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How will consumer-centric markets impact distribution grids considering AC-OPF?

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Abstract

The continuous incentives for the proliferation of small-scale energy resources, along with the advances in the Internet of Things (IoT) and consumer awareness for climate changes, has been contributing to the growth of prosumers. Prosumers are consumers that can both consume and produce energy, playing a proactive role in the electricity market. This paradigm shift encourages consumers to take part in the transition, changing the way they perceive the electricity market, so peer-to-peer (P2P) electricity markets have emerged as a consumer-centric market approach, where prosumers are allowed to exchange energy directly between each other. This innovation is not only economically beneficial to these proactive consumers, but it also increases the system's efficiency. However, the development of P2P markets presents some challenges regarding the operation of the distribution system. Some of these challenges are related to technical constraints on the network that must be respected, in order to ensure that the energy is supplied with high levels of system reliability and power quality. Therefore, those issues have to be addressed so that the network security is not compromised.

In this context, this dissertation contributes with a method of a P2P electricity market model that takes into account the network constraints, allowing to solve potential congestion and voltage problems. The suggested way of keeping a reliable and secure operation of the system is through the design of a P2P market, integrating network constraints in the form of an alternating current optimal power flow (AC-OPF), solving the problem in a centralized fashion. Furthermore, the proposed model is analysed and compared to a recent method available in the literature. This recent method consists of an iterative process with product differentiation, which is able to avoid congestion problems by applying weights to P2P trades that may cause the problem, so it encourages prosumers to reduce electrical grid usage.

Both methods are simulated, tested and validated using a typical distribution network, considering high renewable energy sources (RES) penetration. Moreover, a detailed analysis of each model is conducted, considering different situations for the simulation in terms of line thermal limits and loads' flexibility. The results show that both models are able to respect the technical limits of the network, providing feasible market results. Nevertheless, market solutions may differ in certain conditions depending on the loads' flexibility and network congestion.

An important conclusion of this dissertation is that, even though both models provide feasible solutions, they can differ significantly when there is a high level of line congestion and loads' flexibility.

Keywords: Distributed energy resources, Distributed optimization, Grid operation, Network constraints, Peer-to-peer trading, Prosumer.

Resumo

O aumento dos recursos energéticos distribuídos e os avanços relacionados com as tecnologias de informação têm contribuído para o crescimento dos *prosumers*. O termo *prosumer* é usado para designar consumidores que, além de consumirem energia elétrica, também a produzem, contribuindo proativamente para o mercado de eletricidade. Esta mudança de paradigma incentiva os consumidores a fazerem parte da transição e daí emergiu uma nova abordagem, designada por *peer-to-peer* (P2P), onde os *prosumers* podem fazer trocas de energia diretamente entre si. Esta é uma inovação que traz não só benefícios económicos para os seus participantes, como também para a eficiência do sistema. Contudo, o desenvolvimento dos mercados P2P acarreta desafios relacionados com a operação do sistema de distribuição, uma vez que os limites técnicos da rede têm de ser respeitados de maneira a não comprometer a segurança e fiabilidade do sistema.

Com esse objetivo, a presente tese contribui com um método que pretende resolver os possíveis problemas de congestionamento e tensão, através de um mercado de eletricidade P2P onde as restrições da rede são tidas em conta. O desenvolvimento de uma estrutura P2P que integra as restrições da rede sob a forma de um trânsito de potências ótimo em corrente alternada, é uma maneira de manter as perdas da rede dentro dos limites e assegurar que a operação do sistema é feita de forma segura. Além disso, este modelo é analisado e comparado com um método desenvolvido recentemente que consiste num processo iterativo com diferenciação de produto, onde é dado um peso diferente às transações, atendendo aos problemas de congestionamento que estas podem causar. Desta forma, garante que as restrições da rede são respeitadas e incentiva os participantes a reduzir o uso da rede elétrica.

Ambos os métodos são simulados e validados a partir de uma rede de distribuição com elevada penetração de fontes de energia renováveis. Com o intuito de obter uma análise mais elaborada, são consideradas diferentes situações em termos de corrente máxima das linhas e flexibilidade das cargas. Segundo os resultados apresentados, os dois modelos respeitam os limites da rede, porém, as soluções de mercado são diferentes em certas condições de simulação.

Uma das mais importantes conclusões desta dissertação é que, ainda que as soluções de ambos os modelos sejam viáveis, estas poderão ter diferenças significativas quando existe um nível de congestionamento elevado e as cargas são flexíveis.

Palavras-Chave: Recursos energéticos distribuídos, Optimização distribuída, Operação da rede, Restrições da rede, Mercado peer-to-peer, Prosumer.

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Catarina Oliveira

"I shall be telling this with a sigh
Somewhere ages and ages hence:
Two roads diverged in a wood, and I—
I took the one less traveled by,
And that has made all the difference."

Robert Frost

Contents

List of Figures

List of Tables

Abbreviations and Symbols

List of abbreviations

AC-OPF	Alternating current optimal power flow
AC-PF	Alternating current power flow
CHP	Combined heat and power
DER	Distributed Energy Resources
DSO	Distribution System Operator
P2P	Peer-to-Peer
PV	Photovoltaic
QoE	Quality of Experience
RES	Renewable Energy Sources
SW	Social Welfare
TC	Total Cost
TR	Total Revenue

List of symbols

Sets

G	Different type of criteria involved in peers' decisions
λ_{nm}	Dual variable, shadow prices
N_B	Number of nodes in the electrical network
Ω_n	All agents in the electrical network
Ω_c	All consumers in the electrical network
ω_n	Agents in the neighbourhood of agent n
Ω_p	All producers in the electrical network

Functions

C_n	Cost function of agent n

Decision Variables

c_n^g	Trade coefficient, preference coefficient of agent n for criterion g
γ_{nm}^g	Trade characteristic, value of criterion g of agent m from perspective of agent n
P_n	Net active power produced (>0) or consumed (<0) by agent n
P_{nm}	Active power traded between agent n and m
Q_n	Net reactive power produced (>0) or consumed (<0) by agent n
V_i	Voltage magnitude at node i
θ_i	Voltage angle at node i

Parameters

a_n, b_n, d_n	Quadratic coefficients of agent n
B	Imaginary part of the admittance matrix
G	Real part of the admittance matrix
$\underline{P_n}$, $\overline{P_n}$	Lower, upper active power limits of agent n
$\underline{Q_n}$, $\overline{Q_n}$	Lower, upper reactive power limits of agent n
S	Apparent power

Chapter 1

Introduction

In this chapter, a brief introduction is made about the topics and the concepts discussed in this dissertation. It gives a framework to the problem and the motivation behind it. In addition, the dissertation structure is also presented.

1.1 Context and Motivation

Over the past few years, there has been a significant increase in the integration of distributed energy resources (DER), particularly at the household level. In fact, at the low-voltage level, the growth of rooftop solar generators has been very prominent, as well as the emergence of electric vehicles (EVs). The increase of DERs has been occurring worldwide with a focus on the Nordic countries where, according to [1], DERs have experienced an increase in installed capacity of 46% between 2005 and 2017. Moreover, Australia has an ambitious goal, in which DERs may cover 30-45% of its electricity needs by 2050.

One of the main reasons for this growth is the pressure on carbon emissions reduction, which has been an important topic discussed by the governments of the most developed countries. For instance, the European Union (EU) is determined to achieve climate neutrality by 2050, in line with the Paris Agreement so, in 2014, targets for the period of 2021-2030 were set in order to cut greenhouse gas emissions by at least 40% by 2030, compared to 1990. Furthermore, the 2030 framework purposes a target of at least 27% of energy consumption and 27% improvement in energy efficiency in 2030 [2]. Another positive impact of DERs is that they can help reduce power losses and improve power supply reliability [3]. Thus, this paradigm shift translates in innovative business models and also in technical and economical challenges, but while the high penetration of DERs may cause congestion problems, it also encourages individuals and agents from different sectors to take part of the transition and benefit from it [1].

As a result of these trends and due to the fall in the cost of renewable energy technologies, especially solar panels, consumers, who have been playing a passive role in the electricity market, are turning into prosumers [4]. The term 'prosumers' refers to consumers who also produce commodities or services and has its origin in the 1980s [5]. The information technology and digital industry brought this term into mainstream use and it soon started being used in the electricity industry to define energy consumers, who also produce and share excessive energy generated by renewable energy sources (RES) with the grid or with other consumers in a community [6]. Some stakeholders have argued that prosumers are a threat to the grid stability and to the existing business models, but others see them as an advantageous and inevitable evolution of the electricity industry. Therefore, the transition strategies must focus on structural changes to the electricity sector and in the reorganization of electricity markets through consumer-centric markets, rather than simply adjust the existing regulation [5].

In this context, peer-to-peer (P2P) electricity markets have emerged as a novel proposal for the design and operation of the distribution network, where prosumers play an active role as they can exchange energy directly between each other. They are brought to the center of the electricity market and are given equal responsibility, as this market design allows them to share energy between each other, while taking into account the concept of sharing economy. However, P2P electricity tradings can be challenging because the network has technical constraints that must be respected, otherwise, networks' security is compromised due to congestion and voltage problems. Moreover, the energy exchanges between the peers are expected to have a very low influence from a central controller. Thus, scientific literature has been pointing out that completely decentralized P2P markets and network operation could be "detrimental in maintaining the technical limit of the network within the safety range" [7]. Centralized and decentralized approaches for exchanging energy need to be discussed and studied in detail, so the identified issues have to be addressed and proper tools must be developed to implement P2P markets, ensuring a secure operation of the future distribution systems.

1.2 Objective

The coordination between a P2P market and the distribution network operation is a key aspect for the successful proliferation of these consumer-centric markets. Thus, the advantages of implementing P2P markets at the distribution level have to be assessed, along with the challenges they bring in terms of network operation. Once these challenges and advantages are identified, methodologies considering the coordination between the P2P market and the network operation will prosper.

In this context, this dissertation offers a significant contribution by developing a market model that combines the P2P market design with the network operation. This model is inspired in the literature and is analysed and compared to a recent similar model, named Iterative P2P market with product differentiation, also available in the literature.

Furthermore, the specific objectives defined for this dissertation were the following:

- Identification of the key aspects for the proliferation of P2P electricity markets in distribution systems;

- Research, design and development of coordinated methods that integrate network constraints into P2P markets;
- Integration of a centralized AC-OPF in the P2P market model;
- Analysis and comparison of two different P2P market models for the coordination of a P2P market with the electrical network, considering economic, technical and fairness indexes.

1.3 Thesis Structure

This dissertation is organized into five chapters. In addition to the present introductory chapter, the structure of this dissertation includes four other chapters, which are described below.

Chapter 2 presents an overview of P2P electricity markets and the related concepts, as well as the advantages and challenges, based on a literature review. In addition, different methods to connect the participants of P2P markets with the electrical network are presented.

In Chapter 3, the model proposed in this dissertation to coordinate the P2P market with the network is described, along with one of the models developed in [8]. Moreover, all the insights of each model are provided, including the mathematical formulations.

In Chapter 4, a radial distribution network at the medium voltage is used to simulate and validate the two models. The models are compared for different levels of demand flexibility and network capacity, so the results are analysed and discussed. Some conclusions are also presented in the final section.

Chapter 5 highlights the main conclusions and contributions of this work, and it presents some suggestions for future work. Regarding the final sections, they include the appendix section and references section.

Chapter 2

Overview of P2P Electricity Markets

The following chapter presents the concept of P2P networks and its application in the electricity market, considering the advantages and challenges to consumers and the grid. The main types of P2P market designs are described and characterised, as well as the tools used to ensure the balance between supply and demand, respecting the grid constraints. Finally, several approaches regarding the link between the P2P market and the power grid are presented and discussed.

2.1 Peer-to-Peer (P2P)

2.1.1 Introduction and Definition

The P2P approach first appeared in the scientific community as an alternative model to the traditional client/server model in Internet-scale distributed systems. The goal was to create a method that would reduce the need for centralized management, making the communication process between client and server less heavy. In fact, network systems like ARPANET[1] are based on this idea and its principles can also be found in file sharing systems, such as Gnutella, Napster or Freenet [9].

Considering the concept of a decentralized model, a distributed network architecture may be classified as a P2P network if the participants share directly their own resources without the need of an intermediary entity. These participants are considered to be equal peers and combine the ability of being resource providers as well as resource requesters [10]. Thus, the resources can be either physical or logical, such as services.

This concept is based not only on the principle of sharing resources, but also on the idea of decentralization and self-organization, increasing system robustness. Unlike the traditional client/server model, if a peer on the network fails, it will not compromise the entire system or result in its collapse. Furthermore, since there is no central node to coordinate all the activities, each node as to self-organize and communicate with the other nodes.

[1] ARPANET (Advanced Research Projects Agency Network) was a computer network developed in the late 1960s and the predecessor to the Internet.

2.1.2 Electricity Market

The deregulation of the energy industry along with the development of renewable energy and Internet technology, such as IoT and smart grids has been contributing to the growth of distributed energy systems. Thus, P2P electricity trading is expected to increase, as these innovations can improve the efficiency of the system and enable the transition from the traditional socioeconomic structures to advanced structures based on community and sharing economy concepts [11].

In electricity trading, P2P refers to cases where the participants can trade energy between each other at a certain negotiated price. They are labelled as producers, consumers or prosumers, playing a proactive role in the system. Each node is given equal responsibility and is able to trade electricity directly with the other nodes. According to [7], a P2P network consists in two layers: i) virtual layer and ii) physical layer. The first one ensures that the market mechanism is appropriate to match supply and demand orders, while the participants have equal access to the information on a virtual platform. The physical layer represents the physical network in which the electricity is transported from producers to consumers once the bilateral settlements are verified on the virtual platform. In the same way as elements like the grid connection and the metering and communication infrastructure are important in the physical layer, the elements in the virtual layer are also the key to the success of energy trading within P2P systems. The information system enables the market operation through payment rules and a defined bidding format. Thus, the energy trading process can be carried out efficiently and allows the peers to follow demand and supply orders in near real-time. Moreover, the pricing mechanisms used in these markets differ from the traditional ones as renewable energies have very low marginal costs, whereas in the traditional electricity markets, part of the electricity price consists of taxes. This means that prosumers can set a price for their energy and make it more profitable, although the pricing mechanism should reflect the network situation.

Indeed, this system allows everyone to participate in energy exchanges, while promoting a competitive energy market that benefits small-scale producers and consumers who can profit as the market is not monopolized anymore by few utility companies. In addition, it gives the peers a wide range of alternative energy sources according to their preferences [12]. On the other hand, the implementation of P2P trading can be advantageous to the grid, as it can reduce peak demand and operation costs as well as minimize reserve requirements. Thus, the restructuring of the energy system and the integration of RES can not only contribute to environmental sustainability but also to the economy [13].

Despite the advantages that it brings in terms of operating costs and sustainability, the P2P system depends on many relevant aspects, among them [12]:

- Demand response optimization;
- Power routing;
- Public energy market;
- Money transaction mechanisms;

- Efficient communication networks.

Considering that P2P electricity trading is directed towards small to medium scale resources (DERs), usually controlled by several independent entities, it is harder to maintain the balance between supply and demand, which may lead to system instability. Moreover, power generation from RES is very unpredictable as it dependents on weather conditions. Therefore, in order to achieve demand response optimization, it is necessary to develop price optimization algorithms and centrally controlled models as well as new methods of energy scheduling. It should be noted that the centralized approach may compromise security and data privacy as it requires customers' information to be sent to the central controller. To overcome these issues, decentralized approaches have been proposed in the literature, focusing on the P2P energy scheduling under anonymous data exchange.

Another important service for P2P systems is related to the transportation of power from producers to consumers, taking into account that they may be far away from each other. Power routing devices are one solution to track the power and, therefore, they should be able to understand location addresses and support bi-directional routing functions. In addition, with distributed heterogeneous power sources, such as wind and solar, power generation has different characteristics like frequency or voltage level, hence power routers must be able to convert power from one form to another. Power routing algorithms have been proposed and could be compared to traditional data packet routing. However, their requirements are different as data packet routing works on best effort delivery basis where packets can be resent if not successfully delivered. This is not suitable for power routing since power signals cannot be resent once they are lost, and thus researchers have been working on a solution for this problem.

There are some other challenges related to P2P markets that must be taken into account. Regarding the transition to these markets, the lack of a clear legal framework in most countries is one of the main obstacles. Botelho et al. addresses in detail the main barriers of current regulatory frameworks in several countries to the spread of P2P business in the energy sector [14]. On the other hand, the current smart grid architecture raises serious concerns with respect to security and data privacy. The entities participating in P2P electricity trading need to communicate with each other, so it compromises the confidentiality and integrity of the system with consequences for the users. In fact, the fine-grained consumption monitoring provided by smart meters could expose the participants' lifestyle and make them vulnerable. Moreover, security issues, such as the submission of fake contracts or attacks on the P2P system, should also be taken into account. Therefore, it is important to ensure that the trading infrastructure is capable of executing contracts between the agents and handling bidding, negotiation and transactions while keeping data privacy [12, 15, 16]. In order to achieve this, blockchain technology can be a promising path for launching distributed data storage and management, as it traces historical activities and preserves users' identities without the need to depend on third parties [17].

2.2 P2P market designs

In this section, different structures of P2P electricity markets are discussed according to their degree of decentralization, as presented in [18]: (i) full P2P market; (ii) community-based market; and (iii) hybrid P2P market.

2.2.1 Full P2P market

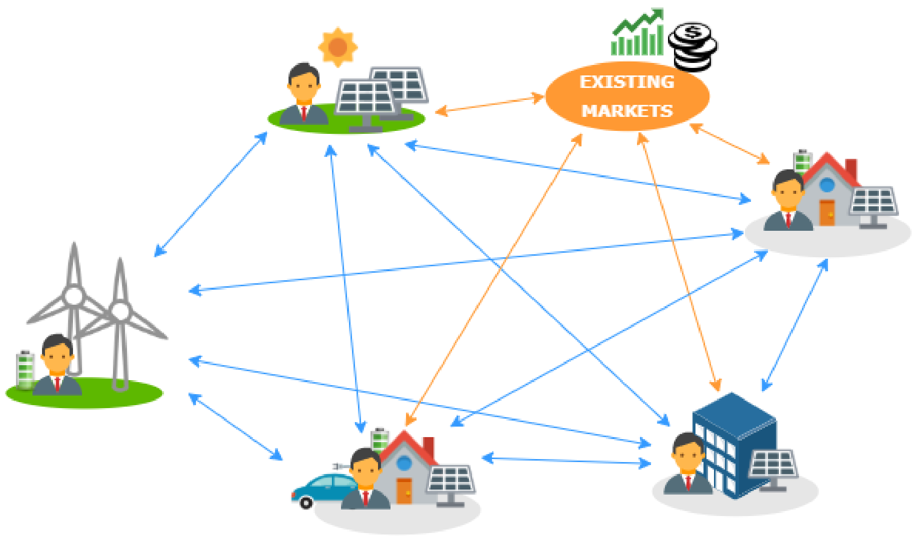

Figure 2.1: Full P2P market design (adapted from [18]).

The full P2P market design consists in the electricity trading between peers without centralized supervision. The participants are given equal responsibility and they can be either consumers or producers. Product differentiation can also be included as in the multi-bilateral economic dispatch formulation proposed by [19]. For instance, product differentiation can be used to express consumers' preferences or to include grid tariffs.

Currently, full P2P market is being implemented as a business model in areas where the energy market is deregulated. As an example, there is the Brooklyn Microgrid project [2], which allows residents and business owners to purchase and sell locally-generated renewable energy through a data platform developed using blockchain technology.

In [20], a new market design for P2P energy trading is presented, using bilateral contracts to include forward and real-time markets, while a distributed price adjustment is used for market clearing.

[2] https://www.brooklyn.energy/

The simplest form of the mathematical formulation is presented below [18]:

$$\min_{D} \quad \sum_{n\in\Omega} C_n \left(\sum_{m\in\omega_n} P_{nm} \right) \tag{2.1a}$$

$$\text{s.t.} \quad \underline{P_n} \leq \sum_{m\in\omega_n} P_{nm} \leq \overline{P_n} \qquad \forall n \in \Omega \tag{2.1b}$$

$$P_{nm} + P_{mn} = 0 \qquad \forall (n,m) \in (\Omega, \omega_n) \tag{2.1c}$$

$$P_{nm} \geq 0 \qquad \forall (n,m) \in (\Omega_p, \omega_n) \tag{2.1d}$$

$$P_{nm} \leq 0 \qquad \forall (n,m) \in (\Omega_c, \omega_n) \tag{2.1e}$$

Where $D = (P_{nm} \in \mathbb{R})_{n\in\Omega, m\in\omega_n}$. Since P_{nm} represents the trade between agent n and m, if it has a positive value, then it corresponds to production (2.1d), whereas if it has a negative value, it means consumption (2.1e).

2.2.2 Community-based market

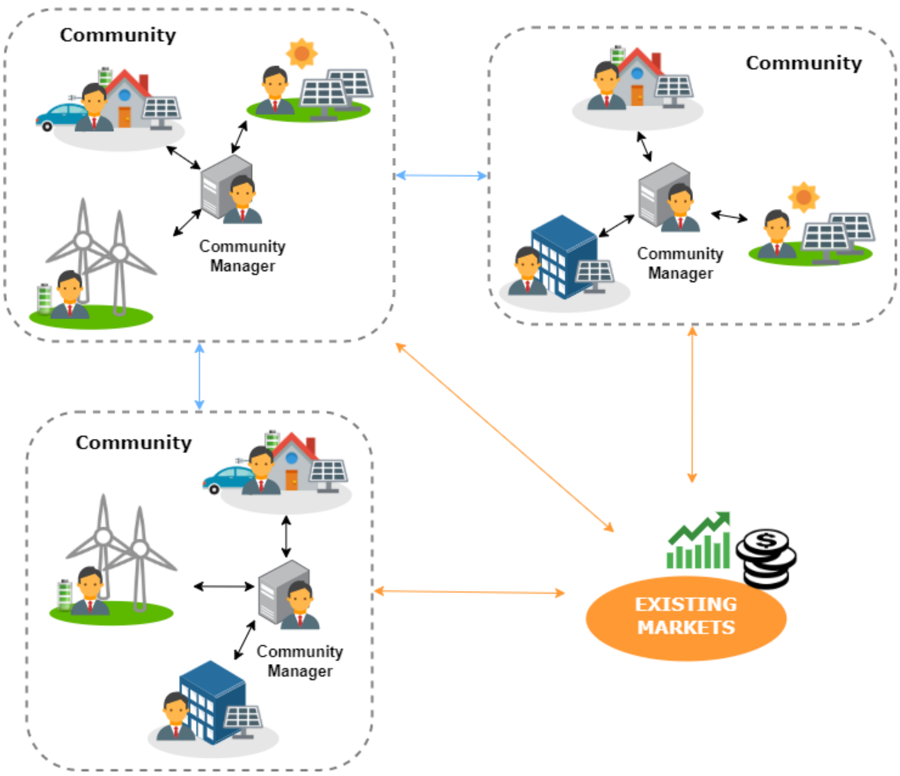

Figure 2.2: Community-based market design (adapted from [18]).

In community-based markets, there is a non-profit central node, known as community manager, responsible for managing the remaining agents. Its purpose is to ensure an optimal use of resources, therefore, it supervises the negotiation process and the trade between the community and the rest of the system [21]. It is an effective way of creating an internal electricity market for microgrids while it simplifies market regulation.

This type of structure is based on the idea of gathering members that share the same goal, such as members that support local renewable energy production, even if they do not live in the same location. It can also be applied to groups of neighbours or residents of a building. Despite the existence of a supervisory node, all prosumers are responsible for their own assets and only share the required information with the community manager.

In [22], a community negotiation process based on distributed optimization concepts is simulated and the impact of the central node on prosumers' behaviour is evaluated through fairness indicators. The mathematical formulation of a community-based market can also be found there.

2.2.3 Hybrid P2P market

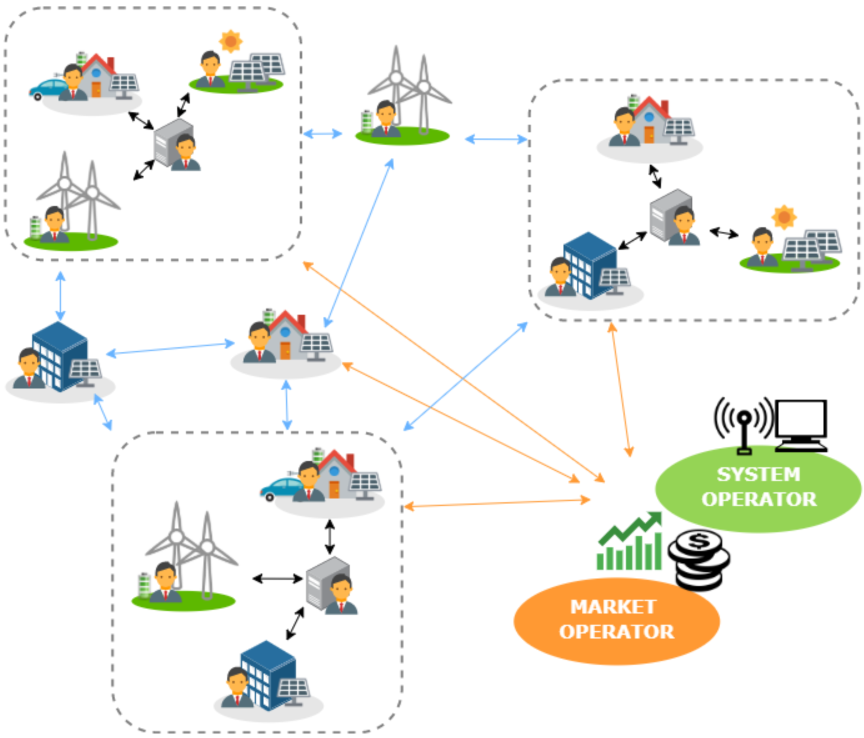

Figure 2.3: Hybrid P2P market design (adapted from [18]).

The hybrid P2P model is the combination of the full P2P design with the community-based design, resulting in multiple layers for trading energy. Thus, this model brings benefits in terms of scalability compared to community-based markets, as the total number of participants can be divided into several communities. This means that the communication and computational costs are reduced with the decrease of number of participants in the market. Since the two previous markets can co-exist and interact in the hybrid structure, a lower and upper level are considered and the coordination of trades at and between them is crucial. In this way, and according to [23]:

- At the lower level, there is a community-based market where peers can trade within the community;
- At the upper lever, the communities can trade with each other.

Regarding the mathematical formulation of the hybrid market design, there is not a generic one, but an oversimplified version can be written combining the two previous formulations.

In [23], a hybrid system is proposed where prosumers can participate in different markets simultaneously, as opposed to a sequential participation. Network utilization charge is used to control network constraints.

In [24], the authors proposed a blockchain-based system with three smart contracts being designed in order to implement a hybrid P2P market. These smart contracts contain all the necessary rules for energy trading, increasing the efficiency of the hybrid energy trading market.

2.3 Link between P2P market and electrical network

When it comes to implementing the P2P electricity market, it is necessary to ensure that the energy exchanges respect network constraints. While being connected to the distribution network, participants in P2P markets are limited by these technical constraints and, if not taken into consideration, this may compromise the system operation. In fact, congestion, power losses and voltage issues represent external costs that can be included in the trading process [25]. For example, Guerrero *et al.* proposed a methodology based on sensitivity analysis to evaluate the impact of the transactions on the network and to internalize the grid constraints into the P2P market model [26]. Considering the existing market design, a more flexible alternative is presented in [27], named 'coordinated multilateral trading'. In this model, the agents agree in a bilateral trading and then submit it to the system operator which accepts or curtails it whether the network constraints are respected or not. Then, the system operator publishes information regarding the network state and guides the participants to avoid future congested lines, aiming to ensure the system security without intervening in any economic decision. In [28], the authors proposed a methodology to coordinate P2P markets and the distribution system operator (DSO), by implementing a grid tariff based on the euclidean distance between prosumers. After performing the P2P market, the results are validated though an AC-PF. This methodology is also compared to a benchmark method that presents the structure of a P2P market without the inclusion of grid characteristics.

Centrally computed algorithms have been applied in order to optimize and control power systems. However, with the increasing penetration of DER, distributed algorithms have emerged has an advantageous alternative. Since the OPF optimization problem is non-convex, it can be difficult to solve it directly, therefore, linear approximations and convex relaxations are used in the algorithms. The DC power flow model is often used as a linear approximation based on several assumptions like the reactive power flow being neglected. Alternatively, the convex relaxation approach is used to make the problem convex. One of its main advantages is the ability to certify a solution as being globally optimal, as the solution from the original non-convex OPF problem can be recovered if the optimal solution of the relaxation satisfies some condition that can be easily inspected [29].

Second-order cone programming relaxation technique (SOCP) is one of the most efficient relaxation methods used to convex the nonlinear non-convex AC-OPF. In this context, Liu *et al.* proposed an optimization problem to minimize energy costs and power losses while incorporating grid constraints, using SOCP relaxation to solve the problem as the non-convex constraints made it hard to solve directly [30]. Moreover, different optimization methods based on augmented Lagrangian decomposition can be applied to solve the convex relaxation problems, such as Dual Decomposition, Auxiliary Problem Principle, Primal-Dual Decomposition and Alternating Direction Method of Multipliers (ADMM). The ADMM is one of the most well-known algorithms for implementing distributed optimization, and the most used in literature for P2P application. Although these methods share a similar concept, they are different in terms of theory and practical performance.

In [31], the authors present the general concept of some decomposition coordination methods that can be used for distributed OPF, including the Auxiliary Problem Principle. The main difference between this technique and the ADMM method is that "the cross-terms in the two-norm expression employed in the augmented Lagrangian are linearized rather than modeled directly" [29] so this decomposes the subproblems of the optimization problem without the need of a central coordinator. Regarding ADMM, it resulted from the combination of Dual Decomposition and the Method of Multipliers for solving augmented Lagrangian problems. The authors in [32] proposed a new auxiliary variable-based ADMM for non-convex AC-OPF that researchers could see as an option for P2P markets. It improves convergence with less iterations in comparison to the existing methods. Morstyn *et al.* proposed a P2P energy market platform based on the concept of multi-class energy management, using ADMM for market clearing and the community manager as supervisor [33]. Since the use of a coordinator means that the optimization method is not fully decentralised, the authors in [34] proposed a primal-dual gradient method that does not require a supervisor. Furthermore, the proposed algorithm uses first-order method, whereas the conventional primal-dual gradient algorithms use the interior-point method to solve sub-problems. This way, it is possible to reduce computation per iteration time.

Despite the different existing techniques to handle the electrical network within P2P electricity markets, there is still a long way to go to get a methodology that can both ensure solution accuracy and scalability. In this context, many researchers are looking for the optimal technique that can guarantee a good range in the solution accuracy, fairness in the energy exchanges, and scalability of the model. This dissertation puts effort into designing a P2P electricity market ensuring power flow accuracy.

Chapter 3

Coordination of P2P Market and Electrical Network

In this chapter, two distinct models for the coordination of P2P markets with the electrical network have been implemented. One approach relies on the design of a P2P market which integrates network constraints in the form of an AC-OPF. The main goal of this approach is to include network constraints together with the P2P market, having the problem modeled and solved in a centralized fashion. This model is compared to an alternative and iterative approach proposed and discussed in [8]. The iterative market approach is a decentralized P2P market that is iteratively updated, taking into account potential network violations. It uses product differentiation to modify agents' behaviour so that the network limits are respected.

Moreover, this chapter provides all the insights of each model, including details of the complete mathematical formulation for both models.

3.1 P2P market with centralized AC-OPF (P2P AC-OPF)

The proposed model is designed as an optimization problem consisting of a P2P market structure modeled and solved in a centralized manner, allowing energy exchanges between peers while considering network constraints. It maximizes the social welfare (SW), so it determines the cheapest solution to cover the electricity demand while it guarantees that all the transactions are executed without compromising the system. Therefore, it combines the share of energy between producers and consumers with technical limitations by implementing an AC-OPF within the P2P market model. The AC-OPF determines the optimal power output in order to meet the demand supplied throughout the distribution network. It should be noted that if no proper tools are used to make the P2P market respect network limits, then the only solution is to resort to load-shedding, otherwise, this can lead to frequent congestion and voltage problems.

Figure 3.1 represents the flowchart of the proposed model. The input data is given by players' bids and network data. Players' bids include consumers' demand, producers' supply and loads' flexibility, whereas network data represents the characteristics of the network regarding lines, buses, consumers' and producers' electrical location. This information is then used for the optimization process where the P2P AC-OPF model is performed. The result is a set of multi-bilateral power trades along with their clearing prices, for each hour. The objective function is characterised by a quadratic function that can either reflect the cost of producing a certain amount of power or the price that a load is willing to pay to cover its demand. Since the problem formulation already includes network constraints, such as voltage and branch limits, it will only converge if all energy exchanges respect those limits. If it is feasible, then the line loading values will be necessarily below the line loading limit and the buses voltage will be within voltage limits.

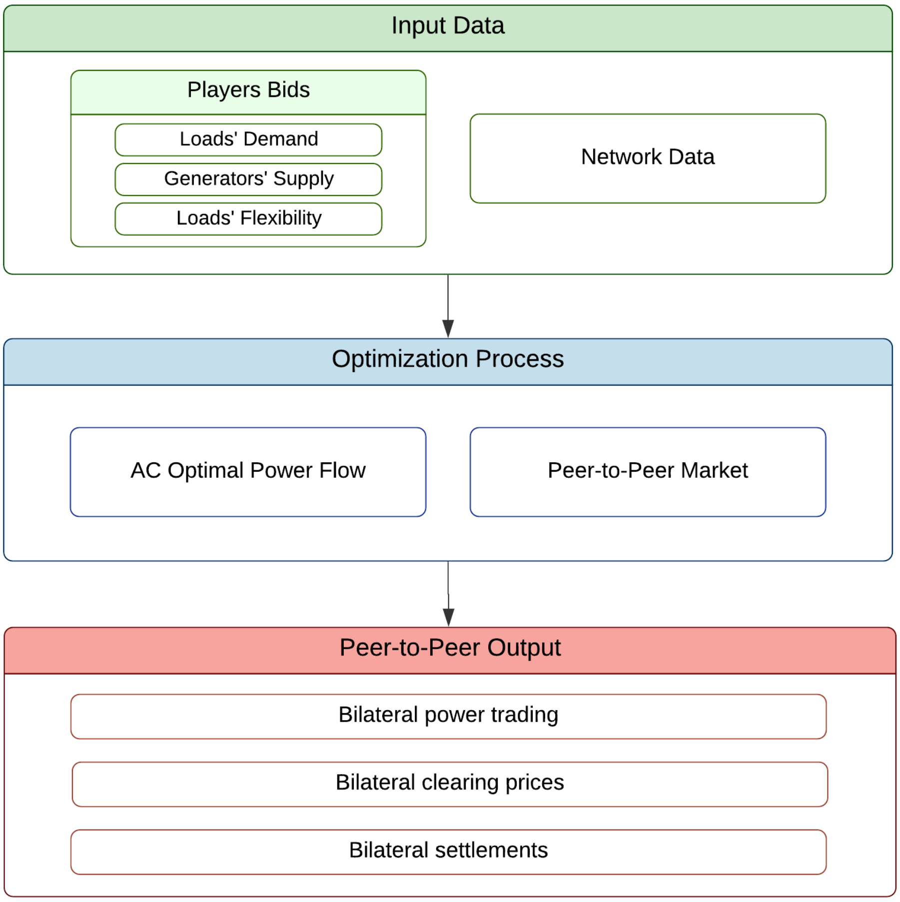

Figure 3.1: Flowchart of the P2P AC-OPF model.

3.1.1 Mathematical Formulation

The optimization problem of the P2P AC-OPF model can be formulated as:

$$\min_{D} \quad \sum_{n \in \Omega} C_n \left(\sum_{m \in \omega_n} P_{nm} \right) \tag{3.1}$$

$$\text{s.t.} \quad \underline{P_n} \leq \sum_{m \in \omega_n} P_{nm} \leq \overline{P_n} \qquad \forall n \in \Omega \tag{3.2}$$

$$P_{nm} + P_{mn} = 0 \qquad \forall (n,m) \in (\Omega, \omega_n) \tag{3.3}$$

$$P_{nm} \geq 0 \qquad \forall (n,m) \in (\Omega_p, \omega_n) \tag{3.4}$$

$$P_{nm} \leq 0 \qquad \forall (n,m) \in (\Omega_c, \omega_n) \tag{3.5}$$

$$\sum_{n \in \Omega_p} P_n^i + \sum_{n \in \Omega_c} P_n^i = G_{ii} V_i^2 + V_i^2 + V_i \times \sum_{j \in L^i} V_j \times (G_{ij} cos\theta_{ij} + B_{ij} sin\theta_{ij}) \\ \forall (i,j) \in \{1, ..., N_B\}, \qquad \theta_{ij} = \theta_i - \theta_j \tag{3.6}$$

$$\sum_{n \in \Omega_p} Q_n^i + \sum_{n \in \Omega_c} Q_n^i = V_i \times \sum_{j \in L^i} V_j \times (G_{ij} sin\theta_{ij} - B_{ij} cos\theta_{ij}) - B_{ii} \times V_i^2 \\ \forall (i,j) \in \{1, ..., N_B\}, \qquad \theta_{ij} = \theta_i - \theta_j \tag{3.7}$$

$$\underline{V^i} \leq V^i \leq \overline{V^i} \qquad \forall (i,j) \in \{1, ..., N_B\} \tag{3.8}$$

$$(G_{ij} \times V_i \times V_j \times cos\theta_{ij} + B_{ij} \times V_i \times V_j \times sin\theta_{ij} - G_{ij} \times V_i^2)^2 \\ + (G_{ij} \times V_i \times V_j \times sin\theta_{ij} - B_{ij} \times V_i \times V_j \times cos\theta_{ij} + B_{ij} \times V_i^2)^2 \leq {S_{Branch(i,j)}^{max}}^2 \\ \forall (i,j) \in \{1, ..., N_B\}, i \neq j \qquad \theta_{ij} = \theta_i - \theta_j \tag{3.9}$$

$$\underline{Q_n} \leq Q_n \leq \overline{Q_n} \qquad \forall n \in \Omega_p \tag{3.10}$$

$$\overline{Q_n} = 0.4 \times P_n \qquad \forall n \in \Omega_p \tag{3.11}$$

$$Q_n = tg\phi \times P_n \qquad \forall n \in \Omega_c \tag{3.12}$$

As previously mentioned, the objective function 3.1 is minimized to give the lowest cost of production, being equivalent to the maximization of the social welfare in the market. The cost function for all peers (producers and consumers) is assumed to follow a quadratic function, as implemented in [35]:

$$C_n(P_n) = \frac{1}{2} a_n P_n^2 + b_n P_n + d_n \tag{3.13}$$

where a_n, b_n, $d_n \geq 0$ and P_n is positive if the power is produced by generators and injected into the grid, or negative if it is consumed by loads. The constant d_n is assumed to be zero for producers and consumers, i.e., startup costs are disregarded.

The objective function is subjected to a set of constraints. Constraint 3.2 shows that the total power traded by each peer is restricted by the lower and upper bound, which are positive for producers and negative for consumers. In 3.3, it is defined the reciprocity property of bilateral trades, meaning that P_{nm} and P_{mn} must have the same value with opposite signs or, in other words, the power that goes from peer m to peer n must correspond to the power, with negative sign, received by peer n from peer m. Regarding constraints 3.4 and 3.5, they are necessary to ensure that producers only sell electricity and producers only buy it. Equations 3.6 and 3.7 represent the active and reactive power balance, respectively, for each bus in the network. Moreover, the voltage constraint 3.8 defines the limits for the voltage magnitude, while 3.9 represents the thermal line constraint. Finally, reactive power limits for producers and consumers are included in 3.10, 3.11 and 3.12.

3.1.2 Optimization Process

The P2P AC-OPF model has been formulated in Python, using Pyomo [1] as an optimization modeling tool. It allows the user to describe the problem in a similar way to the notation used in mathematical formulations and it supports many different solvers, such as IPOPT (Interior Point Optimizer) [2] which is used, in this case, to minimize the objective function, considering all constraints. IPOPT is an open source Nonlinear Programming (NLP) solver that implements an interior-point line-search filter method, so it can solve large problems efficiently [36].

3.1.3 Revenue and cost calculation

From the dual variable $\lambda_{n,m}$ of constraint 3.3, it is possible to obtain the bilateral contract prices for each hour. There is a total cost (TC) paid by each consumer and the total revenue (TR) gained by each producer, which are calculated using the following equations, respectively:

$$TC = -\left(\sum_{m \in \omega_n} \lambda_{n,m} P_{nm} \right) \tag{3.14}$$

$$TR = \sum_{m \in \omega_n} \lambda_{n,m} P_{nm} \tag{3.15}$$

Since $P_{nm} < 0$ for loads, equation 3.14 must take a negative sign. Moreover, the cost for covering power losses is included in the cost calculation.

3.2 Iterative Process for P2P market with Product Differentiation (P2P Prod. Diff.)

The second model consists of an iterative P2P market, considering peers preferences through product differentiation. The P2P market model is solved and the solutions are technically validated through an AC-PF. All the process is performed iteratively until a market solution that does not violate the network constraints is found. In each iteration, product differentiation is used and the euclidean distance between buses is applied as the criterion to penalize the exchanges that create congestion or voltage problems. The main purpose of product differentiation is to reduce grid usage in congested branches of the grid, enabling market solutions to be technically feasible. Moreover, it aims to evaluate peers' behaviour on the market, more precisely the consumers' choices, as this criterion penalizes trades between peers that are far away from each other and it

[1] http://www.pyomo.org/
[2] https://github.com/coin-or/Ipopt

is only applied to loads. Therefore, the participants are entrusted with the responsibility of their bilateral trades on the network. It should be noted that the bilateral trade prices given by the dual variable $\lambda_{n,m}$ from constraint 3.3 may be different after product differentiation is implemented. Contrary to the pure P2P market without product differentiation, there is not a global clearing market price.

The objective function is similar to the one presented in the previous model but includes now an additional component besides the quadratic cost function 3.1. It can be represented by the following equation:

$$C_n(P_n) = \left(\frac{1}{2}a_n P_n^2 + b_n P_n + d_n\right) + \sum_{g\in G}\sum_{m\in\omega_n}(c_n^g \gamma_{n,m}^g P_{n,m}) \tag{3.16}$$

where c_n is the trade coefficient, which represents the preference value given by a peer n to a certain criterion, whereas the matrix $\gamma_{n,m}$ is the trade characteristic and it corresponds to the euclidean distances between the buses measured in km. A more detailed description of this model and its mathematical formulation can be found in [8].

Figure 3.2 shows the schematic representation of the P2P Prod. Diff. model. The input data comprehends players bids and the initial values of the trade coefficient c_n and trade characteristic $\gamma_{n,m}$. After the first P2P market is cleared, which does not include product differentiation as $\gamma_{n,m} = 0$, the results are used as input to the AC-PF validation that determines the feasibility of the P2P market taking into account the network constraints. If those limits are respected and there is no network congestion, the market is cleared and the iterative process ends. Otherwise, both the trade coefficient and the trade characteristic are updated and the P2P market is cleared again followed by the AC-PF validation. This process is performed iteratively until the market solution is technically feasible.

3.2.1 Optimization process

To achieve the AC-PF for the grid operation feasibility, a Python based tool is used, named pandapower [37], which uses an element-based model (EBM) to define the electric grid. The optimization of the P2P Prod. Diff. model is simulated with the Gurobi Python interface [38].

3.2.2 Revenue and cost calculation

In this model, there is not a single market clearing price. As previously mentioned, the bilateral contract prices are determined by the dual variable $\lambda_{n,m}$ and the marginal prices of $\lambda_{n,m}$ differ from each other due to the implementation of product differentiation. Those prices include marginal costs as well as product differentiation costs that represent the network fees paid to the DSO for each transaction and reflect the euclidean distance between the peers. Thus, the total cost paid by each consumer (TC) and the total revenue obtained by each generator (TR) are calculated as follow:

$$TC = -\left(\sum_{m\in\omega_n}\lambda_{n,m}P_{n,m}\right) \tag{3.17}$$

$$TR = \sum_{m \in \omega_n} \lambda_{n,m} P_{n,m} - \sum_{m \in \omega_n} c_n \gamma_{n,m} P_{n,m} \tag{3.18}$$

In equation 3.17, the total cost has a negative sign because $P_{n,m} < 0$ for loads. Regarding equation 3.18, the second part of it represents the product differentiation cost paid to the DSO, so it is subtracted from the revenue obtained by generators. It should be noted that power losses are also considered in the cost calculation [8].

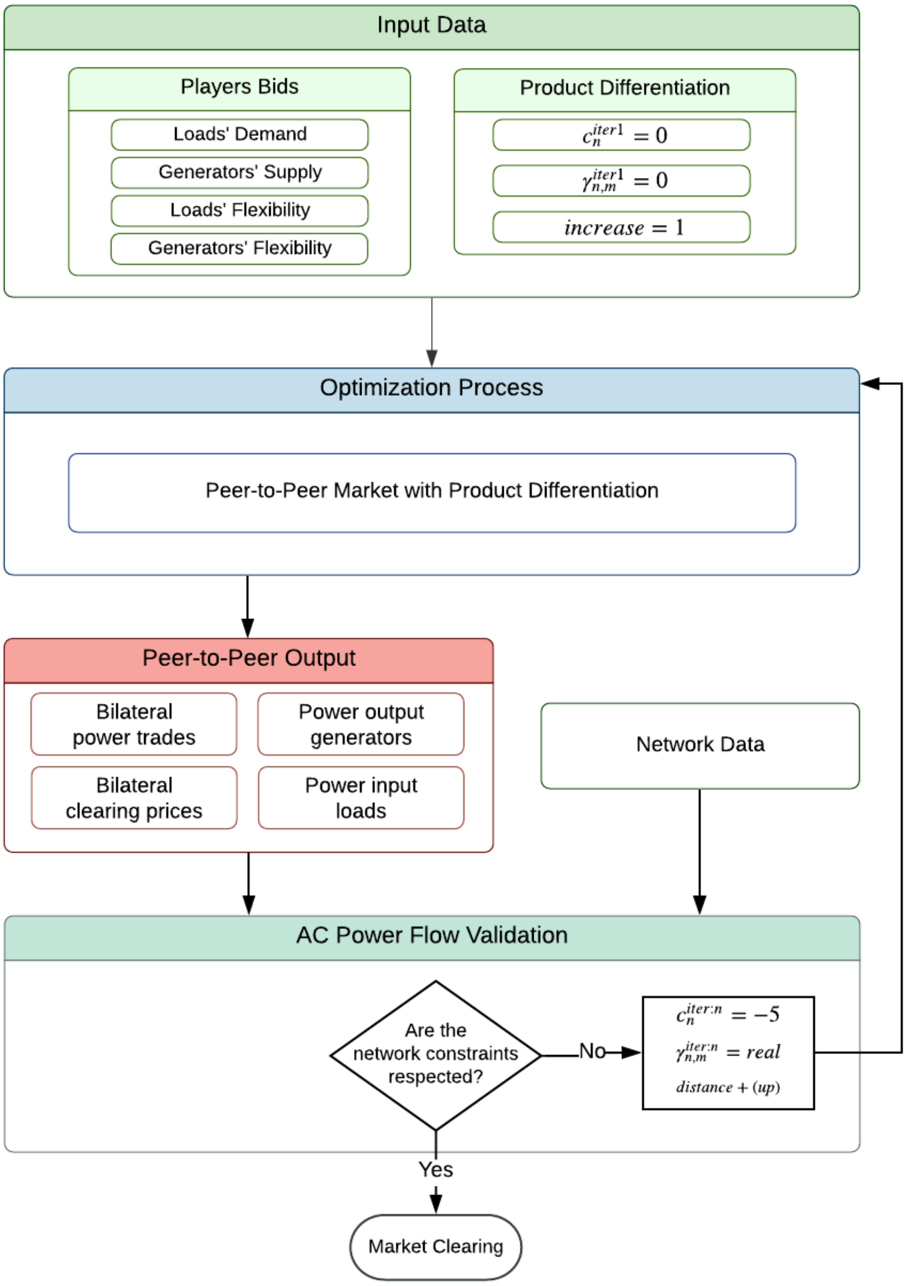

Figure 3.2: Flowchart of the P2P Prod. Diff. model (adapted from [8]).

Chapter 4

Case Study

In this chapter, the case study is presented along with all the data used to test the proposed model. Both models, described in the previous section, are validated based on a typical distribution network with high RES penetration. The results are discussed and compared for different levels of demand flexibility and network capacity. The goal is to analyse the models' behaviour using different criteria and to compare, in particular, the influence on grid usage and line loading congestion.

4.1 Network Description

In this section, the test case used to validate the models is presented. Since the purpose of the study is to compare the developed model (P2P AC-OPF) with the second model (P2P Prod. Diff.), the network is the same used in [8]. It consists of a radial distribution network at the medium voltage (MV) level with a 11 kV bus voltage, as depicted in Figure 4.1. There are 22 flexible loads and 27 flexible DER throughout the network which is composed of 37 buses. Branch data is displayed in Table A.3 in the appendix.

For each bus, there can be more than one consumer grouped in one agent, therefore, the network is considered to have 1908 single consumers distributed in 1850 households, 50 commercial stores, 6 service buildings and 2 industries.

Regarding the generators, they can be divided according to their type:

- 3 conventional units: combined heat and power plants (CHP)
- 2 wind farms
- 22 solar photovoltaic systems (PV)

The network is connected to an upstream network at bus 0, which allows to import and export energy from the main network. The agent representing the energy that flows from the the main grid to the distribution network is called external supplier. It is assumed that the external supplier simultaneously negotiates in the P2P market and in the spot market. Therefore, the price for imports depends on the spot price.

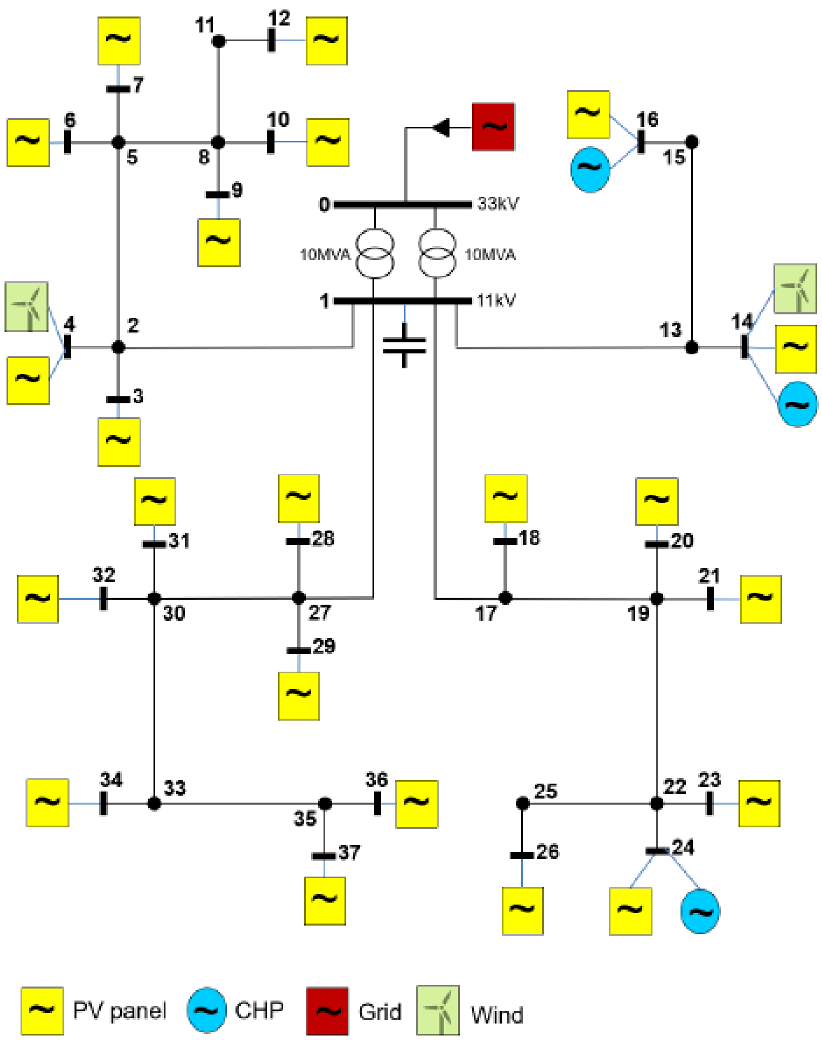

Figure 4.1: 37-bus radial distribution network (reproduced with authorization from [8]).

4.1.1 Production

As previously mentioned, there are 27 generators distributed throughout the network. The values concerning renewable generators are presented in Tables A.4 and A.5, in the appendix, and correspond to the same forecast values used in [8]. However, in order to have the demand fully covered by renewable generation, during day-time, and to ensure that loads' flexibility affect the P2P market clearing, those values were adjusted. For wind generators, they were increased by 3 times, whereas for PV generators they were increased by 4 times.

The limits for the active power generation are the following:

$$0 \leq P_{out} \leq P_{max} \tag{4.1}$$

Regarding reactive power limits, they were set according to the generators' type:

$$0 \leq Q_{out} \leq P_{max} \times tan(\phi) \tag{4.2}$$

where $tan(\phi) = 0.4$ for renewable generators and $tan(\phi) = 0.3$ for CHP units.

To model generators' cost curve, the marginal curve is usually used to determine it, representing the incremental cost for producing an additional megawatt-hour of electrical energy. However, in this case, the cost curve of the external supplier is modelled considering that the import price from the grid is constant regardless the amount of electricity injected in the network, so coefficient a_n of the quadratic function 3.13 is null. The price to purchase electricity from the grid is equal to the average price of the Iberian electricity market at the time of the work developed in [8] (40€/MWh) plus a grid tariff of 18€/MWh, therefore, coefficient b_n is set to 58€/MWh for the external supplier. Furthermore, the cost curve of CHP is set according to [8] and it results in a convex parabola. All values can be found in Table A.6, in the Appendix.

Regarding renewable generators, their cost curve is nearly zero since the marginal cost is null, which means that a_n is equal to zero. In this case, coefficient b_n is the same to all renewable units so there is no difference in the price to purchase electricity by the consumers in the P2P AC-OPF model. The value of b_n is defined as 4€/MWh in order to avoid the hours when PV production reaches its maximum and the electricity price would be zero.

It should be noted that the goal is to give priority to DER and the resulting price of the P2P market follows the merit order, so renewable generators are the first to enter in the market, followed by CHP units and then the external grid, which is used as last resort to cover the demand.

4.1.2 Consumption

The 22 existing loads in the network have their flexibility set on 30% of their base load, for the upward and downward direction. Therefore, for each hour, the total consumption is between the minimum and the maximum load considering the generation mix available at that same hour. This is important because it helps to balance the network and clear the market, while it allows the consumers to react to changes in prices according to the generation mix. Thus, the active power limits are the following:

$$0.7 \times P_{base} \leq P_{out} \leq 1.3 \times P_{base} \tag{4.3}$$

where P_{base} corresponds to the base load power of each consumer. A representation of the electricity demand and flexibility can be found in Figure 4.2.

The reactive power consumption depends on the active power consumption obtained from the market clearing and is determined by the following equation:

$$Q_{out} = P_{out} \times tan(\phi) \tag{4.4}$$

where $tan(\phi) = 0.3$, according to [8].

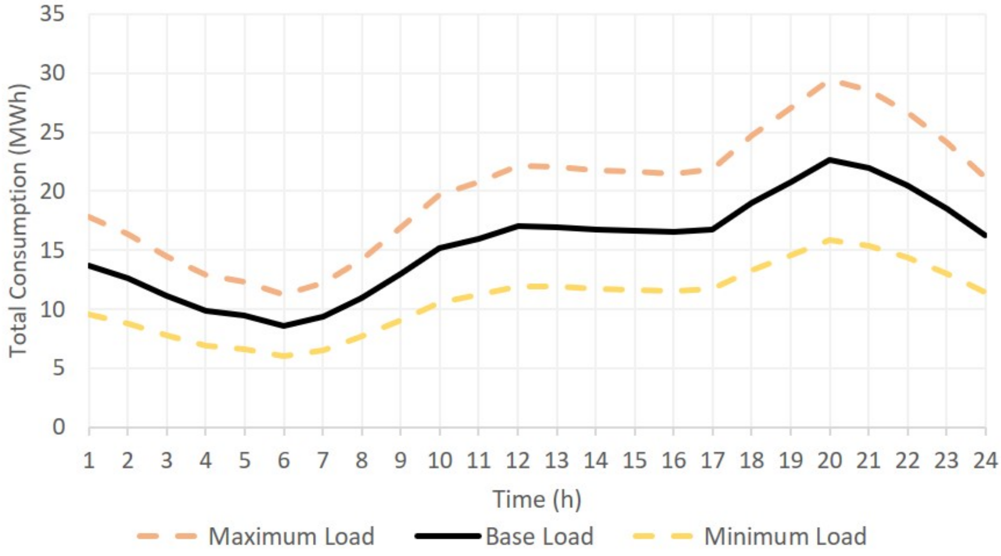

Figure 4.2: Total electricity demand and flexibility.

With regard to loads' cost curve, it represents the amount that consumers are willing to pay for the electricity. It is obtained from the marginal utility function, which consists of an affine function, as shown in Figure 4.3.

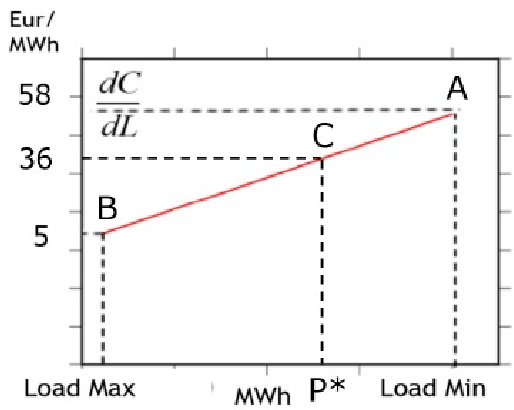

Figure 4.3: Marginal utility function (reproduced with authorization from [8]).

Point A corresponds to the minimum load so consumers are willing to pay the highest price to cover the demand, whereas point B represents the case where the load is maximum and consumers are willing to pay the cheapest price.

4.2 Results

4.2.1 Base Case

In this section, both models are tested and validated for one day simulation, considering that the maximum current in all lines is equal to 245 A. The first part focuses on the P2P market clearing, while the following sections assess the power losses and the social welfare outcomes.

4.2.1.1 P2P market clearing

As Figure 4.4 shows, the generation mix determined by the P2P market clearing depends on the time of the day. During the day, from 09:00 until 16:00, there is only renewable production (wind and PV), whereas from 1:00 until 04:00 and from 18:00 until 24:00 the external supplier (representing the energy flowing from the upstream network) is needed to meet the demand as the PV production is null. It should be noted that the results for the P2P AC-OPF model are the same as the ones obtained for the P2P Prod. Diff. model, as the loading values of all lines are very reduced for both models. This means that the grid can handle any transaction and there is no congested lines or voltage problems.

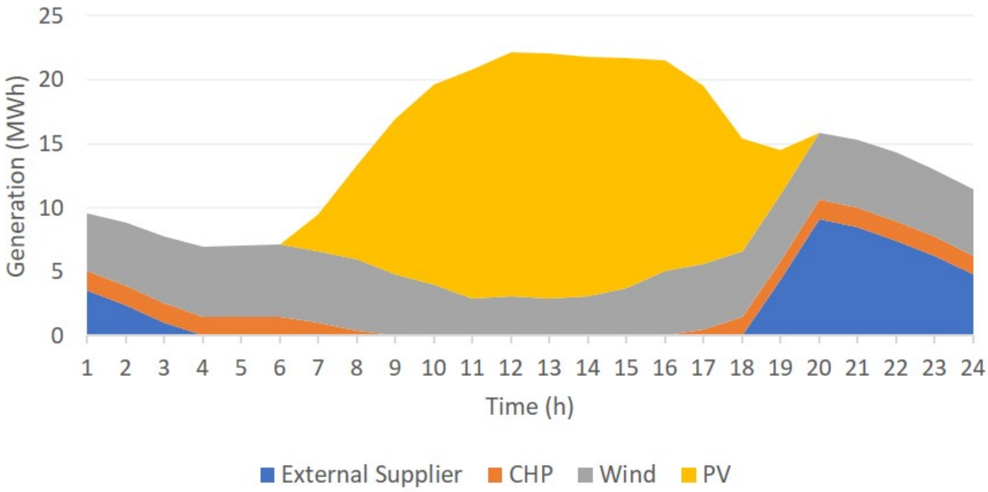

Figure 4.4: Production results for P2P AC-OPF model.

The total production for the 24 hour period, in both models, is about 256.52 MW and the results by type of generator are very similar as expected, with just some minor differences as shown in Table 4.1.

Table 4.1: Comparison of total production by type of generator.

	P2P AC-OPF	**P2P Prod Diff**
External Supplier (MW)	47.46	47.47
CHP (MW)	21.39	21.39
Wind (MW)	114.17	121.67
PV (MW)	173.50	166.00

Considering that the electricity price is established according to the type of production, the results of the total consumption vary between the minimum and maximum load. As Figure 4.5 shows, when there is electricity being imported from the external supplier, the price is equal to the wholesale market price (58€/MWh) so the consumers are willing to pay that price only to cover their minimum load. On the contrary, during the time when there is only renewable generation, the electricity price is equal to 4€/MWh, therefore, consumption is set to its maximum. Regarding the hours when CHP is dispatched and the external supplier is not used, the price corresponds to the value of the dual variable of constraint 3.3. Again, these results were the same for the P2P Prod. Diff. model.

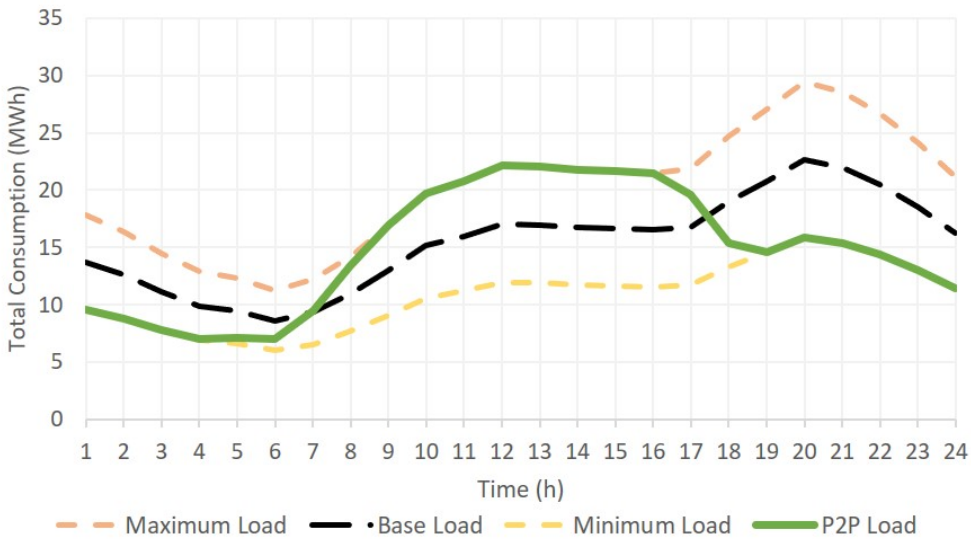

Figure 4.5: Consumption results for P2P AC-OPF model.

4.2.1.2 Power Losses

Regarding power losses, Figure 4.6 represents the total losses for a 24-hour period, distributed by lines, which are the same for both models. Although the lines have low loading values and are not congested, the figure shows that some of them have higher power losses than others.

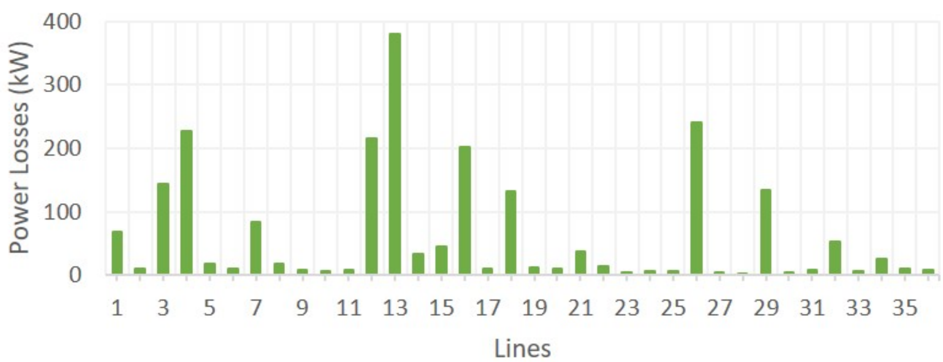

Figure 4.6: Total power losses for 24-hour period.

For instance, by looking at Figure 4.7 it is possible to conclude that lines 12 and 13 present higher values of power losses because bus 14 and bus 16 have five generators in total and each bus has only one load. Consequently, there is an excess of power production that flows through line 12 to meet the demand in other regions of the network, so the line becomes more congested and the power losses are higher.

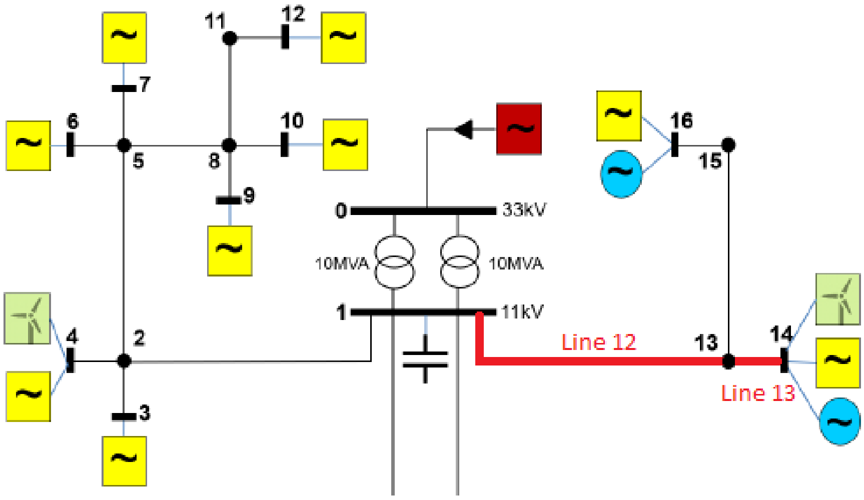

Figure 4.7: Highlight of lines 12 and 13 of the distribution network.

4.2.1.3 Social Welfare (SW)

As previously said, since the maximum current is 245 A, the grid can operate with all kinds of transactions so both models maximize the SW and the results are the same. For a 24-hour period, the result of the social welfare is 21963.48 €. There is no difference between producing more wind power or PV power because the price is the same, but if the lines are more congested or if there are voltage problems, some differences will arise between the two models.

4.3 Models' behavior under congested network

Knowing that both models behave very similarly when there are no congestion problems in the network, it is important to assess their behavior when the network has a higher probability of being congested. To this end, the models are compared considering that the maximum current in all lines is about 81.7 A (three times lower than in the base case), so they will be naturally more congested and the models' results will be different. Since the penetration level of RES is higher for hour 12:00, the results are analysed paying special attention to this hour and the peers' data can be found in Tables A.1 and A.2 in the appendix. In addition, the competition between peers and the high flexibility of loads at this hour, makes the comparison between the two models more reliable. Thus, different levels of demand flexibility are addressed in this study.

4.3.1 Loads' Flexibility of 1%

Since loads' flexibility is used as a parameter, this analysis starts by assuming a 1% flexibility.

4.3.1.1 Line Loading

Considering that loads' flexibility is almost non-existent, the P2P Prod. Diff. model stops by the first iteration, so the network limits are respected but the coefficient value of $c_n = -5€/(km \times MWh)$ is not applied to loads.

Figure 4.8 shows the line loading results for both models. As previously stated, the integration of a centralized AC-OPF guarantees that the line loading limits are respected if the problem is feasible. For the P2P Prod. Diff model, the lack of a second iteration means that buses are not completely balanced, so its overall probability of congestion is not that far from the one of the P2P AC-OPF model. However, P2P Prod. Diff. model still presents lower values in some lines and, as it will be further observed, this difference is more evident for higher values of loads' flexibility.

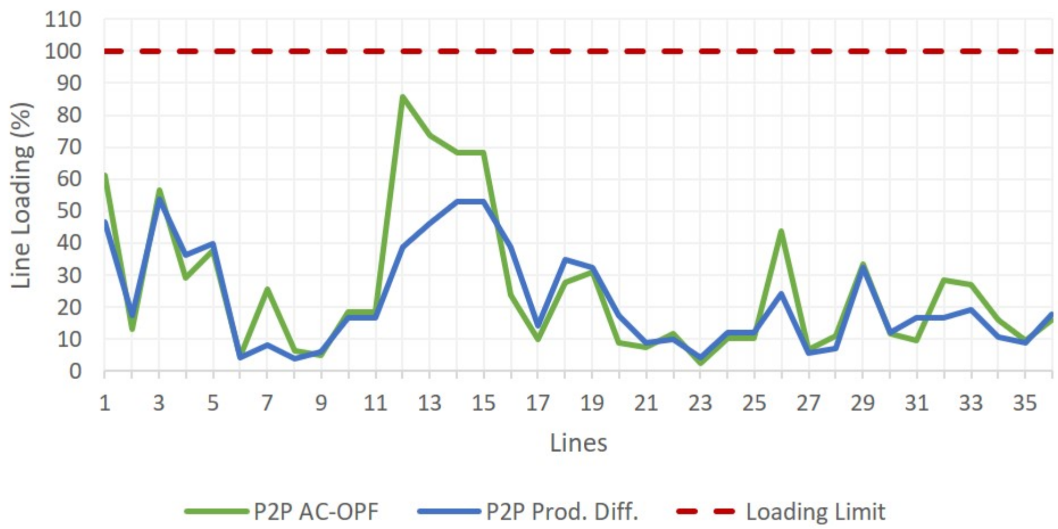

Figure 4.8: Line loading results at 12:00, considering loads' flexibility of 1%.

Regarding the values of the total generation and consumption for hour 12:00, as Table 4.2 shows, the results are similar because, without loads' flexibility, none of the models have network fees, allowing the peers to make bilateral agreements without taking into account the distance between them. The difference is that the P2P Prod. Diff. model does not have the AC-PF validation integrated in the market.

Table 4.2: Power generation and consumption at 12:00, considering loads' flexbility of 1%.

	P2P AC-OPF	**P2P Prod. Diff.**
External Supplier (kWh)	0	0
CHP (kWh)	0	0
Wind (kWh)	1693.26	2006.71
PV (kWh)	15502.85	15189.41
Consumption (kWh)	17196.12	17196.11

4.3.1.2 Power Losses

In both models, power losses are included in the market and consumers pay an amount to cover them, which is proportional to their power demand at the wholesale market price (58€/MWh). This cost is added to the total cost for purchasing electricity from the P2P day-ahead market.

Considering the previous results of line loading, it is expected to obtain the same behaviour in terms of power losses. Indeed, Table 4.3 shows that active power losses of the P2P AC-OPF model are higher than in the P2P Prod. Diff. model and correspond to 0.088% of the total production, having a cost of 1.13 €. Meanwhile, the P2P Prod. Diff model presents power losses of about 0.059% of the total power produced in the network and their cost is 0.72 €.

Table 4.3: Power losses and cost at 12:00, considering loads' flexbility of 1%.

	P2P AC-OPF	**P2P Prod. Diff.**
Power Losses (kW)	19.55	12.44
Price (€)	1.13	0.72

4.3.1.3 Cost and Revenue

Regarding the total cost, revenue and social welfare, Table 4.4 shows that with no grid fees and a flexibility in consumption close to 0%, the results become the same in both models.

Table 4.4: Total cost, revenue and social welfare at 12:00, considering loads' flexbility of 1%.

	P2P AC-OPF	**P2P Prod. Diff.**
Cost (€)	68.79	68.78
Revenue (€)	68.79	68.78
Social Welfare (€)	23029.89	23029.89

It can also be used a fairness indicator, named Quality of Experience (QoE), to assess the consumers' satisfaction based on the perceived price of electricity:

$$QoE = 1 - \frac{\sigma}{\sigma_{max}} \tag{4.5}$$

where σ represents the standard deviation of the prices and σ_{max} is the maximum price deviation. For a 1% flexibility, both models have a QoE=1 as the marginal prices are equal for all loads.

In order to have a better understanding of the generators' revenue, the 37-bus network was divided into four areas, as it is shown in Figure 4.9. The average revenue, by area, is depicted in Figure 4.10 and it is possible to observe that Area B is the only one where the average revenue of P2P Prod. Diff. model is higher, most precisely 31.8% higher than the average revenue of the P2P AC-OPF model in that same area. This will be further analysed in section 4.3.2.3.

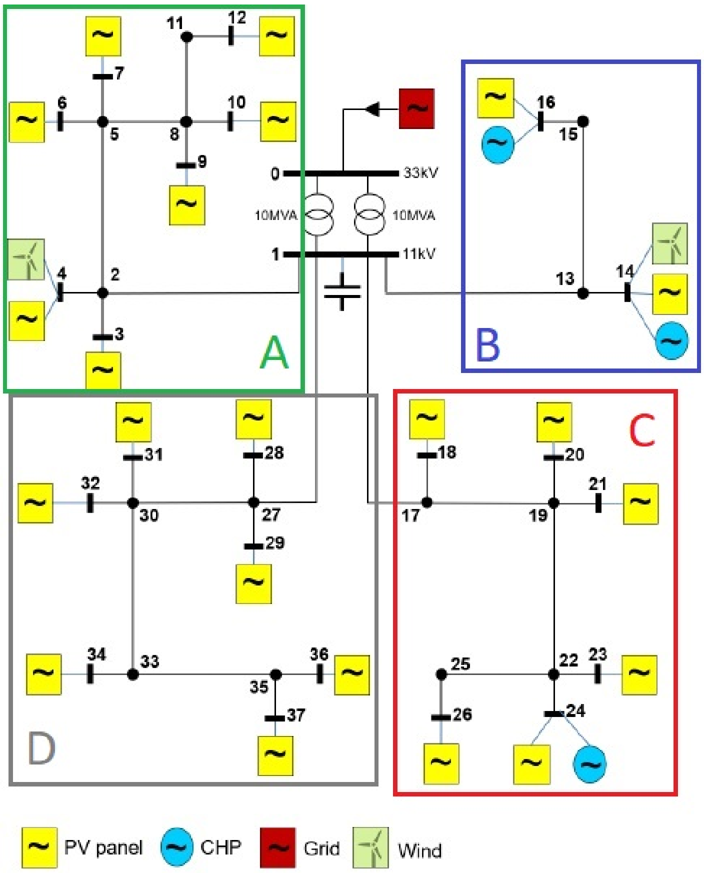

Figure 4.9: 37-bus radial distribution network divided into four areas.

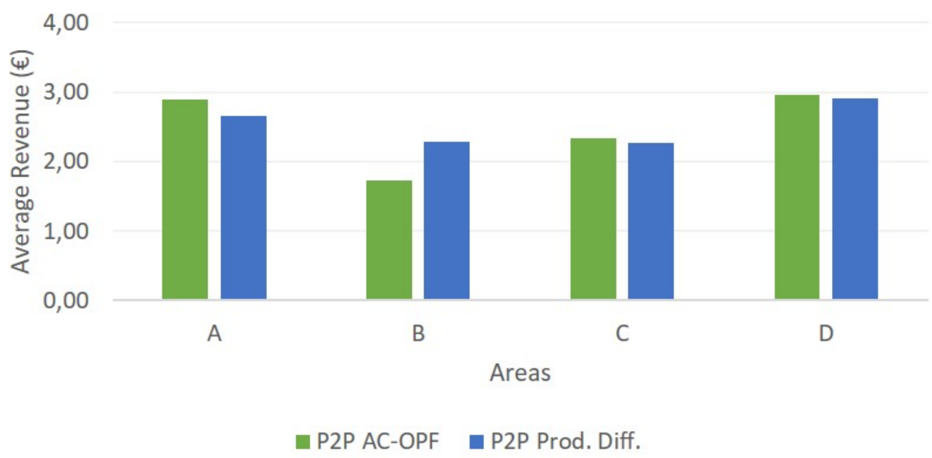

Figure 4.10: Generators' revenue at 12:00, by area, considering loads' flexibility of 1%.

4.3.2 Loads' Flexibility of 15%

In this section, loads' flexibility is increased to 15%, in order to explore the models' behaviour and compare it with the previous results.

4.3.2.1 Line Loading

Although the flexibility is higher than in the previous case, the P2P Prod. Diff. model is still solved in a single iteration. This means that the line limits are respected, as in the P2P AC-OPF model, but the line loading values are now getting closer to those limits. In fact, as Figure 4.11 shows, the line loading values of the P2P Prod. Diff. model in line 13 have almost doubled comparing to the previous case where loads' flexibility was about 1%. On the other hand, the results for the P2P AC-OPF model have barely increased. From this analysis, it is possible to conclude that with the increase of the flexibility, the lines become gradually more congested until it is necessary another iteration in the P2P Prod. Diff., while for the P2P AC-OPF the results do not suffer changes in such an evident way and are always kept under the limits.

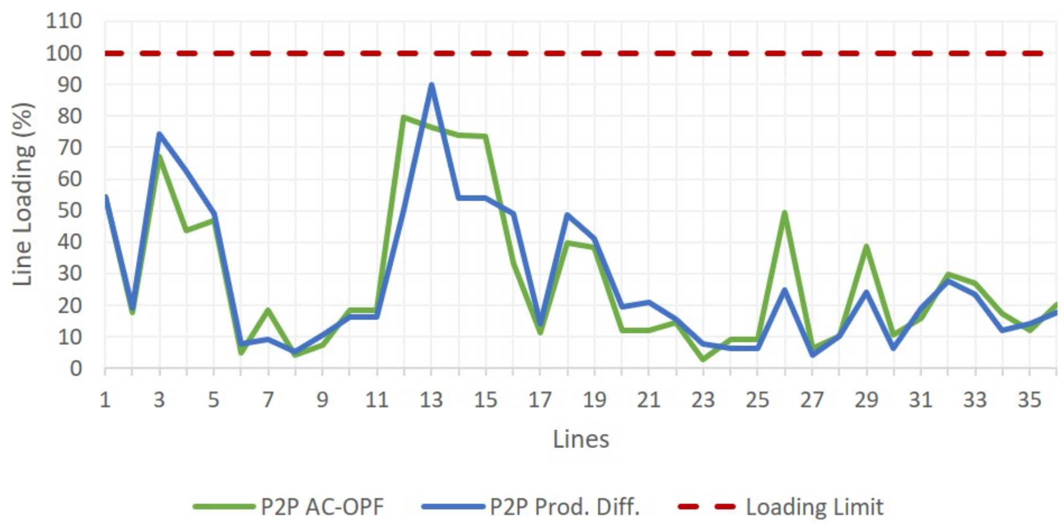

Figure 4.11: Line loading results at 12:00, considering loads' flexibility of 15%.

The results of the total production by type of generator and the total consumption for hour 12:00 are presented in 4.5. Comparing to the situation where loads' flexibility was equal to 1%, the total production increased by 13,86% as well as the total consumption, which implies that a higher flexibility reflects in more power flowing through the network.

Table 4.5: Power generation and consumption at 12:00, considering loads' flexibility of 15%.

	P2P OPF	**P2P Prod. Diff.**
External Supplier (kWh)	0	0
CHP (kWh)	0	0
Wind (kWh)	2133.91	3103.11
PV (kWh)	17445.83	16476.62
Consumption (kWh)	19579.74	19579.73

4.3.2.2 Power Losses

Regarding power losses, as Table 4.6 shows, the values increased in both models, as expected, and now the results for the P2P AC-OPF model are just slightly higher than in the P2P Prod. Diff. model. Moreover, active power losses of the P2P AC-OPF model represent now 0.12% of the total production, while for the P2P Prod. Diff. model they correspond to 0.11% of the total power produced in the network.

Table 4.6: Power losses and cost at 12:00, considering loads' flexibility of 15%.

	P2P OPF	**P2P Prod. Diff.**
Power Losses (kW)	22.88	21.19
Price (€)	1.32	1.23

4.3.2.3 Cost and revenue

The values of the total cost, generators' revenue and social welfare are displayed in Table 4.7. The two simulations present the same values and, with an increase of loads' flexibility, the Social Welfare has a lower value in this case. Since there is more power consumption and production, the cost for loads and generators' revenue present higher results comparing to when the flexibility was equal to 1%. Furthermore, the fairness indicator QoE keeps the same value as in the previous case (QoE=1) as all loads face the same marginal prices in both models.

Table 4.7: Total cost, revenue and social welfare at 12:00, considering loads' flexibility of 15%.

	P2P OPF	**P2P Prod. Diff.**
Cost (€)	78.32	78.32
Revenue (€)	78.32	78.32
Social Welfare (€)	2008.55	2008.55

Similar to what happened with a lower flexibility, in this case, Figure 4.12 shows that the average revenue, by area, of the P2P AC-OPF model is higher in all areas except in area B. Since this area aggregates bus 14 and 16, the power production in these buses should be look at. As Table 4.8 shows, the production in both buses is lower for the P2P AC-OPF model, which means that this model avoids branches with high probability of congestion. On the contrary, the P2P Prod. Diff. model has a different behaviour and that is why the average revenue in area B is higher.

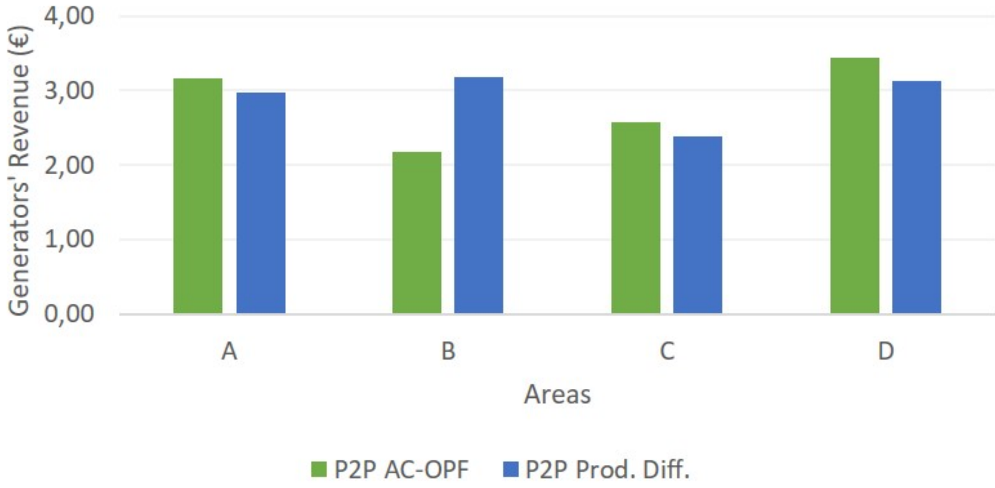

Figure 4.12: Generators' revenue at 12:00, by area, considering loads' flexibility of 15%.

Table 4.8: Power production in bus 14 and 16 at 12:00, considering loads' flexibility of 15%.

Bus	P2P AC-OPF	P2P Prod. Diff.
14	941.10 kW	1140.63 kW
16	802.75 kW	1109.27 kW

4.3.3 Loads' Flexibility of 30%

The final comparison of the models is made assuming a 30% flexibility of loads, while keeping the maximum current of 81.7 A in all lines. Due to the higher flexibility, the P2P Prod. Diff. model will now run through another iteration so the coefficient value of $c_n = -5€/(km \times MWh)$ is applied to loads in this case.

4.3.3.1 Power trade comparison

Figures 4.13 and 4.14 show the difference between the two models in terms of power traded between each producer and the consumers. For the simulated hour (12:00), there is only renewable production, so there are no results for generator 1,2,3 and 4 as they represent the external supplier and CHPs. In the P2P Prod. Diff. model, the power produced by each generator goes only to one or two loads because this model is designed to encourage the peers to consume as locally as possible, in order to avoid congestion problems. For example, generator 5 has an agreement with loads 2 and 3, which are located close to this generator. In fact, load 2 is placed in the same bus as generator 5, therefore, almost 80% of the production goes to that load. On the contrary, the production in the P2P AC-OPF model is distributed through all loads, as depicted in Figure 4.14. This model does not take into consideration the euclidean distance between peers and the only way of making the market trades respect network limits is to have an integrated AC-OPF.

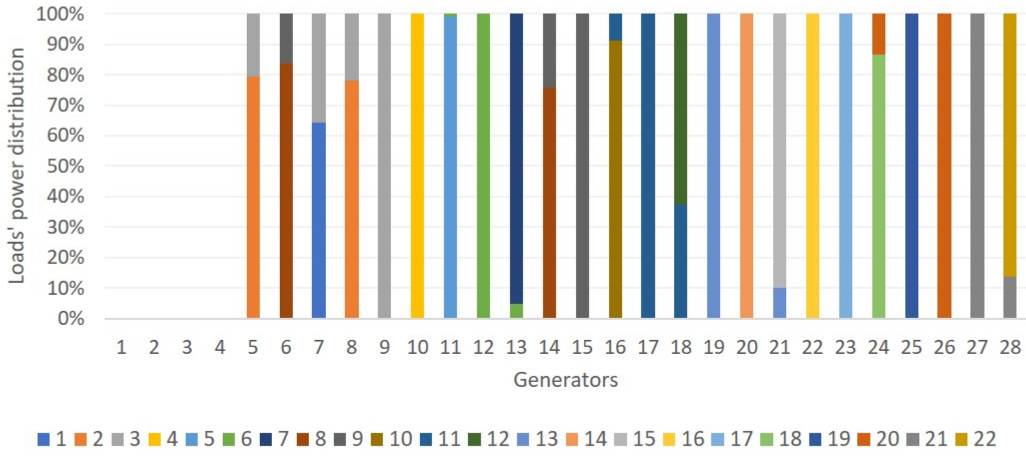

Figure 4.13: Power distribution by load for each generator at 12:00 (P2P Prod. Diff.).

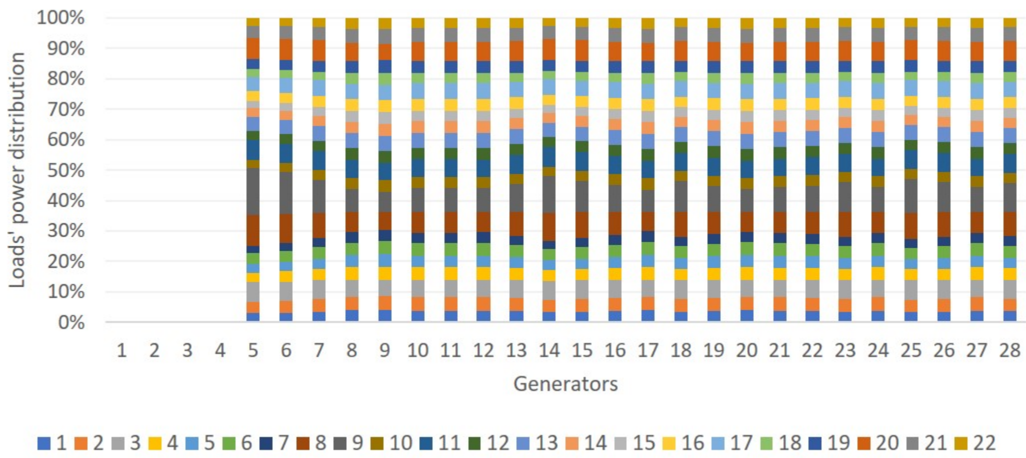

Figure 4.14: Power distribution by load for each generator at 12:00 (P2P AC-OPF).

It is important to highlight that these are economical agreements, which means that the results do not necessarily correspond to the actual power flow in the network. It is not possible to determine if the power purchased by a certain consumer to a certain producer will correspond to the real power flow that goes from the bus where the producer is located to the the consumer's bus. The power balance on each bus is what actually defines the power flow.

4.3.3.2 Line Loading

Both models respect the loading limit in all lines, as can it be seen in Figure 4.15. However, in general, the P2P Prod. Diff. model presents less usage of the network branches, comparing to the P2P AC-OPF model. Moreover, with loads' flexibility of 30%, it is possible to observe that there is a decrease in the load supply of the P2P Prod. Diff model and the opposite happens with the P2P AC-OPF model, comparing to lower values of flexibility. This is explained by the fact that the power balance in each bus influences line loading values so, by having product differentiation which affects consumers' behaviour, the buses are more balanced. With less power flowing through the network, the line loading results are inferior to the ones from the P2P AC-OPF. It is also concluded that, with this level of flexibility, there is a greater contrast between the two models' performance.

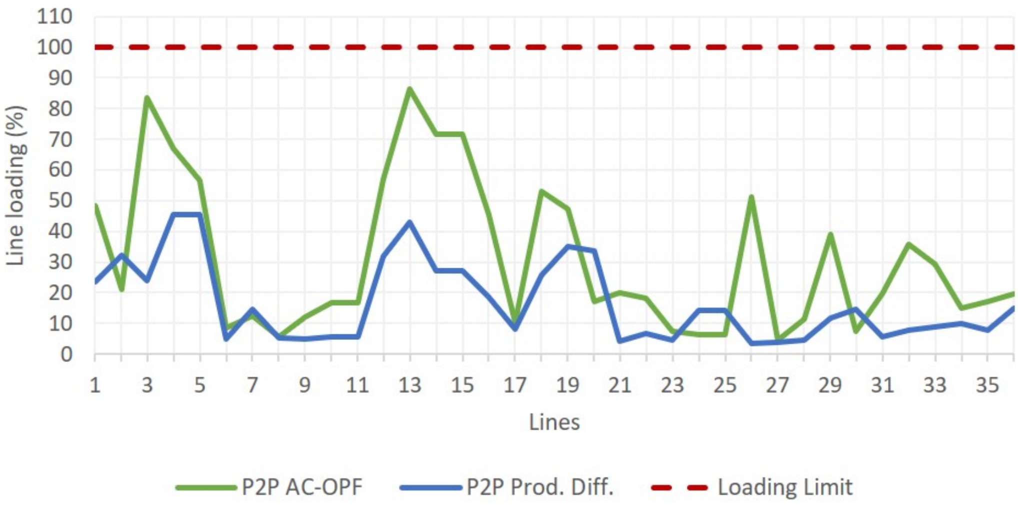

Figure 4.15: Line loading results at 12:00, considering loads' flexibility of 30%.

Indeed, line 13 is more congested in the P2P AC-OPF model because the high generation in bus 14 is not covered by load consumption in the same bus or in a close one as in the P2P Prod. Diff. model, so this raises the power flow in that line.

Table 4.9 shows the total power generation by type of generator and the total consumption. Detailed results for each bus can be found in Tables B.1 and B.2, in the appendix. In the P2P Prod. Diff. model, the wind generation is less than in the P2P AC-OPF model, as the loads located in the same buses or close to them are not sufficient to purchase their power. In addition, the loads located in more distant buses prefer to pay less and cover their demand by making agreements with the nearest producers. Thus, wind generation is curtailed. Moreover, by having grid fees based on the euclidean distance criterion, the load consumption decreases about 4.08%, as the cost for purchasing power is higher than the cost in the P2P AC-OPF model. In section 4.3.3.4, a more detailed analysis of the costs is presented.

Table 4.9: Power generation and consumption at 12:00, considering loads' flexibility of 30%.

	P2P AC-OPF	**P2P Prod. Diff.**
External Supplier (kWh)	0	0
CHP (kWh)	0	40.13
Wind (kWh)	2903.92	2210.67
PV (kWh)	19229.70	18979.26
Consumption (kWh)	22133.62	21230.05

4.3.3.3 Power Losses

The results of active power losses are expected to have the same behaviour as the line loading results, so Table 4.10 shows that in the P2P AC-OPF model, the values are higher than in the P2P Prod. Diff. model. This difference results from the lower grid usage in the P2P Prod. Diff. model, which is particularly important to reduce power losses in distribution networks with line resistance greater than reactance. Regarding hour 12:00, power losses in the P2P AC-OPF model represent 0.12% of the total power produced in the network and the total cost is equal to 1.56€. On the other hand, P2P Prod. Diff. model presents power losses that correspond to 0.036% of the total production and their cost is about 0.44€.

Table 4.10: Power losses and cost at 12:00, considering loads' flexibility of 30%.

	P2P AC-OPF	**P2P Prod. Diff.**
Power Losses (kW)	26.84	7.64
Price (€)	1.56	0.44

4.3.3.4 Cost and Revenue

The total cost, revenue and social welfare for both simulations at hour 12:00 are shown in Table 4.11. The highest value of social welfare is reached by applying the P2P AC-OPF model because it allows the consumers to set bilateral contracts with the generators without taking into consideration the distance between them. This maximizes the social welfare while the introduction of product differentiation affects consumers' behaviour, resulting in a lower value. Moreover, the costs for loads are higher in the P2P Prod. Diff. model due to the introduction of grid fees. Having fewer generators at a low price leads to a decrease in load consumption, as stated in section 4.3.3.2.

Table 4.11: Total cost, revenue and social welfare at 12:00, considering loads' flexibility of 30%.

	P2P AC-OPF	**P2P Prod. Diff.**
Cost (€)	88.53	173.15
Revenue (€)	88.53	153.03
Social Welfare (€)	1292.97	1287.70

It should be noted that the marginal price paid by loads to cover their demand is the same in the P2P AC-OPF model but not in the P2P Prod. Diff. model. In the P2P Prod. Diff. model, grid fees are proportional to the distance between peers, so the marginal price will be different. That is not advantageous for consumers because from their perspective, it is fairer to purchase electricity at the same marginal cost. In fact, in terms of fairness, the result of the QoE for the P2P Prod. Diff. model is equal to 0.61, which is lower than the result of the P2P AC-OPF model (QoE=1).

4.4 Observations

This section presents the main observations of the case study, regarding the comparison between the P2P AC-OPF model and the P2P Prod. Diff. model. The case study covers different situations that were carefully selected in order to demonstrate the most relevant features and models' behavior. More precisely, line thermal capacity and loads' flexibility features were modified to cover a diversity of network and market operation conditions.

On the first analysis, for a maximum current in all branches equal to 245 A, the grid could operate with all kind of transactions, so the models presented the same results and they both maximized the SW. However, as the line thermal capacity is decreased to 81.7 A, the network became more congested, so the differences between the two methods were more evident as it was observed in section 4.3.

Considering that the network can be under congestion (the maximum current in all lines is reduced to 81.7 A) and the loads' flexibility is set to 1%, the SW and electricity consumption is the same for both models. However, the P2P AC-OPF model generally has a higher level of line loading and, consequently, higher power losses than the P2P Prod. Diff. This may be justified by the different scheduling of RES, as the P2P AC-OPF dispatches more wind than PV, when compared to the P2P Prod. Diff. As PV sources are in greater number and distributed throughout the network, a higher dispatch of PV power may induce smaller power losses when compared to the dispatch based on wind turbines. This makes sense as the price for all type of RES is the same. For the case of 15% load flexibility, there were still no congestion problems, therefore, the P2P Prod. Diff. model did not require another iteration, so the models presented a behavior similar to the previous case, in which the load flexibility was equal to 1%. In addition, the QoE for both situations presented its maximum value (QoE=1) as all loads faced the same marginal prices in both models.

Nevertheless, as the loads' flexibility increased, there was a change in the models' response. For loads' flexibility of 30%, line loading results were reduced substantially in the P2P Prod. Diff. model, as it ran through another iteration where product differentiation was used. On the contrary, the P2P AC-OPF suffered an increase in terms of line congestion. Despite this advantage for the P2P Prod. Diff. model, it was observed that, by having grid fees based on the euclidean distance, the costs for purchasing power were higher, resulting in less consumption comparing to the P2P AC-OPF model. Hence, wind generation had to be curtailed. Consequently, the social welfare had a lower value than in the P2P AC-OPF model and the fairness indicator (QoE) was 0.61, while the P2P AC-OPF model consistently had a QoE value of 1, as all loads faced the same marginal price regardless the level of loads' flexibility.

Chapter 5

Conclusion and Future Works

In this chapter, the main conclusions of this dissertation are presented and a critical analysis of the proposed model is made, along with a description of its contribution. Furthermore, the lines for future works, that can be developed in order to extend the study on P2P electricity markets, are introduced.

5.1 Main conclusions and contributions

The development of renewable energy and Internet technology has been contributing to the growth of distributed energy systems. Thus, P2P electricity trading in distribution systems has emerged and is being explored as the so-called next generation energy management technique, allowing prosumers to directly exchange energy while having an active participation in the market. This innovation translates into an increase of the system's efficiency and it also enables the transition from the traditional socioeconomic structures to advanced structures based on the sharing economy concept. However, the deployment of P2P markets presents some challenges in the operation of the distribution system, as the electricity trades must respect technical limits, otherwise, the network's security is compromised. Therefore, innovations are essential to guarantee that the energy service is provided without congestion and voltage problems.

To that end, this dissertation contributes with a method for a P2P electricity market, considering network constraints through a centralized AC-OPF in order to ensure that energy exchanges respect the network limits. Furthermore, this model was designed, analysed and compared to an alternative model found in literature, named P2P Prod. Diff. The P2P Prod. Diff. model simulates the P2P market and network operation iteratively. Product differentiation is used in the market formulation to change the market solution in such way that makes the network operation feasible. In both models, loads' elasticity was incorporated, enabling higher flexibility to the market. The loads' flexibility is considered an important parameter to assess the behaviour of the two models. Particular attention was also paid to RES penetration.

An analysis has been conducted for both models taking into account the economic and technical operation perspectives. The test case consisted of two cases with different levels of line thermal capacity and loads' flexibility. The simulation of the models showed that their behaviour is very similar when there are no congestion issues in the network. On the other hand, if the line thermal capacity is limited (i.e., considering a decrease in the maximum current of all lines), the line loading values increase and, in certain scenarios of loads' flexibility, the results of the models are considerably different.

Since the effectiveness of the models is reflected in the results, it is possible to identify the advantages and disadvantages of each model, taking into account its characteristics. The P2P Prod. Diff. model offers better results when the grid does not present congestion problems and for lower levels of loads' flexibility, as it uses product differentiation. In fact, the power losses are about 38.4% lower, in average, than those of the P2P AC-OPF model. The P2P AC-OPF model, in its turn, has a better performance for situations with a high level of loads' flexibility and, thus, with a higher probability of congestion. In those situations, despite the higher values of power losses, the P2P AC-OPF model presents better results in terms of costs and social welfare. For example, the results showed that the costs for loads were 48.9% lower than in the P2P Prod. Diff. model. In addition, the proposed model can be considered fairer than the P2P Prod. Diff. model, taking into account that the fairness indicator, QoE, presents its maximum value regardless of the loads' flexibility.

Therefore, this dissertation contributes to a comparative analysis which shows interesting results regarding the security of systems' operation, as well as the advantages the models bring in terms of benefits to prosumers. Furthermore, the development of a methodology in which a P2P market integrates network constraints in the form of an AC-OPF can be seen as an alternative to the existing approaches for the coordination of P2P markets with the electrical network.

5.2 Perspectives for Future Work

Throughout the development of this work, several ideas have arisen to potentially proceed with the evolution of the present work. Thus, some suggestions for the further development of P2P electricity markets can be identified:

- Solve the P2P problem through a decentralized optimization, contrary to the method used on the P2P models described in this thesis. The main advantage is that it preserves the peers' identities, by solving the optimization problem while keeping the data private;

- Include storage systems to improve the network flexibility and to save renewable power from being wasted, considering that the marginal cost of RES production is close to zero, so it would be counterproductive to curtail it;

- Implement a hybrid P2P market where an adequate grid management framework is developed for each layer of the structure, so that several communities can be considered.

Appendix A

Network data

A.1 Peers characteristics for hour 12:00

Table A.1: Loads characteristics

Load number	Bus location	Base Load (kW)	P min (kW)	P max (kW)
1	**3**	608.60	426.02	791.18
2	**4**	716.34	501.44	931.24
3	**6**	1029.76	720.83	1338.69
4	**7**	643.63	450.54	836.72
5	**9**	605.02	423.52	786.53
6	**10**	674.35	472.05	876.66
7	**12**	526.59	368.61	684.57
8	**14**	1345.32	941.72	1748.92
9	**16**	1683.28	1178.29	2188.26
10	**18**	572.09	400.46	743.71
11	**20**	1029.76	720.83	1338.69
12	**21**	608.60	426.02	791.18
13	**23**	824.24	576.97	1071.51
14	**24**	605.02	423.52	786.53
15	**26**	526.59	368.61	684.57
16	**28**	619.81	433.87	805.75
17	**29**	866.17	606.32	1126.02
18	**31**	511.92	358.34	665.49
19	**32**	655.56	458.89	852.23
20	**34**	1089.04	762.33	1415.75
21	**36**	757.57	530.3	984.85
22	**37**	526.59	368.61	684.57

Table A.2: Generators characteristics

Generator number	Bus location	Primary Energy	P Max (kW)
1	**1**	External supplier	20000.0
2	**14**	CHP	500.0
3	**16**	CHP	500.0
4	**24**	CHP	500.0
5	**4**	Wind	2016.59
6	**14**	Wind	3179.19
7	**3**	Photovoltaic	1240.64
8	**4**	Photovoltaic	716.28
9	**6**	Photovoltaic	504.28
10	**7**	Photovoltaic	787.06
11	**9**	Photovoltaic	771.48
12	**10**	Photovoltaic	833.92
13	**12**	Photovoltaic	1048.11
14	**14**	Photovoltaic	1834.11
15	**16**	Photovoltaic	1678.35
16	**18**	Photovoltaic	1038.22
17	**20**	Photovoltaic	721.8
18	**21**	Photovoltaic	1227.05
19	**23**	Photovoltaic	941.21
20	**24**	Photovoltaic	736.86
21	**26**	Photovoltaic	822.45
22	**28**	Photovoltaic	943.12
23	**29**	Photovoltaic	1191.59
24	**31**	Photovoltaic	804.31
25	**32**	Photovoltaic	1275.52
26	**34**	Photovoltaic	1224.3
27	**36**	Photovoltaic	788.62
28	**37**	Photovoltaic	1073.25

A.2 Branches characteristics

Table A.3: Branches characteristics

Line	From bus	To bus	Distance (km)	R (Ω/km)	X (Ω/km)	I max (kA)
1	**2**	**1**	0.6	0.32	0.113	0.245
2	**3**	**2**	0.75	0.32	0.113	0.245
3	**4**	**2**	0.8	0.32	0.113	0.245
4	**5**	**2**	0.75	0.32	0.113	0.245
5	**6**	**5**	0.8	0.32	0.113	0.245
6	**7**	**5**	0.6	0.32	0.113	0.245
7	**8**	**5**	0.75	0.32	0.113	0.245
8	**9**	**8**	0.8	0.32	0.113	0.245
9	**10**	**8**	0.75	0.32	0.113	0.245
10	**11**	**8**	0.6	0.32	0.113	0.245
11	**12**	**11**	0.8	0.32	0.113	0.245
12	**13**	**1**	0.75	0.32	0.113	0.245
13	**14**	**13**	0.8	0.32	0.113	0.245
14	**15**	**13**	0.6	0.32	0.113	0.245
15	**16**	**15**	0.8	0.32	0.113	0.245
16	**17**	**1**	0.75	0.32	0.113	0.245
17	**18**	**17**	0.6	0.32	0.113	0.245
18	**19**	**17**	0.8	0.32	0.113	0.245
19	**20**	**19**	0.75	0.32	0.113	0.245
20	**21**	**19**	0.8	0.32	0.113	0.245
21	**22**	**19**	0.6	0.32	0.113	0.245
22	**23**	**22**	0.75	0.32	0.113	0.245
23	**24**	**22**	0.8	0.32	0.113	0.245
24	**25**	**22**	0.75	0.32	0.113	0.245
25	**26**	**25**	0.6	0.32	0.113	0.245
26	**27**	**1**	0.8	0.32	0.113	0.245
27	**28**	**27**	0.75	0.32	0.113	0.245
28	**29**	**27**	0.6	0.32	0.113	0.245
29	**30**	**27**	0.75	0.32	0.113	0.245
30	**31**	**30**	0.6	0.32	0.113	0.245
31	**32**	**30**	0.8	0.32	0.113	0.245
32	**33**	**30**	0.75	0.32	0.113	0.245
33	**34**	**33**	0.8	0.32	0.113	0.245
34	**35**	**33**	0.6	0.32	0.113	0.245
35	**36**	**35**	0.75	0.32	0.113	0.245
36	**37**	**35**	0.8	0.32	0.113	0.245

A.3 Renewable generators

Table A.4: PV power bid

Bus Location	PV power (kW)
3	1229.83
4	723.57
6	526.53
7	776.46
9	778.6
10	761.65
12	1016.56
14	1638.7
16	1579.63
18	979.28
20	687.26
21	1243.15
23	905.38
24	710.78
26	830.26
28	889.11
29	1116.55
31	811.22
32	1293.68
34	1193.31
36	817.91
37	1069.39

Table A.5: Wind power bid

Bus Location	Wind power (kW)
4	2109.81
14	3255.49

A.4 Coefficients a_n and b_n

Table A.6: Coefficients a_n and b_n of generators

Bus location	**Primary Energy**	a_n **(€/MWh^2)**	b_n **(€/MWh)**
1	External supplier	0.0	58.0
14	CHP	10.0	30.0
16	CHP	1.5	20.0
24	CHP	5.0	10.0
4	Wind	0.0	4.0
14	Wind	0.0	4.0
3	Photovoltaic	0.0	4.0
4	Photovoltaic	0.0	4.0
6	Photovoltaic	0.0	4.0
7	Photovoltaic	0.0	4.0
9	Photovoltaic	0.0	4.0
10	Photovoltaic	0.0	4.0
12	Photovoltaic	0.0	4.0
14	Photovoltaic	0.0	4.0
16	Photovoltaic	0.0	4.0
18	Photovoltaic	0.0	4.0
20	Photovoltaic	0.0	4.0
21	Photovoltaic	0.0	4.0
23	Photovoltaic	0.0	4.0
24	Photovoltaic	0.0	4.0
26	Photovoltaic	0.0	4.0
28	Photovoltaic	0.0	4.0
29	Photovoltaic	0.0	4.0
31	Photovoltaic	0.0	4.0
32	Photovoltaic	0.0	4.0
34	Photovoltaic	0.0	4.0
36	Photovoltaic	0.0	4.0
37	Photovoltaic	0.0	4.0

Appendix B

Results for the two models at 12:00, considering loads' flexibility of 30%

Table B.1: Loads' active power consumption

Load	Bus	P2P AC-OPF (kW)	P2P Prod. Diff. (kW)
1	**3**	791.18	791.18
2	**4**	931.24	931.24
3	**6**	1338.69	1213.37
4	**7**	836.73	776.46
5	**9**	786.53	772.83
6	**10**	876.66	802.23
7	**12**	684.57	684.57
8	**14**	1748.92	1748.92
9	**16**	2188.26	1997.40
10	**18**	743.71	743.71
11	**20**	1338.69	1225.02
12	**21**	791.18	777.40
13	**23**	1071.51	982.87
14	**24**	786.53	750.91
15	**26**	684.57	684.57
16	**28**	805.75	805.75
17	**29**	1126.02	1116.55
18	**31**	665.492	665.49
19	**32**	852.23	852.23
20	**34**	1415.75	1295.55
21	**36**	984.85	926.96
22	**37**	684.57	684.57
Total		**22133.62**	**21230.05**

Table B.2: Generators' active power production

Generator	Bus	P2P OPF (kW)	P2P Prod. Diff. (kW)
1	**1**	0.00	0.00
2	**14**	0.00	0.00
3	**16**	0.00	0.00
4	**24**	0.00	40.13
5	**4**	1512.82	858.05
6	**14**	1391.10	1352.62
7	**3**	1114.36	1229.83
8	**4**	690.98	321.37
9	**6**	504.52	526.53
10	**7**	733.39	776.46
11	**9**	735.83	778.60
12	**10**	720.36	761.65
13	**12**	942.35	719.37
14	**14**	1265.89	814.37
15	**16**	1080.97	1579.63
16	**18**	901.94	815.73
17	**20**	648.28	687.26
18	**21**	1056.25	1243.15
19	**23**	828.84	905.38
20	**24**	670.36	710.78
21	**26**	773.93	762.05
22	**28**	833.19	805.75
23	**29**	1010.51	1116.55
24	**31**	766.95	767.72
25	**32**	1148.28	852.23
26	**34**	1048.09	1193.31
27	**36**	770.21	817.91
28	**37**	984.24	793.62
Total		**22133.62**	**21230.05**

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