** | |
| | **aggregation possible within the market** | not specified |
| | **can participants indicate specific preferences?** | not specified |
| **algorithms** | **peers bidding algorithm** | from the distributed ADMM |
| | **market matching/clearing algorithm** | |
| | **problem class** | distributed optimization for welfare allocation, degree of centralization for market clearing |
| | **additional relevant properties** | Interesting as P2P trading incentive mechanism, and DSO could this way ensure the cumulative quantity of flexibility and then leave to the second algorithm the benefit allocation among the individual players. no mention of network constraints, nor how we can implement those. |
| **other information** | **info provided by** | Giancarlo Marzano (N-SIDE) |
| | **additional comments** | |
| | **applications in the real world?** | theoretical, software simulation |
| | | |

| Category | Detail | |
|---|---|---|
| **general info** | **title** | A novel decentralized platform for peer-to-peer energy trading market with blockchain technology |
| | **authors** | Esmat, A., de Vos, M., Ghiassi-Farrokhfal, Y., Palensky, P., & Epema, D |
| | **document type** | journal publication |
| | **year** | 2021 |
| | **web link (doi)** | https://doi.org/10.1016/j.apenergy.2020.116123 |
| **consumer-centric market design** | **market operator** | decentralized platform where agents submit bid |
| | **trade mechanism** | P2P |
| | **market type** | discrete - clearing and delivery intervals |
| | **trade frequency** | other - variable duration |
| | **traded commodity** | electricity |
| | **product duration** | other - variable duration |
| | **how are network operators' needs considered?** | not considered |
| | **is there trade/physical exchange with the rest of the network** | assumed no |
| | **pricing scheme** | decentralized, multi stage and multi hour uniform pricing auction mechanism for price determination |
| | **can peers trade in other markets? If yes, please specify how** | not specified |
| **participants** | **type of participants** | no restrictions mentioned |
| | **locality of participants** | assumed within same distribution network |
| | **role of the DSO** | no involvement |
| | **who are the other considered players and their tasks?** | |
| | **aggregation possible within the market** | not specified |
| | **can participants indicate specific preferences?** | not specified |
| **algorithms** | **peers bidding algorithm** | a distributed version of the ant colony optimization algorithm |
| | **market matching/clearing algorithm** | |
| | **problem class** | distributed optimization |
| | **additional relevant properties** | PRO: decentralized clearing, very few information shared between agents, fast convergence and close to centralized optimum.<br><br>CONS: not considering nodal information. Not really possible to include DSO requirements in the DeMarket Platform |
| **other information** | **info provided by** | Giancarlo Marzano (N-SIDE) |
| | **additional comments** | |
| | **applications in the real world?** | theoretical, software simulation |
| | | |

| Category | Detail | |
|---|---|---|
| **general info** | **title** | Optimizing rooftop photovoltaic distributed generation with battery storage for peer-to-peer energy trading |
| | **authors** | Su Nguyena , Wei Penga,⁎ , Peter Sokolowskib , Damminda Alahakoona , Xinghuo Yu |
| | **document type** | journal publication |
| | **year** | 2018 |
| | **web link (doi)** | |
| **consumer-centric market design** | **market operator** | Not specified peer-to-peer platform |
| | **trade mechanism** | No reference, rather pure p2p |
| | **market type** | continuous |
| | **trade frequency** | irregular - when there is a match |
| | **traded commodity** | electricity |
| | **product duration** | not specified |
| | **how are network operators' needs considered?** | *no* |
| | **is there trade/physical exchange with the rest of the network** | yes |
| | **pricing scheme** | pay-as-bid |
| | **can peers trade in other markets? If yes, please specify how** | no |
| **participants** | **type of participants** | residential |
| | **locality of participants** | homes with rooftop panels |
| | **role of the DSO** | no involvement |
| | **who are the other considered players and their tasks?** | feed-in tariff impact (regulation) considered |
| | **aggregation possible within the market** | not specified |
| | **can participants indicate specific preferences?** | yes - renewable production |
| **algorithms** | **peers bidding algorithm** | MILP |
| | **market matching/clearing algorithm** | MILP |
| | **problem class** | |
| | **additional relevant properties** | |
| **other information** | **info provided by** | NODES Grzegorz Onichimowski |
| | **additional comments** | Paper is more dedicated to the structure of the distributed generation - roof PV + batteries and which one offers better return on p2p market then to market as such |
| | **applications in the real world?** | Theoretical case study |
| | | |

| Category | Detail | |
|---|---|---|
| **general info** | **title** | Bidding in local electricity markets with cascading wholesale market integration |
| | **authors** | Fernando Lezama , Joao Soares , Ricardo Faia , Zita Vale, Olli Kilkki, Sirpa Repo, Jan Segerstam |
| | **document type** | journal publication |
| | **year** | 2021 |
| | **web link (doi)** | |
| **consumer-centric market design** | **market operator** | Not specified peer-to-peer platform |
| | **trade mechanism** | p2p via third party |
| | **market type** | continuous |
| | **trade frequency** | irregular - when there is a match |
| | **traded commodity** | electricity |
| | **product duration** | not specified |
| | **how are network operators' needs considered?** | |
| | **is there trade/physical exchange with the rest of the network** | yes |
| | **pricing scheme** | no |
| | **can peers trade in other markets? If yes, please specify how** | yes |
| **participants** | **type of participants** | All kinds |
| | **locality of participants** | within the same local distribution system |
| | **role of the DSO** | no involvement |
| | **who are the other considered players and their tasks?** | Aggregator - link to wholesale market, LEM facilitator |
| | **aggregation possible within the market** | yes |
| | **can participants indicate specific preferences?** | yes |
| **algorithms** | **peers bidding algorithm** | high accuracy of load forecasts, HEMS, power limits by TSO, aggregator participates in wholesale market |
| | **market matching/clearing algorithm** | not specified |
| | **problem class** | |
| | **additional relevant properties** | |
| **other information** | **info provided by** | NODES Grzegorz Onichimowski |
| | **additional comments** | Paper is more dedicated to the coordination of local and wholesale market to maximize benefits for the agents not to local market as such |
| | **applications in the real world?** | Theoretical case study |
| | | |

| Category | Detail | |
|---|---|---|
| **general info** | **title** | Designing microgrid energy markets: A case study: The Brooklyn Microgrid |
| | **authors** | Esther Mengelkamp, Johannes Gärttner, Kerstin Rock, Scott Kessler, Lawrence Orsini, Christof Weinhardt |
| | **document type** | journal publication |
| | **year** | 2018 |
| | **web link (doi)** | http://dx.doi.org/10.1016/j.apenergy.2017.06.054 |
| **consumer-centric market design** | **market operator** | Not specified peer-to-peer platform |
| | **trade mechanism** | pure p2p (direct bilateral trade) |
| | **market type** | continuous |
| | **trade frequency** | irregular - when there is a match |
| | **traded commodity** | other energy forms |
| | **product duration** | not specified |
| | **how are network operators' needs considered?** | |
| | **is there trade/physical exchange with the rest of the network** | yes |
| | **pricing scheme** | pay-as-bid/auctions |
| | **can peers trade in other markets? If yes, please specify how** | yes |
| **participants** | **type of participants** | local/hyper local consumers & prosumers, prosumers mainly PV systems |
| | **locality of participants** | within the same local distribution system |
| | **role of the DSO** | not specified |
| | **who are the other considered players and their tasks?** | Prosumers/consumers without specification |
| | **aggregation possible within the market** | not specified |
| | **can participants indicate specific preferences?** | yes |
| **algorithms** | **peers bidding algorithm** | not specified |
| | **market matching/clearing algorithm** | not specified |
| | **problem class** | |
| | **additional relevant properties** | |
| **other information** | **info provided by** | NODES (G.Milzer) |
| | **additional comments** | virtual microgrid may be decoupled from the physical grid to prevent instabilities |
| | **applications in the real world?** | yes |
| | | |

| Category | Detail | |
|---|---|---|
| **general info** | **title** | Cooperative energy management of a community of smart-buildings: A Blockchain approach |
| | **authors** | Olivier van Cutsem, David Ho Dac, Pol Boudou, Maher Kayal |
| | **document type** | journal publication |
| | **year** | 2019 |
| | **web link (doi)** | https://doi.org/10.1016/j.ijepes.2019.105643 |
| **consumer-centric market design** | **market operator** | no |
| | **trade mechanism** | p2p |
| | **market type** | continuous |
| | **trade frequency** | irregular |
| | **traded commodity** | electricity |
| | **product duration** | not specified |
| | **how are network operators' needs considered?** | not specified |
| | **is there trade/physical exchange with the rest of the network** | yes |
| | **pricing scheme** | not specified |
| | **can peers trade in other markets? If yes, please specify how** | not specified |
| **participants** | **type of participants** | prosumers in a smart building community |
| | **locality of participants** | within the same local distribution system |
| | **role of the DSO** | not specified |
| | **who are the other considered players and their tasks?** | Prosumers/consumers without specification |
| | **aggregation possible within the market** | yes |
| | **can participants indicate specific preferences?** | yes |
| **algorithms** | **peers bidding algorithm** | high accuracy forecasts, HEMS, information of local energy actors |
| | **market matching/clearing algorithm** | not specified |
| | **problem class** | game theory |
| | **additional relevant properties** | |
| **other information** | **info provided by** | NODES (G.Milzer) |
| | **additional comments** | exclusively about blockchain use for energy management in smart buildings |
| | **applications in the real world?** | Theoretical case study |
| | | |

| Category | Detail | |
|---|---|---|
| **general info** | **title** | Pricing and operation strategy for peer-to-peer energy trading using distribution system usage charge and game theoretic model |
| | **authors** | Yunsun Jin, Jeonghoon Choi, Dongjun Won |
| | **document type** | journal publication |
| | **year** | 2019 |
| | **web link (doi)** | |
| **consumer-centric market design** | **market operator** | no |
| | **trade mechanism** | p2p |
| | **market type** | continuous |
| | **trade frequency** | irregular when needed |
| | **traded commodity** | electricity |
| | **product duration** | not specified |
| | **how are network operators' needs considered?** | upon buyers feedback |
| | **is there trade/physical exchange with the rest of the network** | yes |
| | **pricing scheme** | various |
| | **can peers trade in other markets? If yes, please specify how** | not specified |
| **participants** | **type of participants** | all kinds |
| | **locality of participants** | within the same local distribution system |
| | **role of the DSO** | system operator |
| | **who are the other considered players and their tasks?** | prosumers, consumers, grid operator |
| | **aggregation possible within the market** | not specified |
| | **can participants indicate specific preferences?** | yes |
| **algorithms** | **peers bidding algorithm** | OPF, battery and RE production price |
| | **market matching/clearing algorithm** | not specified |
| | **problem class** | game theory |
| | **additional relevant properties** | various case scenarios to evaluate influence of P2P trading on electricity prices |
| **other information** | **info provided by** | NODES (G.Milzer) |
| | **additional comments** | |
| | **applications in the real world?** | possibly planned in Korea |
| | | |

| Category | Detail | |
|---|---|---|
| **general info** | **title** | Peer-to-peer electricity trading in grid-connected residential communities with household distributed photovoltaic |
| | **authors** | Zhenpeng Li , Tao Ma |
| | **document type** | journal publication |
| | **year** | 2020 |
| | **web link (doi)** | https://doi.org/10.1016/j.apenergy.2020.115670 |
| **consumer-centric market design** | **market operator** | not specified |
| | **trade mechanism** | various OTC, P2P, P2P via a third party |
| | **market type** | continuous and auction |
| | **trade frequency** | 15 min, hourly |
| | **traded commodity** | electricity |
| | **product duration** | not specified |
| | **how are network operators' needs considered?** | no |
| | **is there trade/physical exchange with the rest of the network** | no |
| | **pricing scheme** | auctions |
| | **can peers trade in other markets? If yes, please specify how** | not specified |
| **participants** | **type of participants** | Consumers, prosumers, Provider |
| | **locality of participants** | energy community |
| | **role of the DSO** | no involvement |
| | **who are the other considered players and their tasks?** | |
| | **aggregation possible within the market** | yes as follow up |
| | **can participants indicate specific preferences?** | not specified |
| **algorithms** | **peers bidding algorithm** | |
| | **market matching/clearing algorithm** | not specified |
| | **problem class** | independent energy communities |
| | **additional relevant properties** | |
| **other information** | **info provided by** | NODES (G.Milzer) |
| | **additional comments** | grid-connected residential communities with household distributed photovoltaic |
| | **applications in the real world?** | not in this case, only simulation |
| | | |

| Category | Detail | |
|---|---|---|
| **general info** | **title** | Decentralized P2P energy trading under network constraints in a low voltage network |
| | **authors** | Guerrero, Chapman and Verbic |
| | **document type** | journal publication |
| | **year** | 2019 |
| | **web link (doi)** | |
| **consumer-centric market design** | **market operator** | not specified |
| | **trade mechanism** | various OTC, P2P, P2P via a third party |
| | **market type** | Continuous double auction |
| | **trade frequency** | |
| | **traded commodity** | electricity |
| | **product duration** | not specified |
| | **how are network operators' needs considered?** | yes |
| | **is there trade/physical exchange with the rest of the network** | no |
| | **pricing scheme** | Continuous double auction |
| | **can peers trade in other markets? If yes, please specify how** | not specified |
| **participants** | **type of participants** | Consumers, prosumers, Provider |
| | **locality of participants** | energy community |
| | **role of the DSO** | Yes through network constraints |
| | **who are the other considered players and their tasks?** | |
| | **aggregation possible within the market** | yes as follow up |
| | **can participants indicate specific preferences?** | not specified |
| **algorithms** | **peers bidding algorithm** | not specified |
| | **market matching/clearing algorithm** | not specified |
| | **problem class** | |
| | **additional relevant properties** | |
| **other information** | **info provided by** | KUL (Md Umar Hashmi) |
| | **additional comments** | P2P transactions will avoid creating new network issues. Since the P2P trades are governed only by price potential and these trades are validated in the outer layer based on approximate network constraints, therefore, such trades will not correct network issues but only avoid creating new network issues. Further, since the loss component will avoid having energy trades between two points separated by large electrical distances makes it a realistic and practically useful framework. |
| | **applications in the real world?** | not in this case, only simulation |
| | | |

| Category | Detail | |
|---|---|---|
| **general info** | **title** | Peer-to-peer market with network constraints, user preferences and network charges |
| | **authors** | Chernova and Gryazina |
| | **document type** | journal publication |
| | **year** | 2021 |
| | **web link (doi)** | |
| **consumer-centric market design** | **market operator** | |
| | **trade mechanism** | Distributed P2P |
| | **market type** | |
| | **trade frequency** | |
| | **traded commodity** | electricity |
| | **product duration** | not specified |
| | **how are network operators' needs considered?** | Yes, network constraints considered |
| | **is there trade/physical exchange with the rest of the network** | no |
| | **pricing scheme** | |
| | **can peers trade in other markets? If yes, please specify how** | not specified |
| **participants** | **type of participants** | Consumers, prosumers, Provider |
| | **locality of participants** | energy community |
| | **role of the DSO** | Yes through network constraints |
| | **who are the other considered players and their tasks?** | |
| | **aggregation possible within the market** | Not specified |
| | **can participants indicate specific preferences?** | not specified |
| **algorithms** | **peers bidding algorithm** | not specified |
| | **market matching/clearing algorithm** | ADMM |
| | **problem class** | |
| | **additional relevant properties** | |
| **other information** | **info provided by** | KUL (Md Umar Hashmi) |
| | **additional comments** | Network constraints are considered using a Matrix of loading vectors. The rows of this matrix contain the sensitivity of line power flows to the changes in bus power injection. This matrix formation uses the approach of power transfer distribution factor approach. Thus, accounts for network constraints in an endogenous manner |
| | **applications in the real world?** | not in this case, only simulation |
| | | |

| Category | Detail | |
|---|---|---|
| **general info** | **title** | Coalition graph game-based p2p energy trading with local voltage management |
| | **authors** | Azim, Tushar and Saha |
| | **document type** | journal publication |
| | **year** | 2021 |
| | **web link (doi)** | |
| **consumer-centric market design** | **market operator** | |
| | **trade mechanism** | P2P via third party |
| | **market type** | |
| | **trade frequency** | |
| | **traded commodity** | electricity |
| | **product duration** | not specified |
| | **how are network operators' needs considered?** | Yes, network voltage violations |
| | **is there trade/physical exchange with the rest of the network** | no |
| | **pricing scheme** | |
| | **can peers trade in other markets? If yes, please specify how** | not specified |
| **participants** | **type of participants** | Consumers, prosumers, Provider |
| | **locality of participants** | energy community |
| | **role of the DSO** | Yes through network constraints |
| | **who are the other considered players and their tasks?** | |
| | **aggregation possible within the market** | Not specified |
| | **can participants indicate specific preferences?** | not specified |
| **algorithms** | **peers bidding algorithm** | not specified |
| | **market matching/clearing algorithm** | Coalition graph game-based P2P |
| | **problem class** | |
| | **additional relevant properties** | |
| **other information** | **info provided by** | KUL (Md Umar Hashmi) |
| | **additional comments** | Coalition graph game-based P2P energy trading framework is developed. The prosumers can form a coalition to negotiate on energy trading parameters, i.e. quantity and price. Myerson value rule is used to allocate the total payoff of the proposed game fairly among the participating prosumers. The stability of such a coalition is confirmed. |
| | **applications in the real world?** | not in this case, only simulation |
| | | |

| Category | Detail | |
|---|---|---|
| **general info** | **title** | Development of operator oriented peer-to-peer energy trading model for integration into the existing distribution system |
| | **authors** | Heo, Kong, Oh and Jung |
| | **document type** | journal publication |
| | **year** | 2021 |
| | **web link (doi)** | |
| **consumer-centric market design** | **market operator** | |
| | **trade mechanism** | Centralised P2P |
| | **market type** | |
| | **trade frequency** | |
| | **traded commodity** | electricity |
| | **product duration** | not specified |
| | **how are network operators' needs considered?** | Yes, through network usage charge |
| | **is there trade/physical exchange with the rest of the network** | no |
| | **pricing scheme** | |
| | **can peers trade in other markets? If yes, please specify how** | not specified |
| **participants** | **type of participants** | Consumers, prosumers |
| | **locality of participants** | energy community |
| | **role of the DSO** | No |
| | **who are the other considered players and their tasks?** | |
| | **aggregation possible within the market** | Not specified |
| | **can participants indicate specific preferences?** | not specified |
| **algorithms** | **peers bidding algorithm** | not specified |
| | **market matching/clearing algorithm** | Coalition graph game-based P2P |
| | **problem class** | |
| | **additional relevant properties** | |
| **other information** | **info provided by** | KUL (Md Umar Hashmi) |
| | **additional comments** | Network usage charge is included. It is designed to compensate for the support of the utilities (under the assumption that there is no dedicated network for P2P trading and the energy trade relies on the network of the current utility), as the current customers pay some amount to the utility for using the network. |
| | **applications in the real world?** | not in this case, only simulation |
| | | |

| Category | Detail | |
|---|---|---|
| **general info** | **title** | Investigating the impact of p2p trading on power losses in grid-connected networks with prosumers |
| | **authors** | Azim, Tushar and Saha |
| | **document type** | journal publication |
| | **year** | 2020 |
| | **web link (doi)** | |
| **consumer-centric market design** | **market operator** | |
| | **trade mechanism** | Centralised P2P |
| | **market type** | |
| | **trade frequency** | |
| | **traded commodity** | electricity |
| | **product duration** | not specified |
| | **how are network operators' needs considered?** | Yes, presents a physical layer analysis of P2P trading to investigate its impact on network losses. |
| | **is there trade/physical exchange with the rest of the network** | no |
| | **pricing scheme** | |
| | **can peers trade in other markets? If yes, please specify how** | not specified |
| **participants** | **type of participants** | Consumers, prosumers |
| | **locality of participants** | energy community |
| | **role of the DSO** | No |
| | **who are the other considered players and their tasks?** | |
| | **aggregation possible within the market** | Not specified |
| | **can participants indicate specific preferences?** | not specified |
| **algorithms** | **peers bidding algorithm** | not specified |
| | **market matching/clearing algorithm** | Coalition graph game-based P2P |
| | **problem class** | |
| | **additional relevant properties** | |
| **other information** | **info provided by** | KUL (Md Umar Hashmi) |
| | **additional comments** | Two categories of simulations performed. The first category of simulation results demonstrates that the P2P transactions do not change the network losses, compared to the non-P2P scenario, if prosumers do not have power dispatch flexibility. Further, It is observed from the second category of simulation results that flexible power dispatch of P2P prosumers can change the network losses at some time instants of a typical day. |
| | **applications in the real world?** | not in this case, only simulation |
| | | |

| Category | Detail | |
|---|---|---|
| **general info** | **title** | Local electricity market designs for peer-to-peer trading: The role of battery flexibility |
| | **authors** | Lüth, Zepter, del Granado and Egging |
| | **document type** | journal publication |
| | **year** | 2018 |
| | **web link (doi)** | |
| **consumer-centric market design** | **market operator** | |
| | **trade mechanism** | decentralised P2P |
| | **market type** | |
| | **trade frequency** | |
| | **traded commodity** | electricity |
| | **product duration** | not specified |
| | **how are network operators' needs considered?** | no |
| | **is there trade/physical exchange with the rest of the network** | no |
| | **pricing scheme** | |
| | **can peers trade in other markets? If yes, please specify how** | not specified |
| **participants** | **type of participants** | Consumers, prosumers |
| | **locality of participants** | energy community |
| | **role of the DSO** | No |
| | **who are the other considered players and their tasks?** | |
| | **aggregation possible within the market** | Not specified |
| | **can participants indicate specific preferences?** | not specified |
| **algorithms** | **peers bidding algorithm** | not specified |
| | **market matching/clearing algorithm** | |
| | **problem class** | |
| | **additional relevant properties** | |
| **other information** | **info provided by** | KUL (Md Umar Hashmi) |
| | **additional comments** | |
| | **applications in the real world?** | not in this case, only simulation |
| | | |

| Category | Detail | |
|---|---|---|
| **general info** | **title** | Centralised and distributed optimization for aggregated flexibility services provision |
| | **authors** | Olivella-Rosell et al. |
| | **document type** | journal publication |
| | **year** | 2020 |
| | **web link (doi)** | |
| **consumer-centric market design** | **market operator** | |
| | **trade mechanism** | decentralised P2P |
| | **market type** | |
| | **trade frequency** | |
| | **traded commodity** | electricity |
| | **product duration** | not specified |
| | **how are network operators' needs considered?** | no |
| | **is there trade/physical exchange with the rest of the network** | no |
| | **pricing scheme** | Cenrealised signal, details not mentioned |
| | **can peers trade in other markets? If yes, please specify how** | not specified |
| **participants** | **type of participants** | Prosumer owned batteries. |
| | **locality of participants** | energy community |
| | **role of the DSO** | No |
| | **who are the other considered players and their tasks?** | |
| | **aggregation possible within the market** | Not specified |
| | **can participants indicate specific preferences?** | not specified |
| **algorithms** | **peers bidding algorithm** | not specified |
| | **market matching/clearing algorithm** | ADMM |
| | **problem class** | |
| | **additional relevant properties** | |
| **other information** | **info provided by** | KUL (Md Umar Hashmi) |
| | **additional comments** | A decomposed solution approach with the alternating direction method of multipliers (ADMM) is used instead of commonly adopted centralized optimization to reduce the computational burden and time, and then reduce scalability limitations. |
| | **applications in the real world?** | not in this case, only simulation |
| | | |

| Category | Detail | |
|---|---|---|
| general info | title | Co-simulation of electricity distribution networks and P2P energy trading platforms |
| | authors | Hayes, Thakur and Breslin |
| | document type | journal publication |
| | year | 2020 |
| | web link (doi) | |
| consumer-centric market design | market operator | |
| | trade mechanism | decentralised P2P |
| | market type | Distributed double auction |
| | trade frequency | |
| | traded commodity | electricity |
| | product duration | not specified |
| | how are network operators' needs considered? | Yes,<br>Co-simulation of DN power flow using OpenDSS platform is performed. |
| | is there trade/physical exchange with the rest of the network | no |
| | pricing scheme | Centralised signal, details not mentioned |
| | can peers trade in other markets? If yes, please specify how | not specified |
| participants | type of participants | Prosumer owned batteries. |
| | locality of participants | energy community |
| | role of the DSO | No |
| | who are the other considered players and their tasks? | |
| | aggregation possible within the market | Not specified |
| | can participants indicate specific preferences? | not specified |
| algorithms | peers bidding algorithm | not specified |
| | market matching/clearing algorithm | ADMM |
| | problem class | |
| | additional relevant properties | |
| other information | info provided by | KUL (Md Umar Hashmi) |
| | additional comments | A key finding of this paper is that a moderate level of peer-to- peer trading does not have a significant impact on distribution network operational performance. Although authors claim that P2P trade could reduce distribution network unbalance. However, in numerical results a meagre reduction of 0.01% in DN unbalance is statistically insignificant |
| | applications in the real world? | not in this case, only simulation |
| | | |

| Category | Detail | |
|---|---|---|
| **general info** | **title** | Game theory based bidding strategy for prosumers in a distribution system with a retail electricity market |
| | **authors** | Liang and Su |
| | **document type** | journal publication |
| | **year** | 2018 |
| | **web link (doi)** | |
| **consumer-centric market design** | **market operator** | |
| | **trade mechanism** | decentralised P2P |
| | **market type** | Distributed double auction |
| | **trade frequency** | |
| | **traded commodity** | electricity |
| | **product duration** | not specified |
| | **how are network operators' needs considered?** | Yes,<br>DistFlow representation of optimal power flow is utilized. |
| | **is there trade/physical exchange with the rest of the network** | no |
| | **pricing scheme** | Centralised signal, details not mentioned |
| | **can peers trade in other markets? If yes, please specify how** | not specified |
| **participants** | **type of participants** | Prosumer owned batteries. |
| | **locality of participants** | energy community |
| | **role of the DSO** | No |
| | **who are the other considered players and their tasks?** | |
| | **aggregation possible within the market** | Not specified |
| | **can participants indicate specific preferences?** | not specified |
| **algorithms** | **peers bidding algorithm** | not specified |
| | **market matching/clearing algorithm** | Bilevel algorithm |
| | **problem class** | |
| | **additional relevant properties** | |
| **other information** | **info provided by** | KUL (Md Umar Hashmi) |
| | **additional comments** | Prosumers need a well-defined strategic bidding mechanism to maximize their operation revenue, while DSOs need a new market clearing mechanism for the changed retail electricity market. Thus, an innovative game-theoretic market framework for a prosumer-centric retail electricity market is proposed. |
| | **applications in the real world?** | not in this case, only simulation |
| | | |