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Renewable Energy Trading Using Peer-to-Peer Business Models

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Resumo

O aparecimento de consumidores mais proativos, vulgarmente designados por prosumers, está a capacitar os consumidores e a trazer novas oportunidades e desafios para a operação de sistemas de energia no âmbito do desenvolvimento dos mercados de electricidade. Recentemente, o conceito peer-to-peer (P2P) permite aos prosumers acima referidos partilhar diretamente a sua energia eléctrica e de assim justificarem e recuperarem mais rapidamente os seus custos de investimento. Esta partilha de energia pode ser feita através de três modelos de negócios distintos, Full P2P (prosumers trocam energia diretamente entre si), Community-Based P2P (uma comunidade de prosumers que queiram colaborar uns com os outros é criada) e Hybrid P2P (permite uma junção de ambos os modelos acima referidos, isto é, diferentes comunidades de prosumers trocam energia diretamente entre si).

Finalmente, esta dissertação pretende comprovar o conceito destes novos mercados P2P. Para tal, inicialmente, foi analisado um caso de estudo sem qualquer modelo P2P, no qual os prosumers apenas trocam energia com a rede. Posteriormente, os modelos P2P mencionados são avaliados individualmente em Python 3, utilizando o otimizador Gurobi 9.0.1, a fim de determinar não só o seu benefício em relação ao caso sem qualquer modelo P2P como também, entre os diferentes modelos, qual o mais vantajoso.

Palavras-Chave: Community-Based Peer-to-Peer, Full Peer-to-Peer, Hybrid Peer-to-Peer, Peer-to-Peer Energy trading, Photovoltaic, Prosumers, Tariffs .

Abstract

The emergence of more proactive consumers, the commonly termed prosumers, is empowering consumers and bringing new opportunities and challenges to the operation of power systems in a market environment. Recently, the so-called Peer-to-Peer (P2P) electricity markets conceptually allow the aforementioned prosumers to share their energy contributing to more rapidly recover their investment costs. This energy sharing can be done through three distinct business models, the Full P2P model (prosumers exchange energy directly with each other), the Community-Based P2P model (a community of prosumers who want to collaborate with each other is created) and the Hybrid P2P model (enables the operation using both previously mentioned models, i.e. different communities of prosumers trade energy directly with each other).

Finally, this dissertation aims to prove the concept of these new P2P markets. To get this objective, a test case without any P2P model was initially created and analyzed, in which prosumers only exchange energy with the main grid. Subsequently, the aforementioned P2P models were individually evaluated in Python 3, using the Gurobi 9.0.1 optimizer, in order to determine not only their benefit in relation to the case without any P2P model but also, among the different models, which one was the most beneficial, for this particular case study.

Keywords: Community-Based Peer-to-Peer, Full Peer-to-Peer, Hybrid Peer-to-Peer, Peer-to-Peer Energy trading, Photovoltaic, Prosumers, Tariffs.

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Miguel Rodrigues Castro Chousal

*“If you can find a path with no obstacles, it.
probably doesn’t lead anywhere.”*

Frank A. Clark

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Abbreviations and Symbols

P2P	Peer-to-Peer
MIBEL	Mercado Ibérico de Electricidade
ERSE	Entidade Reguladora dos Serviços Energéticos
HV	High-Voltage
MV	Medium-Voltage
LV	Low-Voltage
TUTN	Tariff for the Use of the Transmission Network
TUDN	Tariff for the Use of the Distribution Network
TGUS	Tariff for the Global Use of the System
TLOC	Tariff for the Logistic Operation of Changing of Retailer
ICT	Information and Communication Technology
SWOT	Strengths, Weaknesses, Opportunities, Threats
PV	Photovoltaic
SW	Social Welfare
UK	United Kingdom
US	United States
IT	Information Technology
IoT	Internet of Things
UPAC	Unidades para Autoconsumo
SW	Social Welfare
CER	Comunidades de Energia Renovável
IU	Instalação de Utilização
RESP	Rede Elétrica de Serviço Público
kW	Kilowatt
kWh	Kilowatt-hour

Chapter 1

Introduction

1.1 Context and Motivation

The appearance of more proactive consumers, the commonly named "prosumers", is empowering the consumers and bringing new opportunities and challenges to the operation of power systems in a market environment. Recently, the so-called peer-to-peer (P2P) electricity markets are contributing to change the current peer to grid paradigm where the generation surplus can only be sold to the grid, allowing the aforementioned prosumers to directly share their generation surplus with other prosumers. This change of paradigm allows the prosumers to:

- Have a wider choice of energy supply;
- Produce and sell their own energy;
- Increase the competition in the retailing market;
- Increase the resilience and the reliability of power systems;
- Promote energy sustainability.

In fact, the P2P electricity markets increase the resilience and the reliability of power systems as a result of mitigating possible power overflows on the transmission/distribution lines during peak hours. Moreover, through this change of paradigm, more green energy will be used to supply the consumers demand, hence promoting the energetical sustainability. An energy community can also be created by prosumers who want to collaborate with each other.

This study, focused on the year of 2019, aims at proving the concept of these new Peer-to-Peer market designs. In order to do this, initially, a grid with clients of the company "Energia Simples" was created and analyzed in Python 3 using Gurobi 9.0.1 optimizer, without any P2P models. Subsequently, these P2P models, for the aforementioned grid, were individually evaluated, in order to determine which one was the most beneficial, for this particular case study.

1.2 Dissertation Structure

This dissertation comprises 6 distinct chapters.

Initially, in **Chapter 1**, an introduction to the work developed throughout this dissertation and the context and motivation are described.

Chapter 2 includes a literature review about how the Iberian Market of electricity works, explaining its formulation. Afterwards, the Portuguese Electricity Tariff System is explained, so that one better understands the prices used in Chapter 4.

In **Chapter 3** a literature review about the Peer-to-Peer electricity markets is provided. Initially, an explanation about each one of the three P2P market designs is made, followed by an analysis of the impact of these market designs on electricity costs and a comparison between them. Afterwards, the current existing P2P trading projects and the legal framework regarding self-consumption in Portugal are assessed.

In **Chapter 4** the experimental procedure and the mathematical formulations of the different P2P market designs are explained. Furthermore, the Case Studies for the different P2P market designs, carried out in Python 3 using Gurobi 9.0.1 Optimizer, are also detailed.

Chapter 5 details the simulation results, performed for distinct time periods, using the mathematical formulations and the experimental procedures of the different Case Studies described in Chapter 4.

Lastly, in **Chapter 6**, the conclusions drawn throughout the development of this dissertation are shown. Moreover, a reference about the possible future work to be done about this subject is also detailed.

Chapter 2

MIBEL and the Portuguese Electricity Tariff System

2.1 Iberian Market of Electricity

The genesis of the Iberian Market of Electricity goes back to the year of 2000. In fact, due to geographical and size reasons, it wouldn't be advantageous for Portugal to develop an isolated electricity market. Moreover, the high amount of transactions that already existed between Portugal and Spain was also a strong point in favour of the establishment of this market, making it profitable for both the economies of Portugal and Spain. In terms of dimension, this market is similar to the other European regional markets, as shown in Figure 2.1.

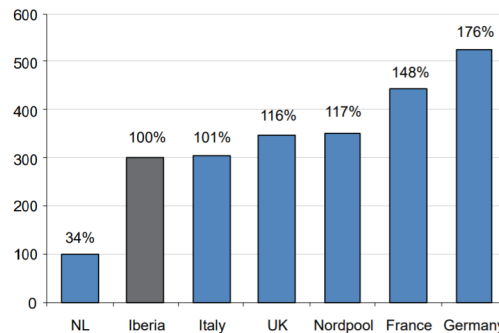


Figure 2.1: Consumptions of the different European Regional Markets (source [1])

According to [1], the main goals for the development of the Iberian Market of Electricity were to:

- Benefit the electricity consumers of both countries;
- Structure the operation of a liberalized electricity market;
- Build a single electricity price for the entire Iberian Peninsula;

- Allow free access to the market, assuring equality, transparency and objectivity;
- Benefit the Economy efficiency of the electric sector companies;
- Promote freedom of competition between the aforementioned companies.

2.1.1 The Pool Model

Nowadays, the electricity markets behave through the connection between energy producers on one side, and eligible consumers and retailers, on the other. In fact, this connection, is fulfilled by the Pool Market. This day-ahead market operates by matching both the producers and consumers bids, taking place on the day $n - 1$ and it is based on energy demand and production forecasting. Moreover, inevitably, there will occur deviations between the forecasted and the real values, hence creating a need for an adjustment market on day n , fixing the aforementioned forecasting deviations.

However, as illustrated in Figure 2.2, the formulation of this market has to comply with the physical properties of power system networks, meaning that, the Market Operator matches the bids from an economic point of view and the System Operator verifies if the limits of the generators production capacity and the transmission grid capacity limits are not surpassed.

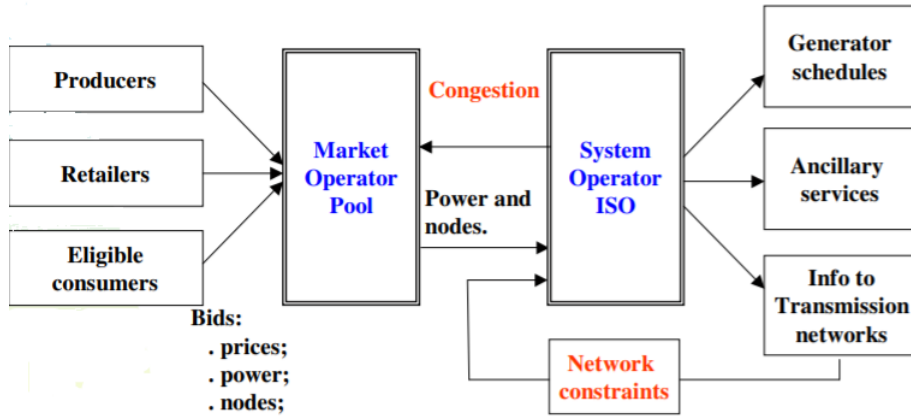


Figure 2.2: Pool Model (source [2])

If a congestion occurs on the transmission grid, both the System and Market Operators need to work together, in order to solve it. If, for any reason, the problem can't be solved, the System Operator has the authority to change the initial dispatch.

Mathematically, the Pool Model is formulated by [2]:

$$\max Z = \sum_{i=1}^{Nd} C_{Di}^{of} * P_{Di} - \sum_{j=1}^{Ng} C_{Gj}^{of} * P_{Gj} \quad (2.1)$$

$$\text{subject to } 0 \leq P_{Di} \leq P_{Di}^{of} \quad (2.2)$$

$$0 \leq P_{Gj} \leq P_{Gj}^{of} \quad (2.3)$$

$$\sum_{j=1}^{Ng} P_{Gj} = \sum_{i=1}^{Nd} P_{Di} \quad (2.4)$$

In this formulation:

- Z - Social Welfare Function;
- Nd - Number of matched purchase bids;
- Ng - Number of matched sale bids;
- C_{Di}^{of} - Purchasing Price of bid i;
- C_{Gj}^{of} - Selling Price of bid j;
- P_{Di}^{of} - Amount of Purchased Energy of bid i (maximum value);
- P_{Gj}^{of} - Amount of Sold Energy of bid j (maximum value);
- P_{Di} - Amount of Purchased Energy of bid i (variable);
- P_{Gj} - Amount of Sold Energy of bid j (variable).

2.1.2 Bilateral Contracts

There are some flaws associated to the Pool Model. In fact, with the presence of the Market Operator, there will never be a direct connection between the producers and the consumers, making the market anonymous, with just a centralized buyer and seller. Additionally, this model is based on short term marginal costs which are very volatile, being influenced by the load, generators, and the transmission grid line capacity. To overcome these pool model weaknesses, bilateral contracts can be used. These allow a direct relationship between the consumers and the producers, regarding not only prices and quantities, but also power modulation and the possibility to choose in which nodes the power is injected. The bilateral contracts duration is usually of over a year or more.

2.1.3 Mixed Structures

Typically, in most countries in which there was a reorganisation of the electricity sector, a mixed structure was adopted allowing market agents, producers, consumers and retailers, to choose the market platform that best suits their own interests. In fact, as shown in Figure 2.3, with this type of structure, market agents can now choose between joining the Pool Market or signing a Bilateral Contract, always having to send the technical information to the System Operator.

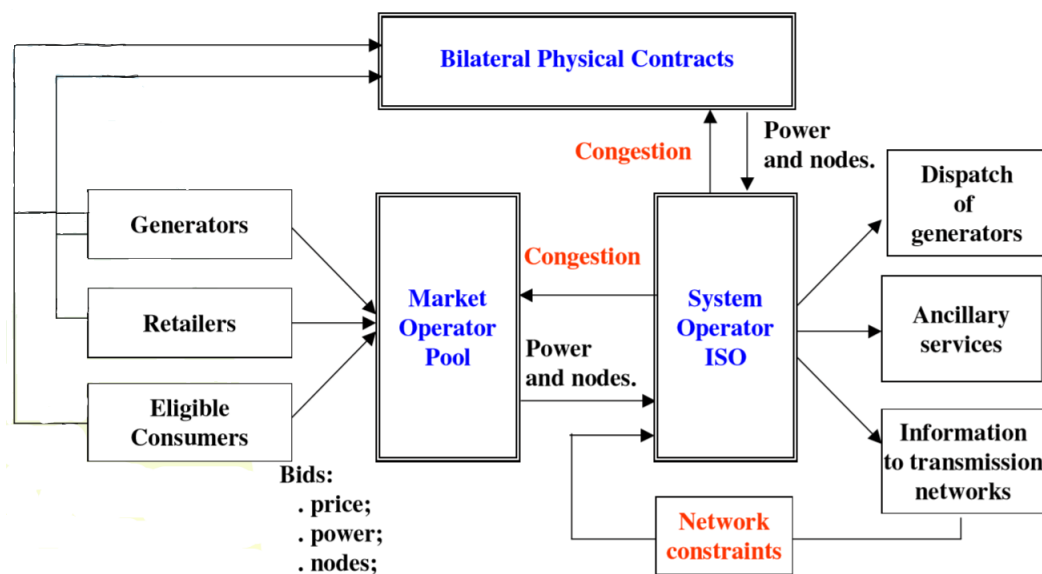


Figure 2.3: Electricity Sector Mixed Structure (source [2])

2.1.4 Market Splitting

A grid congestion can be internal (inside of the control area of each country), inter-area (between control areas) or extra-areas (between the control areas internal to the Iberian Market and the control areas outside of the Iberian Market of Electricity). Moreover, it is detected by the System Operators. In fact, after the grid congestion is detected, it is subsequently solved by a co-operation between the aforementioned System Operators and the Market Operator. Regarding the inter-area congestion case, more specifically in the case of the Iberian Market of Electricity (areas concerning Portugal and Spain), the congestion problems are solved through a technique called *Market Splitting*. In fact, to solve the congestion problem through this mechanism, the market is divided in two different market areas, originating a different price for both Portugal and Spain (one for each area).

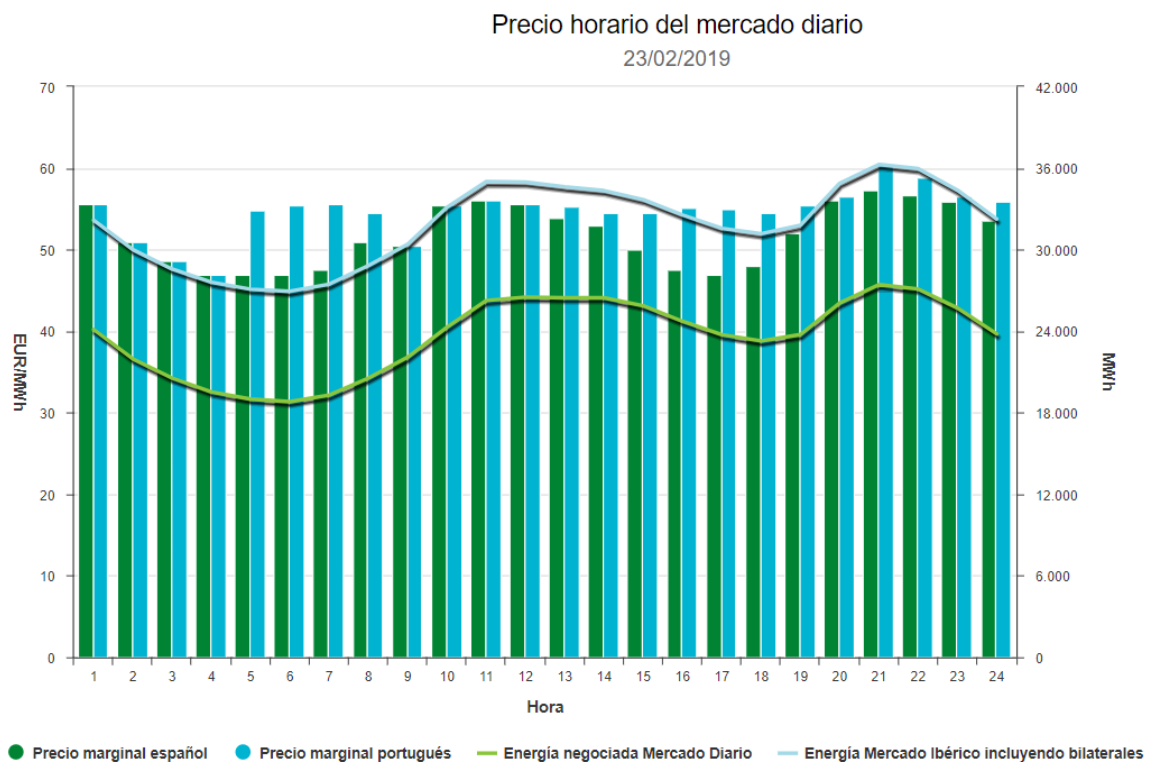


Figure 2.4: Graphic representation of Market Splitting (source [3])

Analyzing Figure 2.4, one can see distinct energy prices for Portugal and Spain on hours 5, 6, 7, 8, 13, 14, 15, 16, 17, 18, 19, 21, 22, 23 and 24. Moreover, for example, on hours 5, 6 and 7 the energy price is higher in Portugal than in Spain, meaning that Spain is exporting energy to Portugal. This energy export is limited by the interconnection lines capacity.

2.2 Portuguese Tariff System

2.2.1 General Tariff Framework

As expected, each country has its own electricity tariff system. However, this section will target the specific case of Portugal. In fact, the Portuguese tariff structure is designed by ERSE and most of the information regarding it can be found in [3].

Each tariff reflects each activity regulated by ERSE, as shown in Figure 2.5. The previously mentioned regulated activities as specified in the Portuguese Tariff Code, are the following:

- Global System Management;
- Transmission of Electricity;
- Distribution of Electricity in HV, MV and LV;
- Logistic Operation of Changing of Retailer;
- Buying and Selling of Electricity;
- Energy Retailing.

Regulated Activities	→	Regulated Tariffs
Global System Management	→	Tariff for the Global Use of the System
Transmission of Electricity	→	Tariff for the Use of the Transmission Network
Distribution of Electricity in HV	→	Tariff for the use of the Distribution Network in HV
Distribution of Electricity in MV	→	Tariff for the use of the Distribution Network in MV
Distribution of Electricity in LV	→	Tariff for the use of the Distribution Network in LV
Logistic Operation of Changing of Retailer	→	Tariff for the Logistic Operation of Changing of Retailer
Buying and Selling of Electricity	→	Energy Tariff
Energy retailing	→	Retailing Tariff

Figure 2.5: Tariffs regarding the respective regulated activity (source [3])

The tariffs have different values depending on the time of the year and the period of the day. The different periods can be categorized by:

- Super Valley Hours - hours in which the energy consumption is very low leading to lower tariffs;
- Valley Hours - hours in which the energy consumption is barely higher than in Super Valley Hours leading to slightly higher tariffs;
- Full Hours - hours in which the energy consumption achieves a considerable value, also leading to higher tariffs;
- Peak hours - hours in which the energy consumption is the highest, leading to the highest tariffs.

2.2.2 Energy Tariff

This tariff is responsible for recovering the costs of purchasing and selling electricity, thus it assumes different values depending on the time of the year and the period of the day, as explained above.

2.2.3 Retailing Tariff

This tariff reflects the costs incurred by the regulated retailer in providing his service. Furthermore, it is distinguished by the voltage level and the type of voltage level supply, establishing three different tariffs:

- Retailing Tariff in High Voltage / Medium Voltage;
- Retailing Tariff in Special Low-Voltage;
- Retailing Tariff in Regular Low-Voltage.

These retailer tariffs are composed by the following prices:

- Fixed term (€/month)
- Active energy price (€/kWh)

2.2.4 Access Tariffs

The Access Tariff is given by the sum of the Tariff for the Use of the Transmission Network (TUTN), the Tariff for the Use of the Distribution Network in High Voltage, Medium Voltage and Low Voltage (TUDN), the Tariff for the Global Use of the System (TGUS) and the Tariff for the Logistic Operation of Changing of Retailer (TLOCR), resulting from the application of the Law Decree n° 38/2017 [4].

2.2.4.1 Tariffs for the Use of the Transmission Network, TUTN

As its name suggests, these tariffs refer to the use of the Transmission Network. They are applied to all the operators that benefit from the use of the transmission network. These tariffs are established considering the following prices:

- Price of the Contracted Power (€/kW/month);
- Price of the Average Power in Peak hours (€/kW/month);
- Price of the Active Energy (€/kWh);
- Price of the Reactive energy (inductive and capacitive) (€/kVARh)

2.2.4.2 Tariffs for the Use of the Distribution Network, TUDN

These tariffs are applied to all the operators that use the Distribution Network. They are formed by the following prices:

- Price of the Contracted Power (€/kW/month);
- Price of the Average Power on Peak hours (€/kW/month);
- Price of the Active Energy (€/kWh);
- Price of the Reactive energy (inductive and capacitive) (€/kVARh)

They are similar to the TUTN because they also benefit from the additivity property. For example, a consumer connected to the Medium Voltage level will pay the tariffs concerning the High Voltage Level and the Medium Voltage level, never paying the tariffs concerning the Low Voltage Level.

2.2.4.3 Tariff for the Logistic Operation of Changing of Retailer, TLOC

In Portugal, before 2017, the costs associated to this tariff were included in the TUDN. As of 2017, due to the law decree n°38/2017 [4] this tariff was separated from the TUDN, having a different cost for each voltage level.

2.2.4.4 Tariff for the Global Use of the System, TGUS

This tariff is applied by the Transmission Network System Operator, the Distribution Network System Operator (HV, MV and LV) to the final customers. Therefore, this tariff is split in two distinct terms (TGUS I and TGUS II). The TGUS I term refers to the cost associated to the system management and includes the cost associated with the control center, with the procurement and contracting of ancillary services and with the system management. The TGUS II term is designed to recover the costs associated with energy and environmental policies, being established through active energy prices.

Chapter 3

Literature Review

In this chapter, the peer-to-peer concept applied to energy trading will be reviewed and clarified. That being said, this chapter includes a detailed analysis performed to the current existing peer-to-peer business models in a worldwide level and the Portuguese regulatory framework behind the aforementioned models.

3.1 Concept of Energy Trading With Peer-to-Peer Models

Peer-to-peer (P2P) energy trading consists of energy trading between distinct local agents, where the generation surplus from small-scale energy resources is traded among local customers. P2P energy trading gives opportunity to trade energy within the neighbourhood, changing the current peer to grid paradigm where the generation surplus from local resources can only be sold to the grid. This will contribute to transform consumers from passive energy and price taking, to active energy and price making. [5]

A standardized 4-layer architecture of the P2P energy trading model, based on the SGAM (Smart Grid Architecture Model) is provided in Figure 3.1.

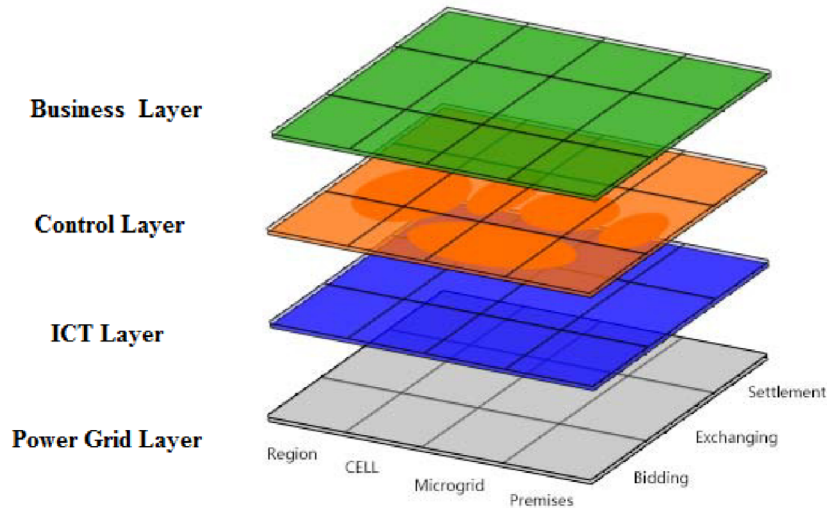


Figure 3.1: Four-Layer Architecture Model of Peer-to-Peer Energy Trading (source [6])

The components of each Layer in this Four-Layer Architecture are [6]:

- Business Layer - Participants in local markets, market authorities and trading platforms;
- Control Layer - Monitoring and control system owned by System Operators and including control functions;
- Information and Communications Technology Layer - Communication network and devices, data storage and information flow;
- Power Grid Layer - Existing power grid with Distributed Generation, flexible loads, storage and Electric Vehicles;

3.2 Peer-to-Peer Market Structures

With the implementation of the peer to peer paradigm, an internal P2P market can be managed using different market structures.

The different market structures proposed for P2P are the following [7]:

- Full P2P market - Agents freely negotiate directly with each other, without the intervention of a third party. Hence, two peers can agree on a transaction without centralized supervision as illustrated in Figure 3.2.

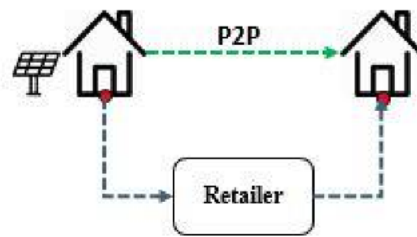


Figure 3.2: Full P2P structure (source [7])

- Community-Based P2P market - there is a third party managing the trading activities within the members of the energy community, as illustrated in Figure 3.3.

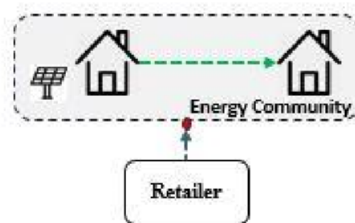


Figure 3.3: Community-Based P2P structure (source [7])

- Hybrid P2P market - a combination between the aforementioned structures, where the members of energy communities hosting P2P markets can also negotiate with each other, as illustrated in Figure 3.4.

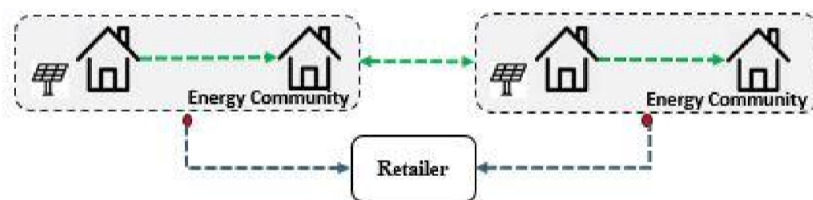


Figure 3.4: Hybrid P2P structure (source [7])

3.2.1 Full Peer-to-Peer Market

Figure 3.5 represents a simple example of a full P2P market where peers 1 and 2 are producers and peers 3 and 4 are consumers.

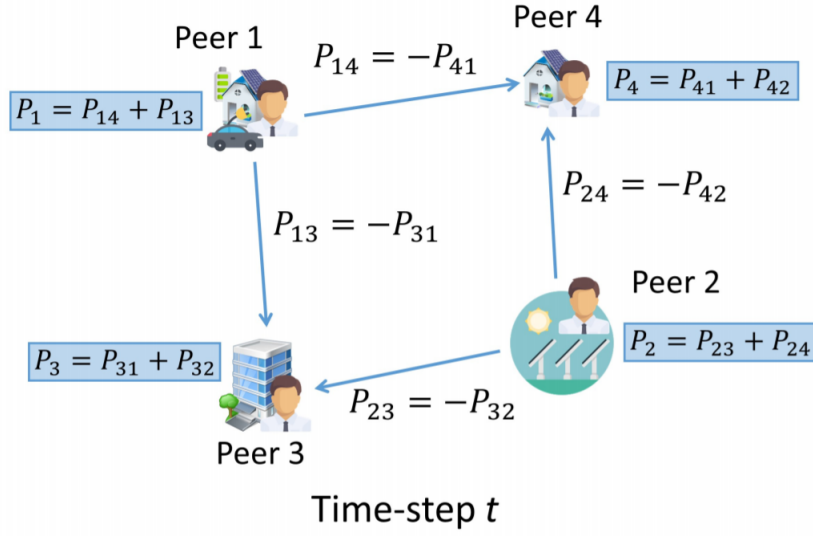


Figure 3.5: Illustrative example of a Full P2P market design (source [8])

The bilateral trades P_{nm} have reciprocity property, meaning that, for example, the power trades P_{23} and P_{32} have to be equal but with opposite signs. [8]

3.2.2 Community-Based Peer-to-Peer Market

This P2P structure has a community manager who manages trading activities not only inside the community, but also between the community and the rest of the grid, as shown in Figure 3.6.



Figure 3.6: Illustrative example of a Community-based P2P market (source [8])

A community is based on members that share common interests and goals, for example, a group of community members that want to share only green energy, even if they don't belong to the same geographical area.

3.2.3 Hybrid Peer-to-Peer Markets

This type of P2P market is the combination of the two previous ones, having different layers of energy trading. This model is illustrated in Figure 3.7.

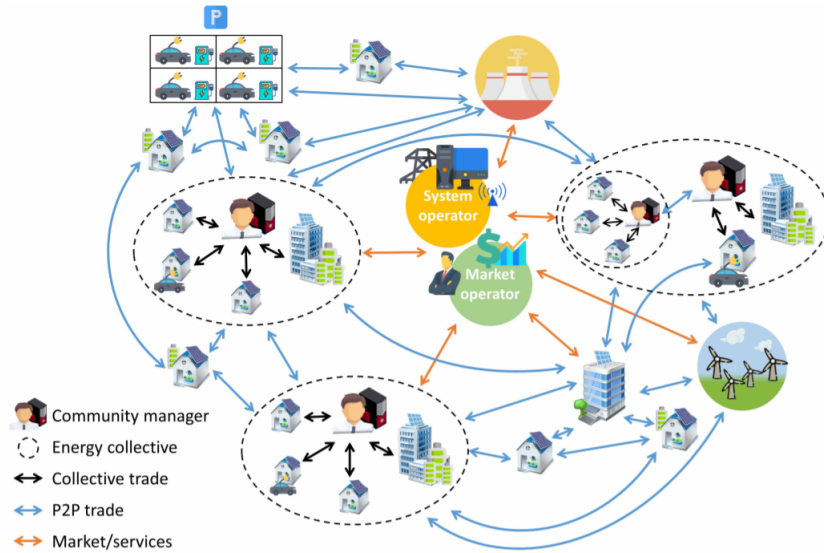


Figure 3.7: Illustrative example of a Hybrid P2P market (source [8])

In each layer, the communities (or energy collectives) and single peers may interact directly with each other. In the upper level, individual peers or energy collectives engage in transactions between themselves, also interacting with the existing markets (as specified in subsection 3.2.1). In the bottom level, the energy collectives behave as a community-based market as previously introduced in subsection 3.2.2, where a community manager controls the transactions within the community.

3.2.4 Comparative Analysis On The Different Peer-to-Peer Market Designs

In order to clarify and structure the concepts associated with these three models, Table 3.1 mentions their advantages and challenges.

Table 3.1: Comparison between the different P2P Markets (source [8])

P2P Market Structure	Advantages	Challenges
Full P2P Market	Energy use adjusted to agent's preference;	Investment and maintenance costs with ICT infrastructures in case of scalability;
		Difficulties to obtain a consensus in the final delivery of energy;
	Freedom of choice and autonomy thus empowering active consumers;	Need to predict system's behaviour by grid operators due to the lack of centralized control;
		Need to guarantee safety and high-quality supply of energy;
Community-based market	Improving the relationship between community members due to the sharing of a common goal;	Satisfying energy needs for all community members simultaneously;
	Providing potential new services for grid operators by the community manager;	Need to have a fair and unbiased share between community members;
Hybrid P2P Market	More predictable to grid operators;	Coordinating internal trades in the communities with trades between high-level agents;
	Can be seen as a combination of the two previous designs, becoming more compatible with the system;	

Analyzing Table 3.1, it is possible to conclude that the Full P2P Market offers the possibility that the energy used is truly aligned with the consumers preferences. On the other hand, there is a scalability problem, meaning that, if this design is applied to the entire power system, there is a real challenge yet to be solved. The main advantages of a Community-Based P2P market design are the enhancement of engagement and cooperation between the community members. The fact that it corresponds to a more structured design allows the community manager to provide additional services to the grid operator as an aggregator, distributing the revenues obtained from these services in a proportional way between all community members. The Hybrid P2P Market

design includes some advantages of the two previous market designs such as empowering the choice of the agents, increasing their engagement and cooperation. Besides that, the scalability of all the system is in a way covered by this design, because the ICT and computational effort is smaller than in the full P2P market design. That being said, the first two previous market designs can co-exist and interact in a hybrid structure, where the coordination of trading operations of both levels is important. [8]

3.2.5 Analysis Of The Peer-to-Peer Market Potential

For a better analysis of this topic, a Strengths, Weaknesses, Opportunities and Threats (in short SWOT) analysis was made and the results are presented in Table 3.2.

Table 3.2: Summary of potential opportunities, threats, strengths, weaknesses (source [8])

Strengths	Weaknesses	Opportunities	Threats
Empowerment of consumers, focusing in trust, transparency and openness;	Sub-optimal energy price of all energy system;	Democratization of energy;	Legal and regulatory obstacles, which influence the transition to these markets;
Consumers have wider choice of supply and possibility to produce and sell their own energy;	Potentially overwhelming transition to this consumer-centric market;	Increase consumers awareness and cooperation towards energetical sustainability;	Energy poverty for some groups of consumers;
Increase the resilience and the reliability of power system;	Heaviness of negotiation and clearing mechanisms;	Create new business models;	Prosumer engagement and its human dimension;
Decrease potential market power from some players in the wholesale market;	Life-cycle assessment of hardware infrastructure;	Boost retailer market, since it lacks competition;	Potential grid congestions;
		Decrease grid investments from system operators;	Technology dependency (e.g blockchain)
			Security and privacy with data;
			Potential failure of these markets if poorly structured;

According to Table 3.2, the empowerment of consumers choice both regarding the type of energy and the energy supplier can be considered as an obvious strength, since it represents the main advantage of the introduction of this type of markets. Contrarily, an unexpected loss of renewable production or a grid congestion represent a major weakness and will need to be solved in a collaborative manner by all peers. Lastly, prosumers will be less volatile to the wholesale market price since they can find alternatives for energy supply in their neighbours. [8]

3.3 Impact of Peer-to-Peer Market on Energy Costs

The growth in technology and the decline in installation costs of renewable generators and storage devices has provided a chance for customers to change their electricity consumption habits and start trying to manage their energy needs by generating / storing their electricity. This new philosophy not only economically benefits the customer but also the environment, since it promotes the increase of the penetration level of renewables. Moreover, this new paradigm is aided by the use of energy batteries due to the unpredictable nature of the renewable energy resources, thus storing the surplus generation and using it when needed. However, there is still a challenge to overcome, which is that customers owning local production / battery system still need to be connected to the grid for reliable electricity service. This paradigm change also carries some downsides, such as the fact that as more customers go off-grid, the cost of the grid infrastructure will be divided among a lower number of customers which will lead to higher electricity bills, namely on what concerns the use of grid tariff components. Besides that, off-grid customers will probably suffer from a low reliability of energy supply in a long-term period. Furthermore, the respective charging/discharging of storage units decline their life duration. To address the abovementioned challenges, peer-to-peer (P2P) energy trading mechanism should be tested, in order to assess its impact on energy costs.

3.3.1 Simulation Case Study of The P2P Market Impact On Energy costs

A study was carried out in [9] to identify and characterize the potential value that is brought by P2P energy trading. The schematic configuration of the network used for the study is shown in Figure 3.8.

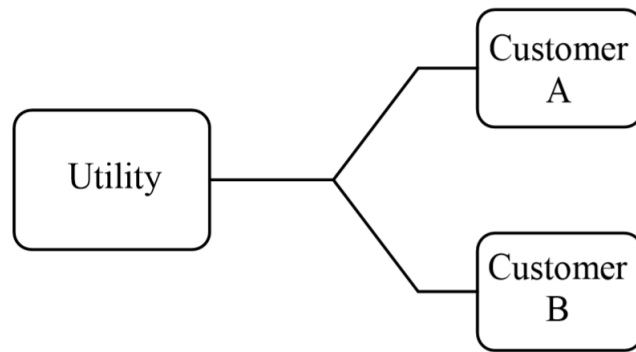


Figure 3.8: Schematic diagram of the network used in simulation study (source [9])

In this scheme, Customer A represents an energy buyer, Customer B has no consumption and has the alternative to invest in solar Photovoltaic/battery unit panels. Two time intervals with 12-hour duration are considered here as off-peak and peak time intervals in each day, respectively, with a specific load/generation profile for each time interval. The study duration is one year. Two different cases are considered, Case I and Case II. In Case I, the P2P market is not considered, while it is considered in case II. [9]

After analyzing the results, it is possible to conclude that it is not economically viable for customer B to invest on PV/battery units in Case I, while it is viable to invest on PV/battery in Case II, because in this case it is possible to recover the initial investment cost by selling energy in the P2P market. [9]

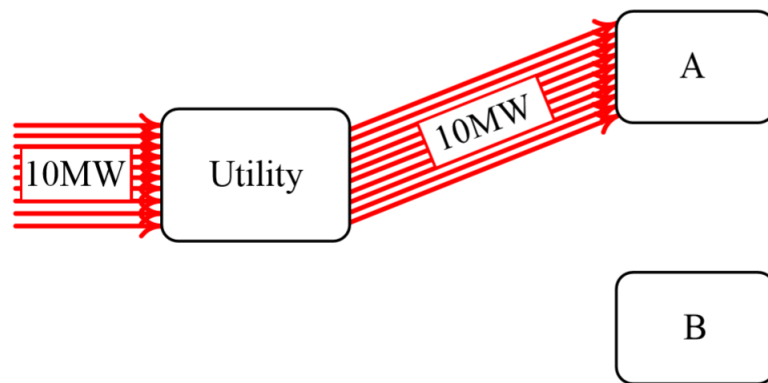


Figure 3.9: Flow of Power in Case I during peak hours (source [9])

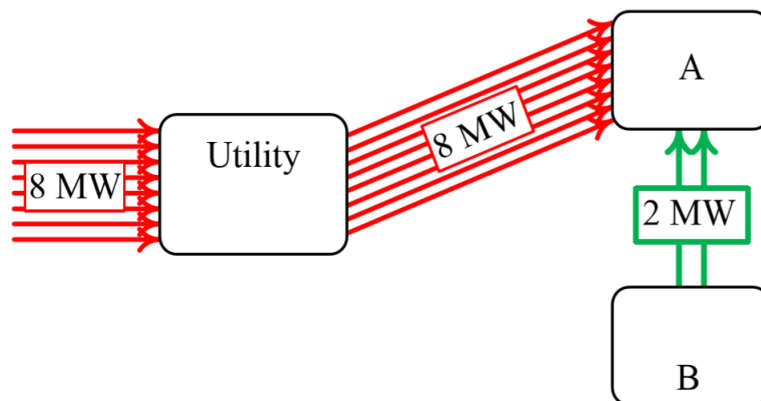


Figure 3.10: Flow of Power in Case II during peak hours (source [9])

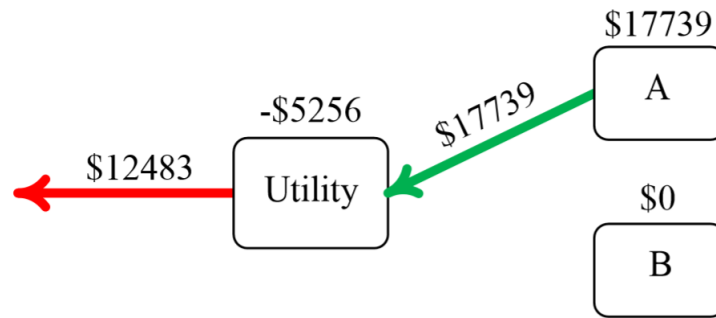


Figure 3.11: Flow of money in Case I (source [9])

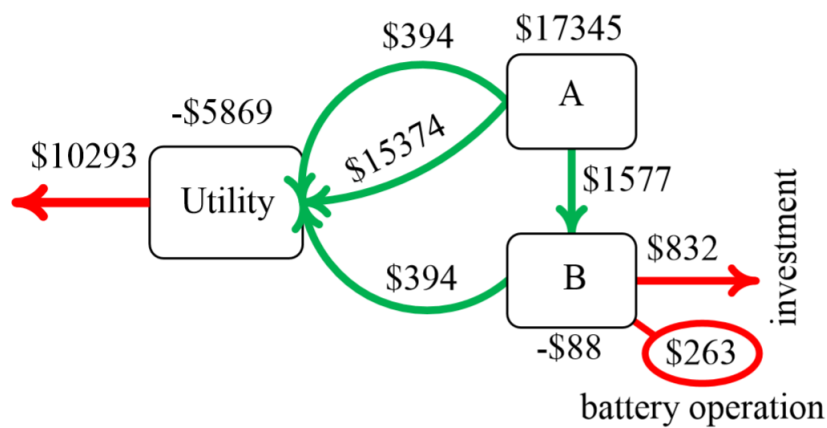


Figure 3.12: Flow of money in Case II (source [9])

The flow of power and money in both cases is shown in Figures 3.9 - 3.12. According to Figures 3.9 and 3.10, the amount of purchased power from the wholesale market decreases during peak hours. In Figures 3.11 and 3.12, red lines show the exported money from the set of utility and customers in terms of purchased power from the upstream grid, investment cost of PV/battery unit, and the operation cost of the battery. According to the Figures 3.11 and 3.12, the annual cost of purchased power decreases from 12483\$ to 10293\$, dividing the resulted benefit among the utility and customers in terms of both cost reduction and benefit increase. The share of the utility in terms of energy selling decreases, but there is an increase in the utility benefit for providing network infrastructure. The utility is likely to have a sustainable flow of benefit due to network charges in the near future grid. To make that happen, there is a need for an optimum plan of investment in the network infrastructure. [9]

To conclude, this simulation study shows that the implementation and development of a P2P Market not only brings benefits to the customers but also to the utility. The employment of the aforementioned market results in less energy purchase during peak hours, which means less power

passes through the substation and feeders, thus preventing the utility from unnecessary investments in grid equipment.

3.3.2 Comparison Between The Impact Of The Different P2P Market Designs On Energy Costs

A study was carried out in [8] in order to compare the impact on the energy costs of the different P2P Market designs described in section 3.2. This simulation was performed considering the grid in Figure 3.13. This grid has 8 prosumers and 11 regular consumers and bus 1 represents the connection to the main grid.

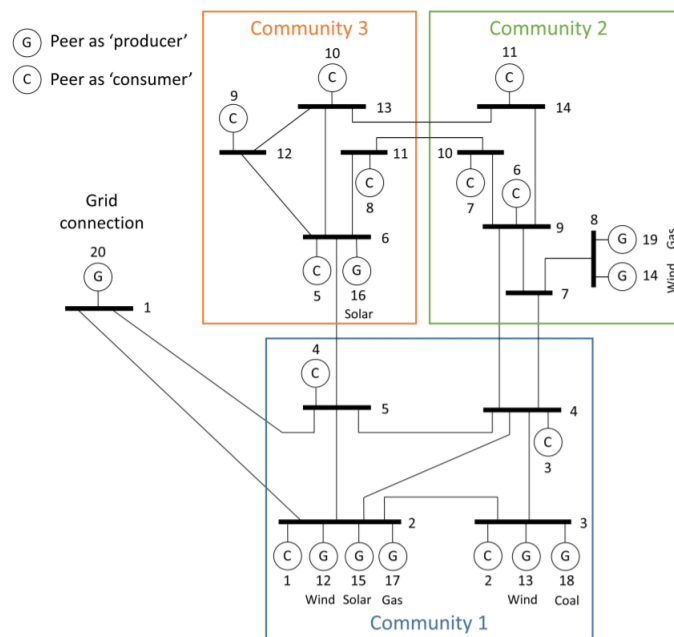


Figure 3.13: IEEE 14-bus network system (source [8])

This test case is simulated over one year with 30 minutes time-step based on available Australian data. A quadratic cost function is used as the cost function of all resources. Nonetheless, the PV and wind turbines are considered as must-take producers. This simulation assumes a tariff of 10 \$/MWh, thus, the importation price from the generator in bus 1 is equal to the market price plus the grid tariff. Contrarily, the export price is equal to the market price minus the grid tariff.

Table 3.3: Results of all P2P market designs (source [8])

Market designs	Total SW [M\$]	Import Cost [M\$]	Export Revenue [M\$]
Full P2P	45.21	0.072	56.66
Community	44.27	2.88	58.95
Hybrid P2P	44.32	2.86	58.71

Analyzing Table 3.3, one can conclude that the highest social welfare is reached with the full P2P design due to the sharing of renewable surplus amongst all peers, while the community design presents the lowest result. This shows that exporting to the main grid is less profitable than trading with other peers between the three communities. Hence, the hybrid P2P design improves the social welfare when compared to the community design. [8]

Table 3.4: Energy trade for all P2P market designs (source [8])

Market designs	Total load [GWh]	Total import [GWh]	Total export [GWh]	Community exchange [GWh]
Full P2P	401.4	2.1	1041.1	54.4
Community	395.1	45.4	1093.4	0
Hybrid P2P	395.7	44.7	1085.5	9.1

Analyzing Table 3.4, the full P2P design achieved the highest energy consumption, due to the same reason (sharing renewable surplus) mentioned when analyzing Table 3.3. This fact illustrates the low energy import and high energy exchange between communities achieved in this design. Differently, the community design presents the highest results for the energy import and export, as expected (communities only trade with the main grid hence the highest results for the energy import and export). To conclude, the best result is obtained by the full P2P design when all peers share the renewable surplus. Despite that, one should not conclude that this is the best design, since the main objective is to have a real test case for assessing different P2P designs with all the network constraints included. [8]

3.4 Review of the Existing Peer-to-Peer Trading Projects

3.4.1 Piclo

Piclo was established in the UK. This platform uses meter data, generator pricing and consumer preference information to match electricity demand and supply every half hour. The generators know and control who buys electricity from them and consumers can choose from which generators to buy electricity from. This project is a partnership between an innovative technology company aiming to democratise energy called "Open Utility" and the renewable energy supplier "Good Energy" where consumers can buy electricity directly from the local renewables. Piclo matches generation and consumption according to the preferences and locality, providing customers with data visualizations and analytics. Good Energy provides contacts, meter data, billing, and balances the market place. Generators could also apply a discount or a premium to their power purchase agreement. Any extra amount paid by a consumer on a premium price is passed through entirely to the generator, while any savings from a discount rate go entirely to the consumer. The generators can also set allocation limits, restrict access to their prices and add a supporting message explaining why consumers should buy at a lower or higher rate. Piclo's main target are companies

that have higher energy consumptions than residential consumers, guiding these companies to the use of renewable energies. [10]

3.4.2 Vandebron

Vandebron is an online platform located in the Netherlands. Furthermore, in this platform, energy consumers can buy electricity directly from independent producers, such as farmers with wind turbines in their fields. It acts very similarly to Piclo, as it links consumers and generators, balancing the whole market. [11]

3.4.3 PeerEnergyCloud

PeerEnergyCloud was a project in Germany. Its objective was to develop a cloud-based technology to deal with local excessive production. It was established in order to investigate innovative recording and forecasting procedures for device specific electricity consumption, to establish a virtual marketplace for power trading within a Microgrid. [12]

3.4.4 Smart Watts

Smart Watts, like PeerEnergyCloud, was a German project. Its main goal was to achieve, through the use of modern information and communication technologies (ICT), greater cost-effectiveness and secure energy supply. [13]

3.4.5 Yeloha and Mosaic

Both Yeloha and Mosaic were projects in the US. These projects allowed interested consumers, like apartment owners and others who do not own solar systems, to pay a portion of the solar energy generated by the hosts solar system. These subscribers get a reduction on their utility bills, so that in total, they save money, even if they move. These projects are similar to Piclo and Vandebron, but more focused on solar energy than in other renewables. [14]

3.4.6 SonnenCommunity

SonnenCommunity is a project in Germany. It was a project developed by SonnenBatteries which is a storage manufacturer. This project consists of a community of sonnenBatteries owners that can share their self-produced energy between themselves. With sonnenBatteries and a photovoltaic system, members can completely cover their needs on sunny days, often even generating a surplus. This surplus is not injected into the conventional power grid, but into a virtual energy pool, generating a local energy market and serving the members that are not producing enough energy due to bad weather. There is a central software platform that connects and monitors all members of the sonnenCommunity balancing energy supply and demand. This project is similar to Piclo and Vandebron, however, sonnenCommunity highlights the importance of having storage systems available. [15]

3.4.7 Lichtblick Swarm Energy

Swarm Energy is a group of services provided by the German energy supplier Lichtblick. These services have a unique IT platform in the energy market called Swarm Conductor. On this

platform, there is a combination of the processes of an increasingly complex world of energy with customer-friendly products and services for residential and business customers. Swarm Energy allows not only a notorious interaction of distributed and renewable energy sources but also an optimization of storage and local power plants. [16]

3.4.8 Community First! Village

Community First! Village is a 1000 square meters community that grants affordable, permanent housing and a supportive community for the disabled, chronically homeless in Austin, Texas. The project owners are trying to supply power to the village through electricity donations. [17]

3.4.9 LO3 Energy

LO3 Energy is a community energy market located in Brooklyn, New York City. It allows its members to buy and sell energy from each other securely and automatically through smart contracts and Ethereum blockchain (cryptocurrency). Home producers can sell their energy surplus to their neighbours, allowing communities to keep their energy resources and increase micro and macro grid efficiency. [18]

3.4.10 Electron

Electron is a revolutionary new platform for gas and electricity metering and billing systems. It is a completely secure, decentralized platform that provides metering, billing and switching service using blockchain and Smart Contracts. The platform will not be owned or controlled by suppliers, making it open source and operating for the benefit of all users. [19]

3.4.11 Dajie

Dajie is a platform based on the combination of Internet of Things devices and the blockchain technology located in the UK. Their IoT devices create a network of nodes in a local MicroGrid allowing the exchange of energy through peer-to-peer models. The blockchain technology allows recording in real time transactions on a distributed database, making them irreversible, safer and more accessible. With this platform, for every kWh of energy produced, one energy coin will be generated. With this energy coin, small prosumers are finally compensated for their CO₂ reduction, being able to redeem a carbon credit with a energy coin. Moreover, energy companies can use the coins and the blockchain to get paid for the energy and services they provide to their customers, substantially reducing their administrative costs. Also, communities will be able to share energy peer-to-peer in a local neighbourhood at a better price than what they can get feeding that energy back to the grid. [20]

3.4.12 Hive Power

HivePower is a platform located in Switzerland. This platform, provides anyone with the possibility to create and manage energy communities on the blockchain, also complying with grid constraints on power quality and current limitations. The market design enhances the cooperation between users, promoting the use of solar energy and batteries. They are currently working on several projects, such as, the optimisation of the use of batteries, Electric Vehicles, heat pumps

and water heating systems, communication protocols preserving users privacy and an innovative business model for P2P energy exchange. [21]

3.4.13 Comparison Between The Existing Peer-to-Peer Trading Projects

To finalize this section, Table 3.5, that can be found in [22], provides the main characteristics of the previously mentioned projects so that the reader can more easily compare them.

Table 3.5: Comparison between the existing Peer-to-Peer trading projects (source [22])

Project Name	Objectives	Network Size	P2P Layers	Status of the Project
SonnenCommunity	P2P energy trading with storage system	National	Business, Power Grid	Ongoing
Lichtblick Swarm Energy	IT platform for energy markets and customers	National	ICT, Power Grid	Ongoing
Community First! Village	Energy sharing from donations	Community	Business	Ongoing
LO3 Energy	P2P energy trading within Microgrids using Blockchain	Grid-Connected Microgrids	Business, Control, ICT, Power Grid	Ongoing
Electron	Energy metering and billing platform using Blockchain	Unknown	Business, ICT, Power Grid	Ongoing
Dajie	P2P energy trading within Microgrids using a combination of IoT devices and blockchain	MicroGrid	Business, ICT, Power Grid	Ongoing
Hive Power	Create and manage energy communities using Blockchain	Community	Control, Power Grid	Ongoing
Piclo	P2P energy trading platform from suppliers perspective	National	Business	Ongoing
Vandebon	P2P energy trading platform from suppliers perspective	National	Business	Ongoing
PeerEnergyCloud	Cloud-based P2P Energy Trading Platform	Microgrids	ICT, Power Grid	Terminated (Research Project)
Smart Watts	Optimizing energy supply via ICT	Regional	ICT, Power Grid	Terminated (Research Project)
Yeloha, Mosaic	P2P energy trading platform focused on solar energy	Regional	Business	Terminated due to funding issues

Analyzing Table 3.5, many of the above trading projects have some similarities. For example, Piclo, Vandebon, Yeloha and Mosaic (project terminated due to funding issues), Community First! Village are platforms that focus only on the Business Layer of the P2P architecture model. In addition, both PeerEnergyCloud and Smart Watts used to focus on ICT technologies suitable

for local energy markets. However, both projects are now terminated because they were just research projects. Furthermore, LO3 Energy, Electron, Dajie, Hive Power are all projects that use blockchain technology into the energy sector to simplify energy markets billing and metering system. Finally, SonnenCommunity is similar to Piclo and Vandebron but highlights the importance of the storage system, while Lichtblick Swarm Energy focuses more on the ICT part of the platform.

3.5 Legal Framework Regarding Self-Consumption In Portugal

Self-consumption can be defined as the ratio of energy use from local generation to the total energy used. In Portugal, in late October 2019, a new Law Decree was passed in order to promote a higher share of renewable production.

According to this Law Decree [23],

"...No âmbito do referido plano, a promoção e disseminação da produção descentralizada de eletricidade a partir de fontes renováveis de energia veio a merecer acrescida relevância, como um dos eixos a desenvolver, de forma a alcançar o objetivo essencial de reforço da produção de energia a partir de fontes renováveis e de redução de dependência energética do país. Alcançar uma quota de 47% de renováveis no consumo final de energia implica que no setor elétrico as renováveis contribuam com pelo menos 80% da produção de eletricidade. Neste sentido, o contributo da produção descentralizada — apenas possível através do regime estatuído neste decreto-lei — será fundamental para alcançar este objetivo, pelo que a capacidade instalada, nomeadamente no solar, deverá atingir pelo menos 1 GW em 2030. ... "

According to article 4º (Remuneration) of this Law Decree [23],

".. A energia excedente do autoconsumo pode ser transacionada:

- a) Em mercado organizado ou bilateral, incluindo através de contrato de aquisição de energia renovável.
- b) Através do participante no mercado contra o pagamento de um preço acordado entre as partes.
- c) Através do facilitador de mercado..."

According to article 5º (Requirement to access this activity) of this Law Decree [23],

"...Podem proceder à atividade de autoconsumo, através de UPAC (Unidades para Autoconsumo), independentemente do nível de tensão das instalações de consumo:

- a) Os autoconsumidores individuais;
- b) Os autoconsumidores coletivos, organizados em condomínios de edifícios em regime de propriedade horizontal ou não, ou um grupo de autoconsumidores situados no mesmo edifício ou zona de apartamentos ou de moradias, em relação de vizinhança próxima, unidades industriais, comerciais ou agrícolas, e demais infraestruturas localizadas numa área delimitada, que disponham de UPAC;

c) As CER (Comunidades de Energia Renovável)..."

According to article 7º (Rights of the self consumer) of this Law Decree [23],
"... O auto consumidor tem o direito de:

- a) Instalar UPAC para produzir eletricidade para consumo próprio, recorrendo a uma qualquer fonte de energia renovável e respetivas tecnologias de produção associadas;
- b) Estabelecer e operar linhas diretas quando não exista acesso à rede pública, e estabelecer e operar redes internas, nos termos do presente decreto-lei, para ligação da UPAC à IU (Instalação de Utilização);
- c) Consumir, na IU associada à UPAC, a eletricidade produzida ou armazenada em instalações próprias, e entregar a produção excedente a terceiros ou à RESP (Rede Elétrica de Serviço Público)..."

According to article 8º (Duties of the self consumer) of this Law Decree [23],
"... Constituem deveres do autoconsumidor de energia renovável:

- a) Suportar o custo das alterações de ligação de IU à RESP, nos termos da regulamentação da Entidade Reguladora do Setor Energético (ERSE);
- b) Suportar os encargos de ligação de UPAC à RESP, nos termos de regulamentação da ERSE;
- c) Suportar o custo associado aos contadores, nos termos previstos no artigo 16º;
- d) Dimensionar a UPAC de forma a garantir a maior aproximação possível da energia elétrica produzida à quantidade de energia elétrica consumida na IU..."

According to article 16º (Metering and availability of the data) of this Law Decree [23],
"... É obrigatória a contagem de energia elétrica total produzida por UPAC:

- a) No caso de autoconsumo coletivo;
- b) No caso de autoconsumo individual, quando a IU associada à UPAC se encontre ligada à RESP e a potência instalada seja superior a 4 kW..."

According to article 17º (Commercial relationship of the self consumer of renewable energy) of this Law Decree [23],

"... O operador da rede deve facilitar a intervenção do autoconsumidor, diretamente ou através de um agregador independente, de um facilitador de mercado, ou de um comercializador que agregue produção, na prestação de serviços de sistema ou na transação de energia elétrica excedente em mercados organizados ou bilaterais..."

According to article 18º (Tariffs due by the production units for self consumption) of this Law Decree [23],

"... 1 - A utilização de redes internas, que não envolva a utilização da RESP para veicular energia

elétrica entre a UPAC e a IU, é isenta de pagamento;

2 - A utilização da RESP, para veicular energia elétrica entre a UPAC e a IU, fica sujeito ao pagamento, pelo autoconsumidor, das tarifas de acesso às redes aplicáveis ao consumo ao nível de tensão de ligação com a IU, deduzidas:

- a) Das tarifas de uso das redes dos níveis de tensão a montante do nível de tensão da UPAC, quando exista injeção de energia a partir da rede pública a montante do nível de tensão de ligação da UPAC;
- b) De parte das tarifas de uso das redes dos níveis de tensão a montante do nível de tensão de ligação da UPAC, no montante a definir pela ERSE, quando exista inversão do fluxo de energia na rede pública para montante do nível de tensão de ligação à UPAC..."

According to article 19^o (Renewable energy communities) of this Law Decree [23],

"... 1 - As CER contribuem para a produção e desenvolvimento do consumo de energia renovável numa lógica de complementaridade com o restante sistema elétrico nacional, de modo a assegurar o cumprimento das metas e objetivos de Portugal em matéria de energia e clima;

2 - O consumidor final, nomeadamente o consumidor doméstico, tem o direito de participar numa CER, mantendo os seus direitos e obrigações enquanto consumidor final;

3 - O exercício do direito previsto no número anterior não pode ser sujeito a condições ou a procedimentos injustificados ou discriminatórios que impeçam a participação na CER;

4 - As CER têm a faculdade de:

- a) Produzir, consumir, armazenar e vender energia renovável, nomeadamente através de contratos de aquisição de eletricidade renovável;
- b) Partilhar, no seu seio, a energia renovável produzida pelas unidades de produção de que são proprietárias, com observância dos outros requisitos previstos no presente artigo, sem prejuízo de os membros da CER manterem os seus direitos e obrigações enquanto consumidores;
- c) Aceder a todos os mercados de energia adequados, tanto diretamente como através de agregação, de forma não discriminatória..."

Analyzing this law decree, it is possible to conclude that its main goal is to increase the amount of renewable production. In fact, article 5 enables individual consumers, collective consumers and renewable energy communities to own self-consumption units. Furthermore, article 18 mentions that the prosumers that use an internal grid, hence not using the main grid, are free from the payment of the upstream grid tariffs. Lastly, article 19 promotes the energy trading within a Renewable Energy Community.

Chapter 4

Peer-to-Peer Markets

This chapter includes a detailed analysis of the mathematical models used to formulate the different Peer-to-Peer markets, in order to allow a better and quicker understanding of the conclusions and results presented on the next chapters.

To begin with, the mathematical formulations behind the aforementioned markets are presented and analyzed. Afterwards, the procedure used to achieve the results is elucidated.

4.1 Full Peer-to-Peer Market

4.1.1 Mathematical Formulation

A general mathematical formulation of the full P2P market design [24] is given by (4.1) to (4.6):

$$\max Z = - \sum_{n \in \Omega_c} C_{Dn} * P_{Dn} - \sum_{n \in \Omega_p} C_{Gn} * P_{Gn} \quad (4.1)$$

$$\overline{P_n} \leq \sum_{m \in \omega_n} P_{nm} \leq \underline{P_n} \quad \forall_n \in \Omega \quad (4.2)$$

$$P_{nm} + P_{mn} = 0 \quad \forall (n, m) \in (\Omega, \omega_n) \quad (4.3)$$

$$P_n = \sum_{m \in \omega_n} P_{nm} \quad \forall_n \in \Omega \quad (4.4)$$

$$P_{nm} > 0 \quad \forall (n, m) \in (\Omega_p, \omega_n) \quad (4.5)$$

$$P_{nm} < 0 \quad \forall (n, m) \in (\Omega_c, \omega_n) \quad (4.6)$$

In this formulation:

- Equation (4.1) - Objective Function that corresponds to the maximization of the sum of all energy purchasing bid prices C_D multiplied by the demanded quantity P_D (the minus signal in this summation is because of equation 4.6 where the energy trades as a consumer are considered negative) minus all of the energy selling bid prices C_G multiplied by the produced quantity P_G (contrarily, the energy trades as a producer are considered positive as a result of equation 4.5). Furthermore, this equation is equal to equation (2.1) since the variable P_D in this formulation is negative. This means that in the Full P2P model we are in fact maximizing the social welfare function that can be obtained by the participants in the energy community.
- Equation (4.2) - Power Generation and Demand boundaries, where ω_n refers to all the trading partners of a peer n .
- Equation (4.3) - Energy Balance of the market, this constraint is associated with the dual variable $\lambda_{n,m}$ that refers to the price of each transaction paid by the agents.
- Equation (4.4) - This constraint represents the Energy per Agent of all the trading partners that trade energy with agent n . If n is a consumer then ω_n corresponds to the producers, if n is a producer then ω_n refers to the consumers.
- Equation (4.5) - If this constraint is verified it means that the trade between agents n and m was a sale/production.
- Equation (4.6) - On the other hand, if this constraint is verified, it means that the trade between agents n and m corresponded to a purchase/consumption.

4.1.2 Illustrative Case Study 1

This model aims to enable the direct trade of energy between two different peers, as explained in Chapter 3. A fictional grid with clients of the company "Energia Simples" was used, in order to, provide a realistic test case to simulate this Peer-to-Peer market.

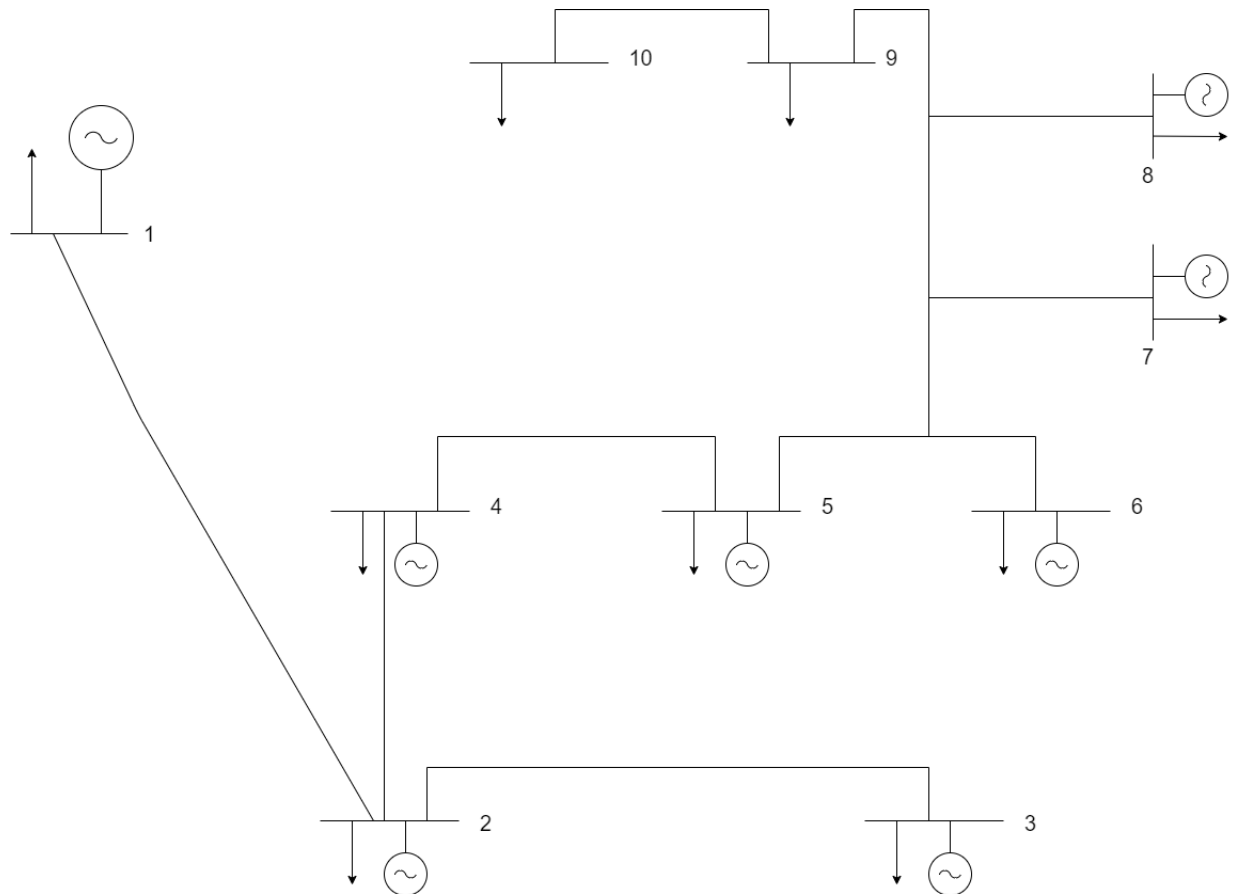


Figure 4.1: Single Line Diagram of the fictional grid

In this grid:

- Bus 1 - Upstream connection with the main grid, where both the generator and the load assume an infinite power.
- Bus 2-6 - PV Prosumers.
- Bus 7 - Prosumer with a 5 kW nominal power wind turbine.
- Bus 8 - Prosumer with a 10 kW nominal power wind turbine.
- Bus 9-10 - Regular Consumers.

All the data was analyzed using the software **Microsoft Office Excel**. More precisely, four data sets were considered for each bus:

- Amount of generated power;
- Amount of demanded power;
- Energy purchase bids;
- Energy sale bids.

In fact, each bus has its own information. Bus 1 has a generator that, assuming an infinite generated power, represents the rest of the grid, having the following sale bid price:

$$C(P_{G1}) = C(P_{G1}) \div 0,45 \quad (4.7)$$

In this expression, $C(P_{G1})$ represents the price of energy for the correspondent hour of the Iberian Electricity market (data from [25]). This price was divided by a 0,45 factor to incorporate the effect of the Access Tariffs that end consumers also have to pay. In average, in recent years, the energy price coming from the daily market represents 45% of the final end user Low Voltage Tariffs. Moreover, Bus 1 also has a load that, assuming an infinite demanded power, represents the rest of the grid, having the following purchase bids:

$$C(P_{D1}) = C(P_{G1}) * 0,9 \quad (4.8)$$

In this expression, $C(P_{G1})$ is the cost of importing energy from the grid (calculated as in equation 4.7). Additionally, according to article 24^o of the law decree [26], self-consumption units can inject their energy surplus on the grid, being paid 90% of the average Iberian Electricity Market price for the month under analysis. In this illustrative example, this rule was applied not to the average monthly market price but to the market price of the hour under analysis.

For the generators in Buses 2-6 (Prosumers with PV), the energy sale bids are formulated by a random number generator function, ranging between 42 €/MWh and 49 €/MWh, having the energy selling bid price given by (4.9):

$$C(P_{G2-6}) = C(P_{G2-6}) \div 0,85 \quad (4.9)$$

In this expression, $C(P_{G2-6})$ represents the price of buying PV energy from prosumers 2-6, divided by a 0,85 factor used to consider the tariff of the use of the Distribution Network in Low Voltage.

For the generators in buses 7-8 (Prosumers with wind turbines), the energy sale bids are also formulated by a random number generator function, ranging between 47 €/MWh and 54 €/MWh. Their energy selling bid prices are given by (4.10):

$$C(P_{G7-8}) = C(P_{G7-8}) \div 0,85 \quad (4.10)$$

In this expression, $C(P_{G7-8})$ represents the price of buying energy from prosumers 7-8, divided by a 0,85 factor used to consider the tariff of the use of the Distribution Network in Low Voltage.

Analyzing all of the above equations (4.7, 4.8, 4.9 and 4.10), one can conclude that, for the majority of the hours, it would be more expensive to buy energy from the generator in Bus 1 due to the energy and grid tariffs (there are some hours in which it is cheaper to buy from the grid because of the high percentage of renewable production in that period, thus lowering the market price), hinting that, for most hours, peers will only buy energy from the generator in Bus 1 if their demand cannot be entirely satisfied by other peers. Furthermore, there are going to be hours that after satisfying the demand of the entire grid there are still going to remain generators with energy surplus. This surplus is going to be sold to the infinite load represented in Bus 1, for the price illustrated in Equation 4.8.

Additionally, all energy purchasing bid prices were considered higher than the highest energy selling bid price, thus ensuring energy supply for all of the consumers demand. These values were adopted in order to have a fair comparison between the objective functions of the different markets. Moreover, by applying this principle, we are now towards a dispatch problem (the load is graphically represented by a vertical line because given the price relations we are now supplying it entirely), meaning that, the goal of the objective function is now to minimize the costs associated with energy production, hence maximizing the Social Welfare.

4.2 Community-Based Market

4.2.1 Mathematical Formulation

A general mathematical formulation of the community-based Peer-to-Peer market [27], is given by (4.11) to (4.16):

$$\max Z = \sum_{n \in \Omega_c} C_{Dn} * P_{Dn} + \sum_{n \in \Omega_p} C_{Gn} * P_{Gn} + c_{exp} q_{exp} - c_{imp} q_{imp} \quad (4.11)$$

$$\rho_n + q_n - \alpha_n + \beta_n = 0, \forall n \in \Omega \quad (4.12)$$

$$\sum_{n \in \Omega} q_n = 0 \quad (4.13)$$

$$\sum_{n \in \Omega} \alpha_n = q_{imp} \quad (4.14)$$

$$\sum_{n \in \Omega} \beta_n = q_{exp} \quad (4.15)$$

$$\overline{P}_n \leq \sum_{m \in \omega_n} P_{nm} \leq \underline{P}_n, \quad \forall_n \in \Omega \quad (4.16)$$

In this formulation:

- Equation (4.11) - Objective Function that accounts for the cost associated with all variables, corresponding to the maximization of the sum of all energy purchasing bid prices multiplied by the demanded quantity minus all energy selling bid prices multiplied by the produced quantity (in the expression there is a plus signal due to the amount of generated energy being considered negative), plus the exported quantity from the community to the grid multiplied by the export price, minus the imported quantity from the grid to the community times the import price. Once again, and following the Full P2P model, one is maximizing the Social Welfare function associated with the participants in the energy community.
- Equation (4.12) - Community Energy Balance equation.
- Equation (4.13) - Each agent trades energy within the community q_n without knowing to which member the energy is sold because the operation is centrally handled by the community manager.
- Equation (4.14) - Amount of Exported Energy to the outside.
- Equation (4.15) - Amount of Imported Energy from the outside to the community.
- Equation (4.16) - Power Generation and Demand boundaries, where ω_n refers to all the trading partners of a peer n .

4.2.2 Illustrative Case Study 2

This model enables the trade of energy between peers within the same community, managed by a central node (community manager), as explained in Chapter 3. Moreover, all peers within the same community function as one, meaning that whether we are towards a situation where there is a need to import energy or export energy, all the energy needs will be summed as if it was only "one peer" linked with the grid. A fictional grid with clients of the company "Energia Simples" was used in order to provide a realistic test case to simulate this Peer-to-Peer market.

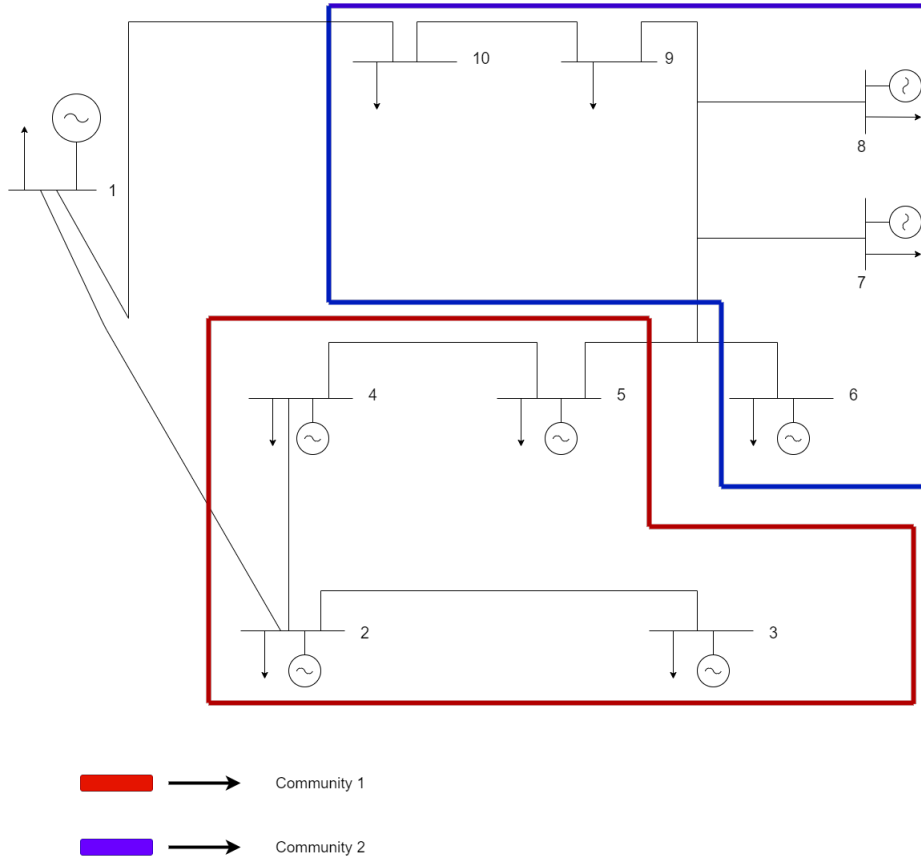


Figure 4.2: Single Line Diagram of the community fictional grid

In this grid:

- Bus 1 - Upstream connection with the main grid, where both the generator and the load assume an infinite power;
- Bus 2-10 - PV prosumers, prosumers with wind turbines and regular consumers all members of community 1 and 2.

Similarly to the Illustrative Case Study 1 procedure of the Full Peer-to-Peer Market, all data was analyzed in the software **Microsoft Office Excel**. However, in this market, six data sets were considered for each bus, as follows:

- Amount of generated power;
- Amount of demanded power;
- Energy price of the purchasing bids;
- Energy price of the selling bids;
- Cost of Exporting energy from the community to the grid;
- Cost of Importing energy from the grid to the community.

As a matter of fact, the equations to determine the energy price of the selling bids of the generators on all buses are the same as in the full Peer-to-Peer Market (equations 4.7, 4.9 and 4.10 of subsection 4.1.2). Furthermore, the cost of exporting energy from the community to the grid is given by equation (4.17):

$$C_{exp} = C_{imp} * 0,9 \quad (4.17)$$

In this expression, C_{exp} represents the cost of exporting energy from the community to the grid and C_{imp} is the cost of importing energy from the grid to the community (calculated as in equation 4.7). Additionally, the 0,9 factor was considered due to the same reasons mentioned in subsection 4.1.2 for equation 4.8. Moreover, all of the energy purchasing bid prices were also considered higher than the highest energy selling bid price as in subsection 4.1.2. In fact, in order to have a fair comparison between the different market designs on the next Chapter, the costs associated for both the importing and exporting of energy must be the same for all of the market designs.

4.3 Hybrid Peer-to-Peer Market

4.3.1 Mathematical Formulation

A general mathematical formulation of a Hybrid Peer-to-Peer Market [8], is given by (4.18) to (4.21):

$$\max Z = - \sum_{n \in \Omega_c} C_{Dn}^u * P_{Dn}^u - \sum_{n \in \Omega_p} P_{Gn}^u * C_{Gn}^u + \sum_{n \in \Omega_c} C_{Dn}^b * P_{Dn}^b + \sum_{n \in \Omega_p} C_{Gn}^b * P_{Gn}^b + c_{exp} q_{exp} - c_{imp} q_{imp} \quad (4.18)$$

s.t upper level - full P2P design

$$\text{constraints in (4.1.1)} \quad \forall \epsilon \Omega^u \quad (4.19)$$

$$\sum_{m \in \omega_n} P_{nm} = q_{exp}^n - q_{imp}^n \quad \forall (n, m) \in (\Omega_{co}, \omega_n) \quad (4.20)$$

bottom level - community-based design:

$$\text{constraints in (4.2.1)} \quad \forall_n \epsilon \Omega^b \quad (4.21)$$

- Equation (4.18) - Objective Function that accounts for the cost associated with all variables, corresponding to an integrated version of the objective function of the full P2P market and the Community-Based P2P market, equations (4.1) and (4.11), where u corresponds to the upper level (Full P2P design) and b to the bottom level (Community-Based P2P design). In this expression, the same indications regarding the signals of the demand and generation variables apply as they were considered for the objective functions of the Full P2P and the Community-Based market design.
- Equation (4.19) - Constraints of the Full P2P market that correspond to the upper level of this design (direct energy trading between community managers).
- Equation (4.20) - The sum of the bilateral trades P_{nm} is equal to the amount of q_{exp}^n minus q_{imp}^n defined by the community manager of each community n.
- Equation (4.21) - Constraints of the Community-Based market that correspond to the bottom level of this design (energy trading within the community).

4.3.2 Illustrative Case Study 3

This model allows energy trading within two different levels. In the bottom level, the energy is traded within the community, as explained in subsection 4.2.2. Furthermore, in the upper level, the energy is traded directly between the community managers, working as a Full P2P market, as explained in subsection 4.1.2. A fictional grid with clients of the company "Energia Simples" was used, in order to, provide a realistic test case to simulate this Peer-to-Peer market.

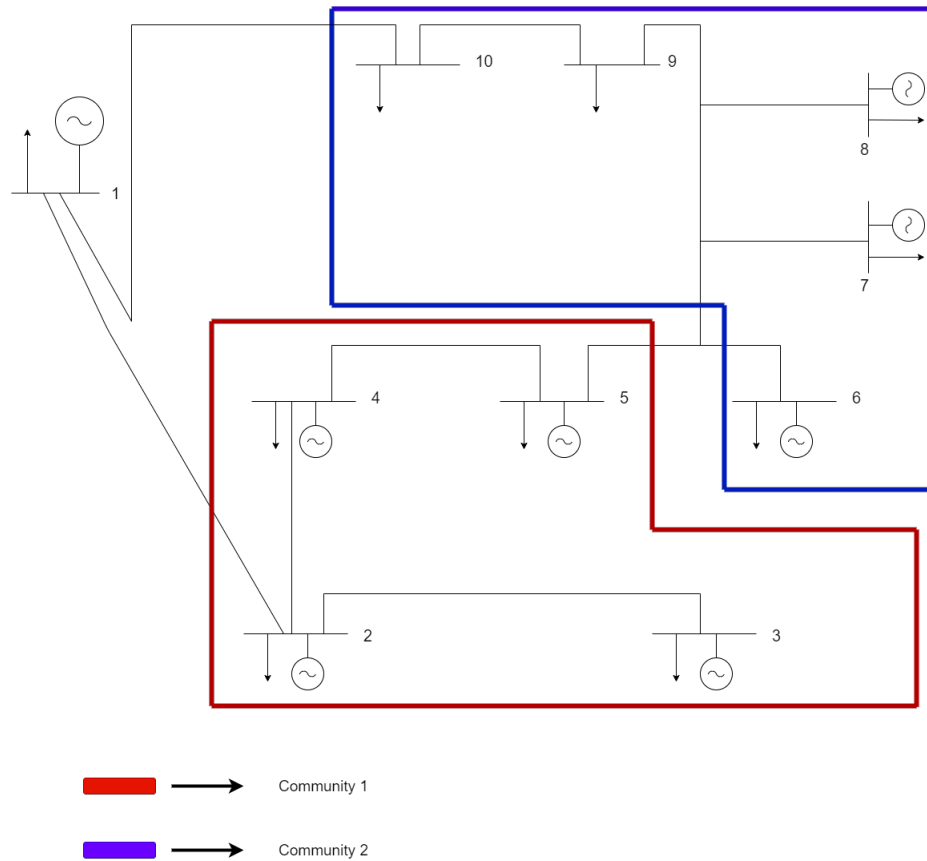


Figure 4.3: Single Line Diagram of the fictional grid

In this grid:

- Bus 1 - Upstream connection with the main grid, where both the generator and the load assume an infinite power;
- Bus 2-10 - PV prosumers, prosumers with wind turbines and regular consumers all members of community 1 and 2.

Analogous to the experimental procedure of the Community-Based Peer-to-Peer market, all data was analyzed in the *software Microsoft Office Excel*, also considering six data sets for each bus:

- Amount of generated power;
- Amount of demanded power;
- Energy price of the purchasing bids;
- Energy price of the selling bids;
- Cost of Exporting energy from one community to another and from the community to the grid;
- Cost of Importing energy from the grid and from another community.

Actually, the equations to determine the energy selling bids of the generators on all buses are the same as in the full Peer-to-Peer market (equations 4.7, 4.9 and 4.10 of subsection 4.1.2). Additionally, all energy purchasing bids were assumed larger than the highest energy selling bid, in order to ensure energy supply for all of the consumers demand. However, both the cost of exporting and importing energy were tested in two different scenarios:

- 1) Exporting/importing energy to the grid with the same cost as exporting/importing energy to other communities, given by equation (4.17) from subsection 4.2.2.
- 2) Different costs for exporting/importing to the grid and exporting/importing to other communities.

4.4 Chapter Overview and Conclusions

To sum up, in the Full P2P market, there is a direct energy trade between two different prosumers. On the other hand, in a Community-Based market, all peers work as one, meaning that there will be certain periods in which one peer can cover the energy needs of the others while there will be other periods in which the aforementioned peer will need the help of the other community peers to cover its energy needs. Moreover, there will also be hours in which the communities represented in Figures 4.2 and 4.3, will need to import energy from the grid. Therefore, not only will the community be rewarded for exporting energy to the grid, but also will need to import energy due to the lack of internal energy production for that specific period (most of the peers are PV prosumers, hence they are only able to produce a significant amount energy, more or less, for 6 hours a day).

Additionally, the Hybrid Peer-to-Peer market combines both markets mentioned above. In fact, this market, works in two distinct levels. At the bottom level, it operates as a community-based design, meaning that, for each community all peers work as one so that their energy needs are covered. At the upper level, in case the aforementioned energy needs are not covered for the

reasons explained above, it works as a Full P2P design, meaning that, the community manager will either buy energy from another community or from the grid, depending on the amount of energy surplus on other communities and also on the prices of those transactions.

Lastly, to have a fair comparison between the different market designs on the next Chapter, all the energy purchasing and selling bid prices are considered the same and so are the costs associated to exporting/importing energy to the grid. Furthermore, all the data sets mentioned above for each design, for each bus, were imported from **Microsoft Office Excel** to the *software Python 3*. Afterwards, the mathematical model was implemented in the aforementioned software and optimized/solved by **Gurobi 9.0.1**, thus achieving the final results.

Chapter 5

Simulation Results

As mentioned in Chapter 4, the data sets for all of the Peer-to-Peer market designs were imported from **Microsoft Office Excel** to the *software* **Python 3**. Subsequently, the mathematical models were implemented in the aforementioned software and optimized/solved by **Gurobi 9.0.1**, hence achieving the final results. As one will understand during this chapter, each one of the different Peer-to-Peer markets change its results according to the input prices. Therefore, the costs of importing/exporting energy to the grid were considered the same for each market, in order to have a fair comparison between each one of them.

To begin with, a data assessment for the day 1/1/2019 is made, followed by a seasonal comparison. Afterwards, this chapter includes a comparison between the different market designs for the entire year of 2019.

5.1 Full Peer-to-Peer Market

5.1.1 Daily analysis

Figure 5.1 and 5.2 present the amount of produced energy, in kWh, of generators 1 to 8 for the day 1/1/2019. These generators correspond to the fictional grid mentioned in Chapter 4, where generators 2 to 6 are PV, generators 7 and 8 are Wind Power and generator 1 represents the amount of energy imported from the grid.

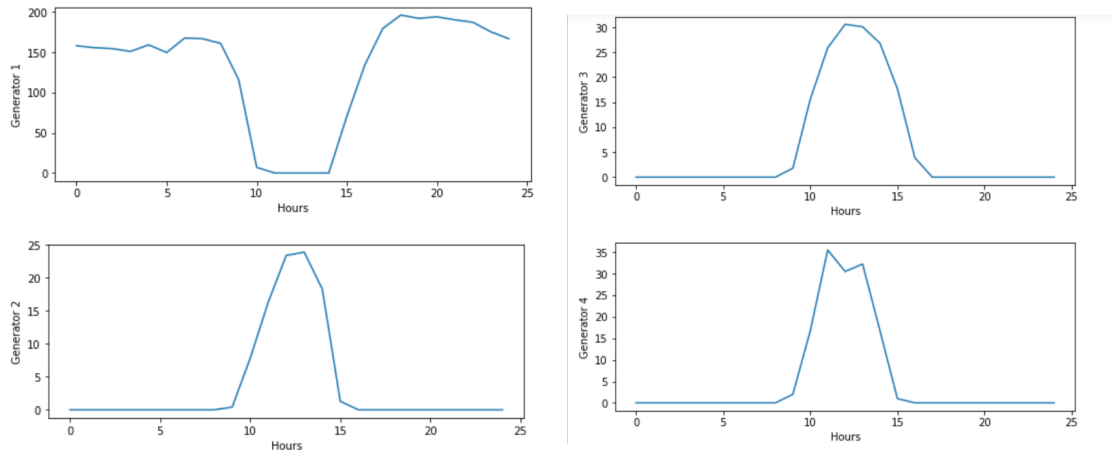


Figure 5.1: Amount of Generated energy of generators 1 to 4, in kWh

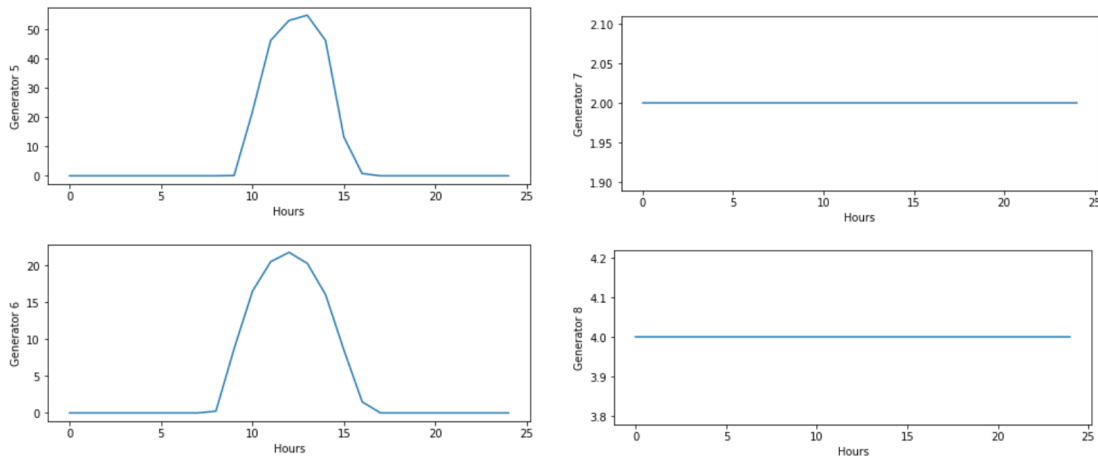


Figure 5.2: Amount of Generated energy of generators 5 to 8, in kWh

In fact, for hours 10-15, PV generators 2, 3, 4, 5 and 6 reach their generation peak due to a higher PV production correspondent to those hours. Moreover, generator 7 that corresponds to a 5 kW nominal power wind turbine, produces continuously 2 kWh for all hours, for that specific time of the year. Generator 8 that corresponds to a 10 kW nominal power wind turbine, will

produce, for all periods, the double of what generator 7 produces. On the other hand, Generator 1 represents the grid and it only supplies energy if the demand can not be entirely satisfied by the other generators, since it is more expensive to buy energy from the grid than from the other prosumers due to the energy and grid tariffs, as explained on Chapter 4. That being said, as one can analyze from Figure 5.1, Generator 1 doesn't supply energy for hours 10-15 because in these periods the demand is fulfilled by Generators 2 to 8.

Analyzing Figure 5.3, one is able to understand the amount of demanded power for loads 1 to 10.

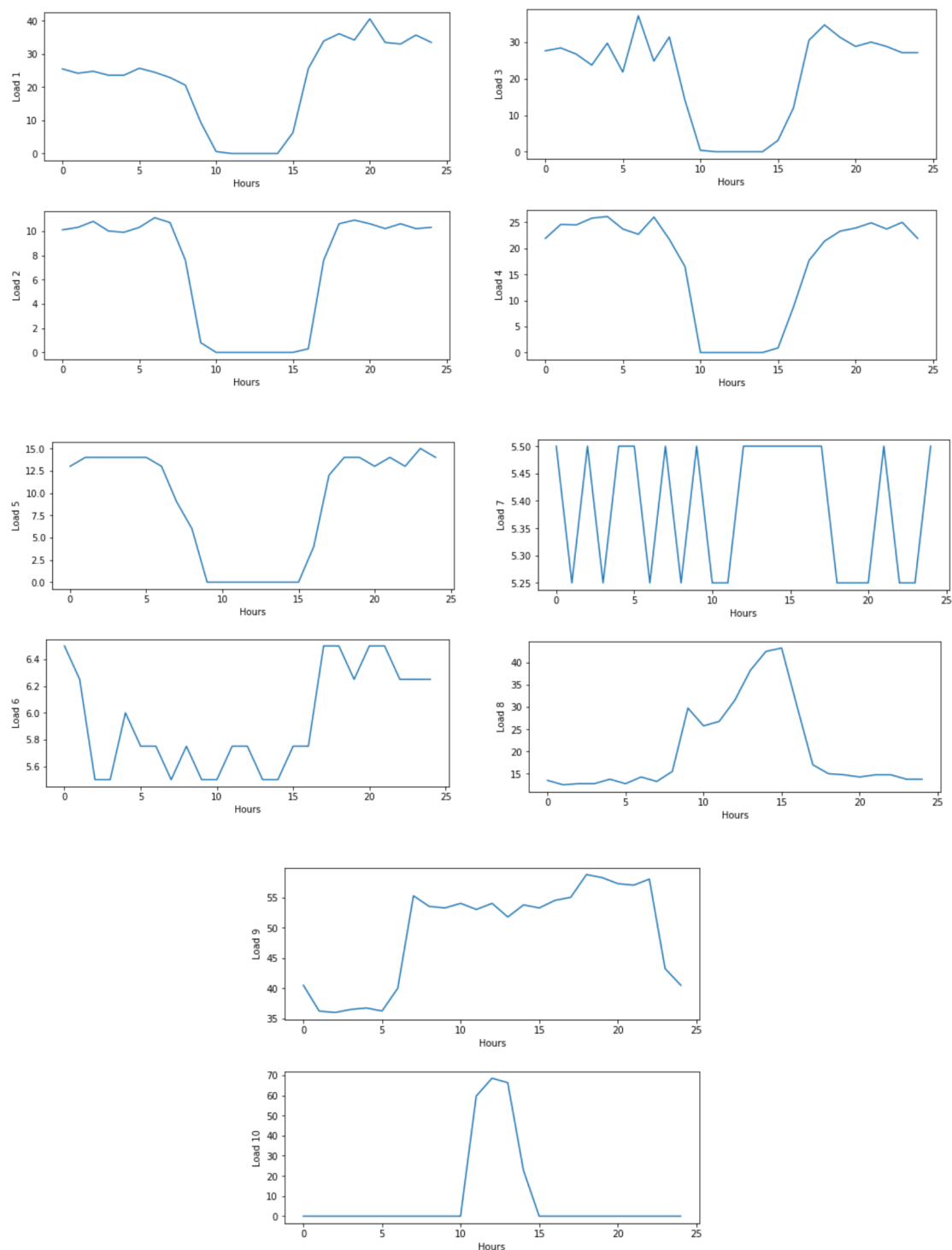


Figure 5.3: Amount of Demand for loads 1 to 10, in kWh

Actually, the loads 1, 2, 3, 4, 5 are entirely self-supplied by their PV Generators for hours 10-15, thus not having any energy supplied by the grid for those periods. Furthermore, loads 6 and 7 have self-supply units, however, since their self-supply units are wind power turbines (2 kWh for load 6 and 4 kWh for load 7 of produced energy, for that specific time of the year) their demand doesn't have an established pattern like loads 1, 2, 3, 4 and 5. For loads 8 and 9, as they represent regular consumers, their demand also has an irregular pattern. Lastly, after assuring that the energy needs of loads 1-9 are entirely satisfied, the generators will sell their surplus energy to the grid (represented by load 10) explaining the values being always zero except for hours 10-15.

Inspecting Figure 5.4, one can evaluate the evolution of the objective function of the Full P2P Market for the day 1/1/2019.

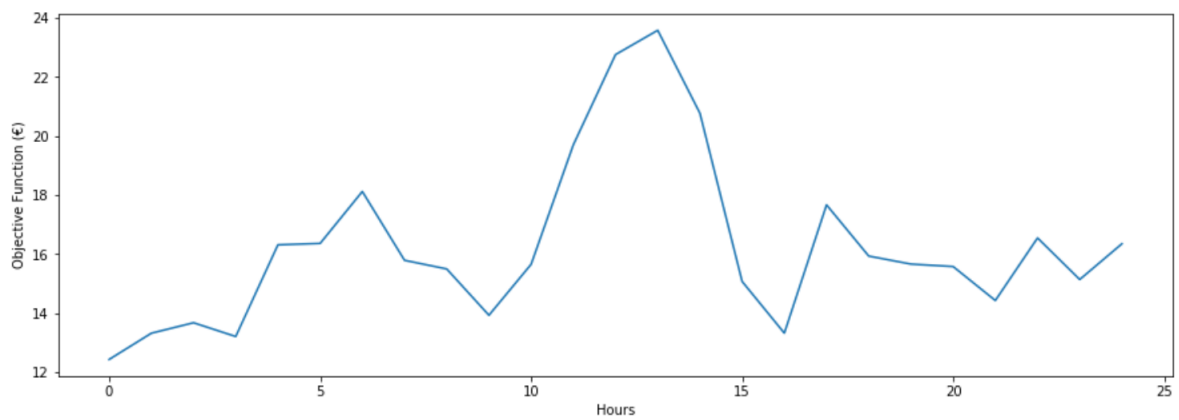


Figure 5.4: Evolution of the Objective Function of the Full P2P Model, in euros

As a matter of fact, as shown in Chapter 4, since all the energy purchasing bid prices are higher than the highest energy selling bid price, one is solving a problem close to a dispatch problem, meaning that the objective is now to minimize the costs associated with energy production, hence maximizing the Social Welfare. That being said, for the hours 10-15 the objective function achieves its best values due to the fact that, since there is a higher contribution of PV generators 1-5 in that period, they will be the firsts to be cleared, originating more reduced generation costs, and thus, a better value for the objective function.

To help better understanding the simulation results for this Test Case, Table 5.1 is shown below.

Table 5.1: Results of the Full P2P Market Design for a 24 hours period

Full P2P	Total Energy Demand (kWh)	Total Energy Generated (kWh)	Total Import (kWh)	Total Export (kWh)	Import Cost (€)	Export Revenue (€)
	3895,49	878,75	3234,01	217,25	456,26	27,99

In fact, as one can interpret through Table 5.1, the sum of the total energy demand (sum of all loads except load 10 that corresponds to the energy export to the grid) with the total energy export (load 10) is equal to the sum of the total energy generated (sum of all generators except generator 1 that corresponds to the energy import from the grid) with the total import, both assuming the value 4112,75 kWh. This shows that, as said before, all of the energy demand is being entirely supplied. Moreover, the costs associated with energy import are much higher than the revenue obtained from exporting energy. This is due to the fact that, since most of the energy generated is PV, there is only more energy export than energy import for about 5 hours in one day, existing a continuous need to import energy from the grid for the remaining 19 hours of the day.

5.1.2 Seasonal Analysis

This market design changes its values according to the time of the year. Therefore, Table 5.2 indicates how the results of this Full P2P evolve along different periods of the year.

Table 5.2: Seasonal Comparison for the Full P2P Market Design

Full P2P						
Months of the Year	Total Energy Demand (kWh)	Total Energy Generated (kWh)	Total Import (kWh)	Total Export (kWh)	Import Cost (€)	Export Revenue (€)
January February March April	1009204,35	54657,39	958961,89	4414,95	119889,76	427,71
May June July August	936580,49	107708,09	844156,89	15284,35	92511,39	1413,97
September October November December	1125864,5	28625,29	1097915,99	675,99	106938,85	59,17

Actually, for the same reasons as the ones explained above, for the months May, June, July and August this market design attains its best results. In fact, since in those months there is a much higher PV production than in the others, there are a large number of periods in which not only the entire demand is self-supplied but there is also a high amount of energy surplus to trade. This makes the clients of the company rely less on energy importing from the grid and also having more energy available to export. Moreover, the months of September, October, November and December have the worst results for the export revenue, total energy demand and total energy generated on account of being the months with the lowest PV generation. However, even though the amount of imported energy for these months is higher than for the months of January, February, March and April, the import costs were lower due to the fact that the price of the Iberian Electricity Market, for the year of 2019, was lower for the months of September, October, November and December than for the months of January, February, March and April.

5.2 Community-Based P2P Market

5.2.1 Daily Analysis

As illustrated in subsection 4.2.2, two different communities were taken into account for this simulation of the day 1/1/2019. Community 1, that is formed by PV Prosumers 1 to 4 and Community 2 that is formed by PV Prosumer 5, Wind Turbine Prosumers 6 and 7 (one with a 5 kW nominal power wind turbine and the other with a 10 kW) and regular consumers 9 and 10. Analyzing Figures 5.5 and 5.6, one can conclude that all the generators behave exactly the same as the ones in the Full Peer-to-Peer market design.

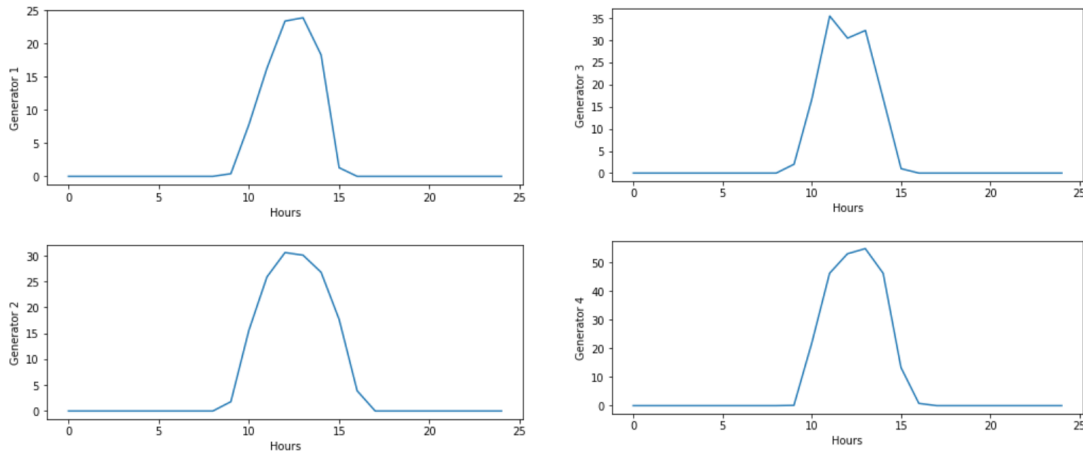


Figure 5.5: Amount of Generated energy of generators 1 to 4 of Community 1, in kWh

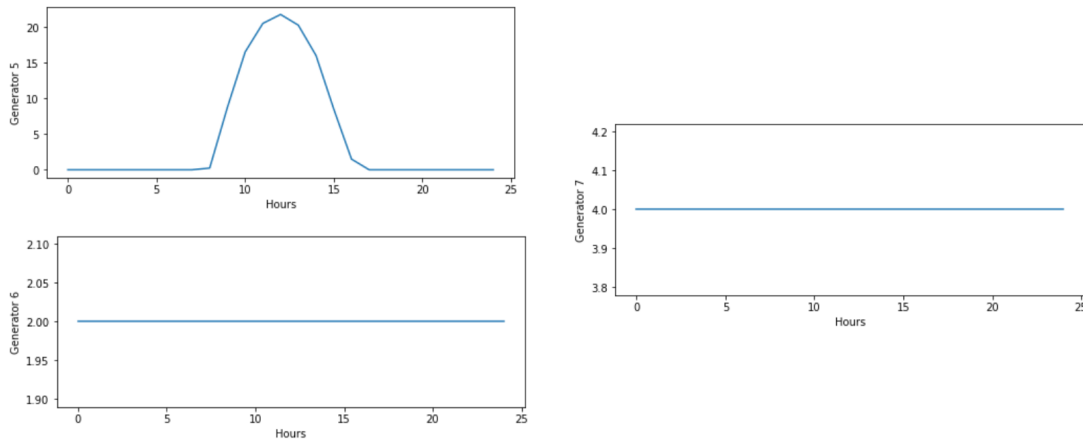


Figure 5.6: Amount of Generated energy of Generators 5 to 7 of Community 2, in kWh

In fact, this happens because all of the PV and wind turbine generators will always generate the maximum amount of energy they can, since after satisfying the energy demand of the other peers, their surplus energy will be exported to the grid.

Analyzing Figures 5.7 and 5.8, one can also conclude that the loads also behave exactly the same for both markets.

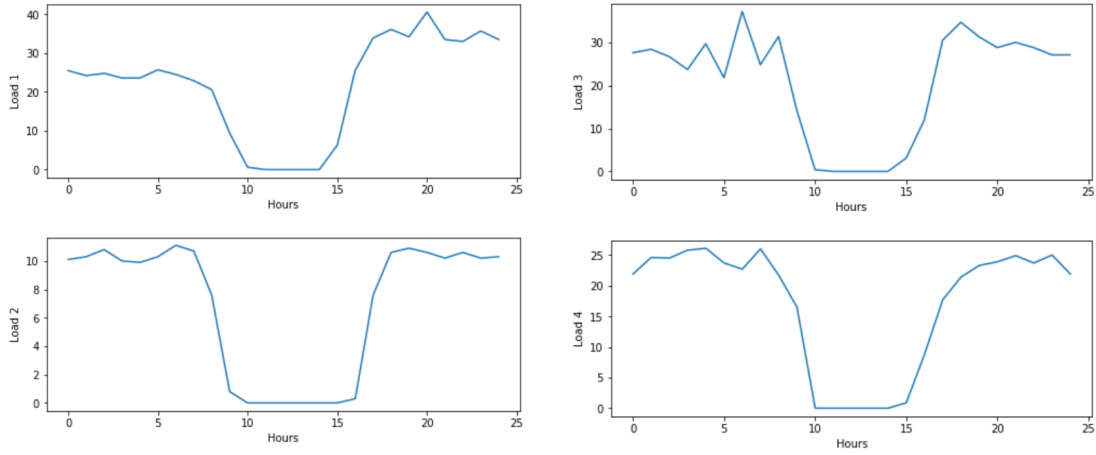


Figure 5.7: Amount of Demand for loads 1 to 4 of Community 1, in kWh

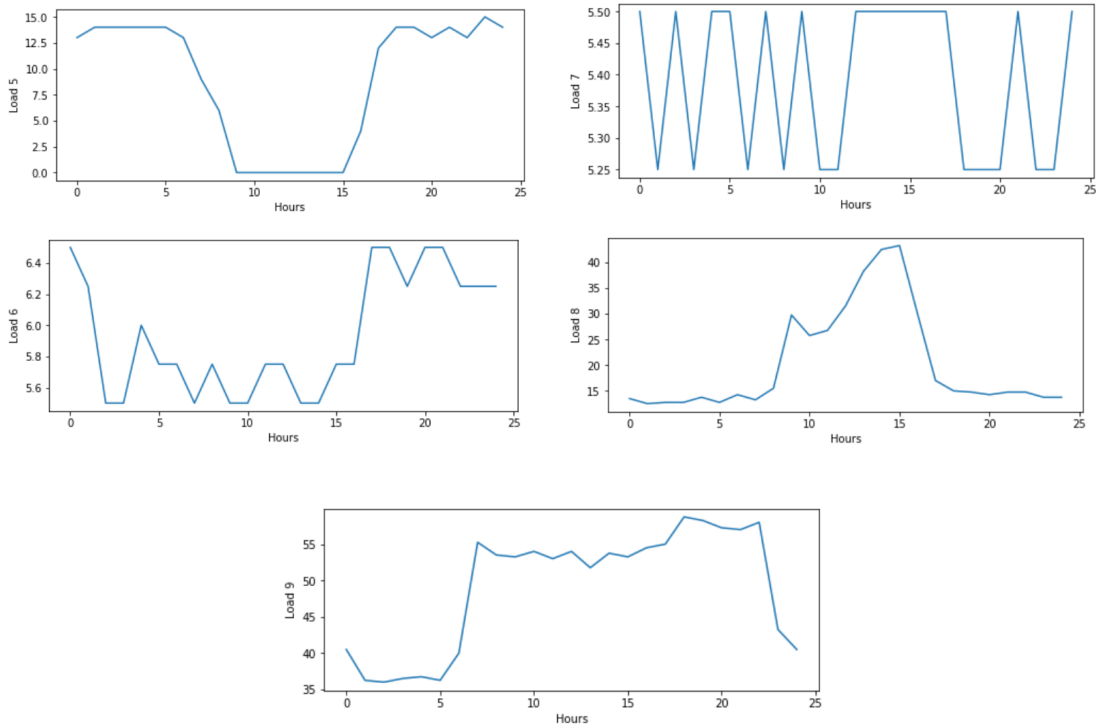


Figure 5.8: Amount of Demand for loads 5 to 9 of Community 2, in kWh

As a matter of fact, the loads also behave exactly the same for both markets because, since one is towards a dispatch problem, the demand of all the loads will be entirely satisfied, meaning

that, if there is no more energy surplus within the community to satisfy the demand, the required demand will be imported from the grid.

Contrarily to the generators and the loads, the imported/exported energy of the different communities will be distinct from the Full P2P Market design, as shown on Figures 5.9 and 5.10.

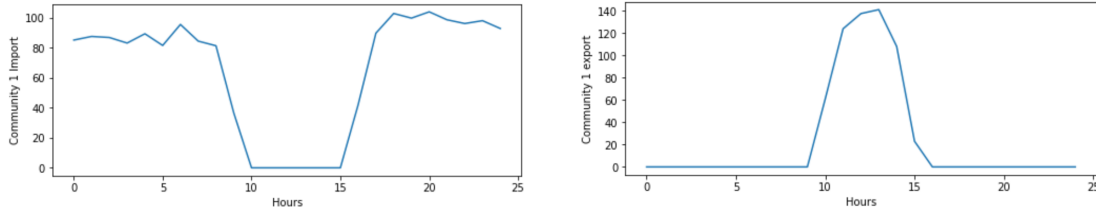


Figure 5.9: Amount of Imported and Exported Energy of Community 1, in kWh

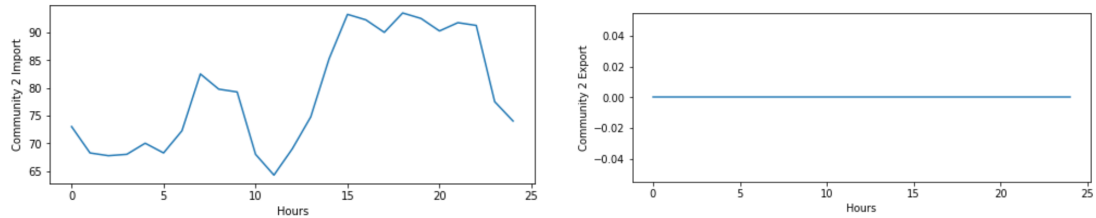


Figure 5.10: Amount of Imported and Exported Energy of Community 2, in kWh

Actually, Community 1, for hours 10-15, besides fulfilling its entire demand, exports a high amount of energy to the grid. Contrarily, Community 2 doesn't produce enough energy to supply its demand, thus needing to import energy from the grid for all of the periods, importing its minimum for hours 10-15 due to the higher PV generation on that period. Additionally, for hours 18-24, it imports the highest amount of energy as a result of those being the hours in which the energy demand reaches its largest value.

Analyzing Figure 5.11, one can visualize how the objective functions for communities 1 and 2 evolve for the day 1/1/2019.

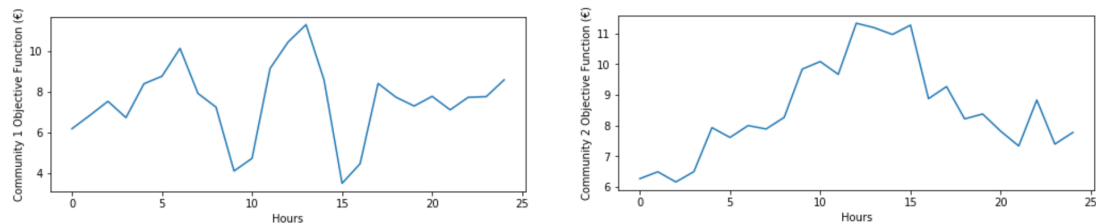


Figure 5.11: Evolution of the Objective Function of Communities 1 and 2, in euros

Moreover, one can conclude that on hours 10-15 both objective functions reach their best values due to the higher PV generation on those periods. As mentioned before, since this is a dispatch problem, the objective is to minimize the costs associated to generation, hence maximizing the Social Welfare. For hours 10-15, the generation costs achieve their minimum due to the fact that, since there is more PV generation and buying from the PV generators is cheaper than buying from the grid, those generators are the first to be allocated, hence lowering the costs. This is similar to what happens on the Full P2P market design. To sum up, on the hours that one relies the most on energy importing from the grid, the objective function will assume its worst values. Contrarily, on the hours in which one besides relying less on energy importing, also exports, the objective function will assume its best values.

To better interpret the Community-Based market design simulation results, Table 5.3 is shown below.

Table 5.3: Results of the Community-Based P2P Market Design for a 24 hour period

Community-Based P2P	Total Energy Demand (kWh)	Total Energy Generated (kWh)	Total Import (kWh)	Total Export (kWh)	Import Cost (€)	Export Revenue (€)
Community 1	1655,00	614,75	1634,70	594,45	230,99	76,33
Community 2	2240,50	264,00	1976,50	0	278,98	0
Total (Com1+Com2)	3895,49	878,75	3611,20	594,45	509,97	76,33

Furthermore, the results presented on Table 5.3 are in accordance with the graphics shown in Figures 5.5, 5.6, 5.7, 5.8, 5.9 and 5.10. After all, Community 1 has more generators and less loads than Community 2, hence it generates and exports more energy and has a lower level of demand and energy import.

5.2.2 Seasonal Analysis

Similarly to the Full P2P Market, the simulation results change according to the time of the year. So, Table 5.4 helps to better understand which months have the best/worst results.

Table 5.4: Seasonal Comparison of both Communities regarding the Community-Based P2P Market Design

Community-Based P2P (Com1+Com2)						
Months of the Year	Total Energy Demand (kWh)	Total Energy Generated (kWh)	Total Import (kWh)	Total Export (kWh)	Import Cost (€)	Export Revenue (€)
January February March April	1009204,35	54657,39	971885,35	17338,39	121531,74	1743,49
May June July August	936580,65	107714,10	877003,45	48136,91	95989,41	4463,52
September October November December	1125864,10	28627,35	1104232,98	6996,23	107214,99	550,40

In fact, equivalently to the Full P2P Market, this market design achieves its best results for the months of May, June, July and August as a result of the higher PV generation for the aforementioned periods. Moreover, the worst results for the export revenue, total energy demand and total energy generated are for the months of September, October, November and December due to the lower PV generation on those periods. Furthermore, similarly to the Full P2P Market, the amount of imported energy is higher for the months of September, October, November and December than for the months of January, February, March and April due to a larger energy demand and a lower energy generation. However, although the amount of imported energy is higher, the import costs are lower, as a result of the prices of the Iberian Electricity market, for the year of 2019 being lower for the months of September, October, November and December than for the months of January, February, March and April.

5.3 Hybrid P2P Market

5.3.1 Daily Analysis

As described on subsection 4.3.2, two different communities were considered for this simulation of the day 1/1/2019. Moreover, since the communities are composed by the same peers as in the Community-based market design, the real difference is that while in the Community-based design the communities only trade energy with the grid, on the Hybrid market design the communities besides being able to trade energy with the grid, also trade with each other. Lastly, in order to better understand the differences between this market design and the Community-Based, two different Scenarios will be considered, as mentioned in subsection 4.3.2:

- Scenario 1) The costs of trading energy between the communities are the same as the costs of trading energy between the communities and the grid;
- Scenario 2) The costs of trading energy between the communities are lower than the costs of trading energy between each community and the grid.

In fact, since the communities have the same agents as in the Community-Based market design and the rule that every load is fully supplied still stands, the amount of generated, demanded, imported and exported energy will be the same as in the Community-Based market design illustrated in subsection 5.2.1, for both scenarios. Therefore, the graphic representations of the aforementioned variables, for the different communities, will be the same as in Figures 5.5, 5.6, 5.7, 5.8, 5.9 and 5.10.

5.3.1.1 Scenario 1

Regarding Scenario 1, being the costs of trading energy between the communities and the grid the same as the costs of trading energy between communities, the objective function of this Scenario will be the sum of the objective functions of both communities described in subsection 5.2.1. That being said, Figure 5.12 represents the sum of the values in the two graphs of Figure 5.11.

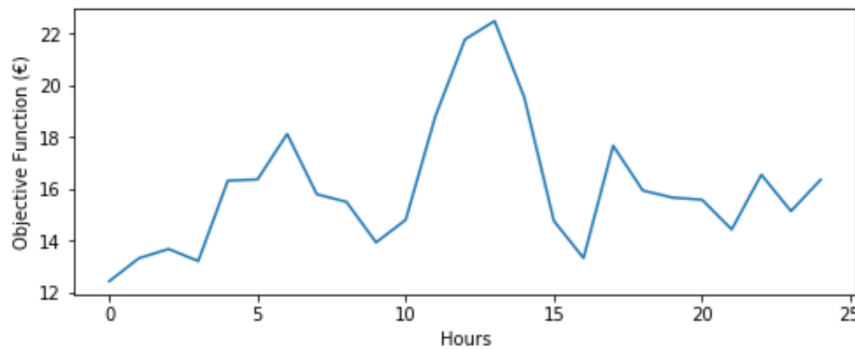


Figure 5.12: Evolution of the Objective Function for the Scenario 1 of the Hybrid P2P Market, in euros

As one can conclude by analyzing Figure 5.12, the best values for the objective function are achieved for hours 10-15 due to the higher PV penetration on those periods. Following the same reasoning mentioned before, the values presented on Table 5.5 are equal to the ones illustrated in the last row of Table 5.3.

Table 5.5: Results for the Scenario 1 of the Hybrid P2P Market Design for a 24 hour period

Hybrid P2P	Total Energy Demand (kWh)	Total Energy Generated (kWh)	Total Import (kWh)	Total Export (kWh)	Import Cost (€)	Export Revenue (€)
Scenario 1	3895,5	878,75	3611,2	594,45	509,98	76,33

Inspecting Table 5.5, one can conclude that, as mentioned before, all the values are equal to the ones on the last row of Table 5.3, because, since the loads need to be entirely satisfied and the costs for the energy trade between communities and between the communities and the grid are the same, this market design will have the same results as in the Community-Based market design.

5.3.1.2 Scenario 2

Regarding Scenario 2, the costs of trading energy between communities are lower than the costs of trading energy between the communities and the grid, hence encouraging the energy trade from one community to another. Furthermore, on this Scenario, the communities will initially trade with each other in order to satisfy their demand, only trading with the grid as a last resort. According to this model, Figure 5.13 represents the objective function considering this Scenario.

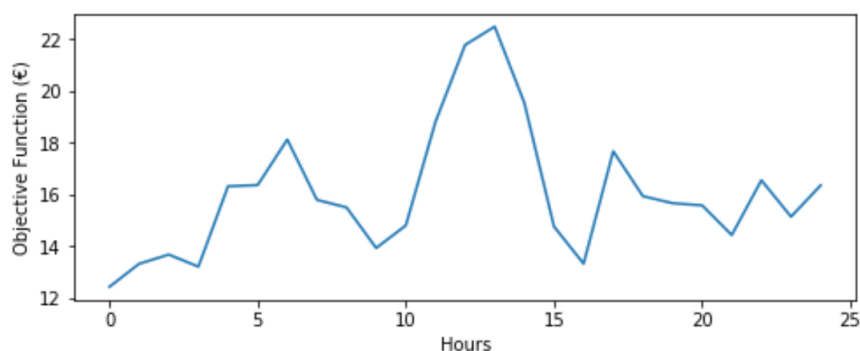


Figure 5.13: Evolution of the Objective Function for the Scenario 2 of the Hybrid P2P Market, in euros

Analyzing Figure 5.13, one can infer that the graphic representation of the objective function of Scenario 2 assumes the same pattern as the one of Scenario 1 (Figure 5.12). Furthermore, the only difference between both objective functions is that the one for Scenario 2 has better values,

since the costs of the energy trade between communities are lower, thus inducing more profit than in Scenario 1. Moreover, the results presented on Table 5.6 are in line with the explanation above.

Table 5.6: Results for the Scenario 2 of the Hybrid P2P Market Design for a 24 hour period

Hybrid P2P	Total Energy Demand (kWh)	Total Energy Generated (kWh)	Total Import (kWh)	Total Export (kWh)	Import Cost (€)	Export Revenue (€)
Scenario 2	3895,5	878,75	3611,2	594,45	507,96	76,33

Analyzing Table 5.6, one can confirm that the only difference between the results from this Table (Scenario 2) and Table 5.5 (Scenario 1) is related with the import cost. In fact, in order to promote the energy exchange between communities, the import costs of Communities 1 and 2 are set at a lower value than the cost of importing from the grid, thus prioritizing the energy import from both these communities over the grid (lower import costs will harm less the objective function, hence its priority).

5.3.2 Seasonal Analysis

Similarly to the Full P2P and the Community-Based market designs, the simulation results change according to the time of the year. Therefore, Table 5.7 presents the results of Scenario 2 of the Hybrid P2P Market design for the different months of the year to help better understanding which months have the best/worst results. Scenario 2 was used instead of 1 because if Scenario 1 was used the results would be the same as in Table 5.4 of subsection 5.2.2, for the reasons mentioned above.

Table 5.7: Seasonal Comparison for the Hybrid P2P Market Design

Hybrid P2P						
Months of the Year	Total Energy Demand (kWh)	Total Energy Generated (kWh)	Total Import (kWh)	Total Export (kWh)	Import Cost (€)	Export Revenue (€)
January February March April	1009204,35	54657,39	971885,35	17338,4	121349,3	1743,49
May June July August	936580,65	107714,1	877003,45	48136,9	95897,51	4463,52
September October November December	1125864,1	28627,35	1104232,98	6996,24	107482,83	550,41

Inspecting Table 5.7, one can figure out that the only difference between the values in this table and Table 5.4 is on the import cost, for the reasons explained in subsection 5.3.1.2. As a matter of fact, as well as for the other market designs, the Hybrid P2P attains its best results for the months of May, June, July and August due to the higher PV generation in these months. Furthermore, the worst results for the export revenue, total energy demand and total energy generated are obtained once again for the months of September, October, November and December as a result of a lower PV production. However, as in the Full P2P and the Community-Based market design, the amount of imported energy is higher for the months of September, October, November and December than for the months of January, February, March and April due to a higher energy demand and a lower energy generation. Despite that, the import costs are lower, as a result of the prices of the Iberian Electricity Market, for the year of 2019, being lower for those months.

5.4 Comparison Between The Different P2P Market Designs

In this section, the three different P2P market designs are evaluated in order to understand which one is more beneficial taking into account this Case Study. Afterwards, these three different P2P market designs are going to be compared with a scenario in which there is no energy trade between peers (all of the energy surplus is sold to the grid and all of the demand that is not satisfied through self-consumption units is bought from the grid), so that the real value of these P2P business models is assessed. All of the analysis made in this subsection is for the entire year of 2019. Moreover, for the Hybrid P2P market design, the Scenario 2 mentioned in subsection 5.3.1.2 will be used because if Scenario 1 was used instead, the results would be the same as in the Community-Based market design. Table 5.8 shows the simulation results, specifically the value of the objective function and the amount and costs associated to the energy import/export for the three different P2P market designs. For the Hybrid and the Community-Based, the total amount of energy import and export refer to the sum of the amounts of both communities, in order to have a fair comparison with the Full P2P market design.

Table 5.8: Simulation results for all the P2P market designs for the year of 2019

Market designs	Objective Function (€)	Total Import (kWh)	Total Export (kWh)	Import Cost (€)	Export Revenue (€)
Full P2P	369870,08	2901033,25	20374,99	319339,95	1900,85
Community-based P2P	369330,49	2953121,78	72471,53	324736,15	6757,42
Hybrid P2P	369337,02	2953121,78	72471,53	324729,65	6757,28

Analyzing Table 5.8, one can conclude that the objective function has its best value for the Full P2P market design and the worst for the Community-Based P2P market design. In fact, in the Community-Based market design the communities only trade with the main grid while in the Full P2P it is possible to share the energy surplus amongst all peers, making it the most beneficial for this Case Study. Moreover, for the Community-Based P2P market design, if one community doesn't produce enough energy to satisfy its demand, it will have to buy the energy needed from the grid. On the other hand, in the Hybrid P2P market design, if one community doesn't produce enough energy to satisfy its demand, it can buy the energy needed from another community and if it is not enough, it will buy the remainder from the grid. For this Case Study, trading energy with the grid is less profitable than with other communities, hence the better value of the objective function for the Hybrid when compared to the Community-based. Furthermore, since in the Full P2P market design the energy surplus is shared amongst all peers, the amount of imported and exported energy is lower than in the other market designs.

As indicated before, in order to assess the real value of these P2P business models, a comparison between them and a Scenario in which the peers only trade energy with the main grid instead

of trading with each other and with the main grid, was studied. The results of this comparison are displayed on Table 5.9.

Table 5.9: Comparison between the different objective functions

Market designs	Objective Function (€)
Full P2P	369870,08
Community-based P2P	369330,49
Hybrid P2P	369337,02
Regular Market	368060,71

As a matter of fact, analyzing Table 5.9, one can conclude that the objective function has the worst value for the Regular Market (market with no P2P transactions). Moreover, in the regular market, all of the agents only trade with the grid instead of trading with each other and the grid, meaning that their energy surplus is sold to the grid and the energy needed to satisfy their demand is bought from the grid. Since it is more expensive to buy energy from the grid than from the other peers due to the grid and energy tariffs, the objective function will assume worse values than when using any Peer-to-Peer business model.

Chapter 6

Conclusions and Future Works

6.1 Conclusions

To sum up, the current paradigm fulfils the conditions to conduct the transition towards P2P markets. In fact, after thoroughly analyzing the simulation results, it is possible to conclude that any of the three P2P markets are more beneficial to the peers than the regular market (market in which the energy trades are only made with the grid), due to the grid and energy tariffs. Additionally, by trading energy with another peer, one pays less tariffs than by trading energy with the grid, hence the financial benefit of the use of these P2P market designs. Besides the aforementioned financial benefit, this new paradigm not only brings environmental advantages as most of the decentralized generation comes from renewable sources, but also contributes to reduce the power flows on transmission/distribution lines during peak hours, thus turning it possible to postpone investments on new grid equipment.

For this particular Case Study, as most of the peers are PV prosumers, the best results are accomplished for hours 10-15. This is true since those are the hours in which, for most cases and for most of the peers, besides satisfying their entire demand through self-consumption, a generation surplus is often generated and consequently exported to other peers in need or to the grid. Moreover, for the hours with no PV generation, the agents involved rely on the grid to satisfy their demand (both of the wind turbine prosumers produce every hour but never enough energy to supply their entire demand). To mitigate this dependence on the grid, the easiest solution would be to install storage units, in order to store the generation surplus and then using it on the hours with no PV generation.

Lastly, for the case studied on this dissertation, the most beneficial P2P market design was the Full P2P, since in this design it is possible to share the renewable surplus amongst all peers. However, when including grid constraints, taking into account a sizable network, the most suitable market design would probably be the Hybrid P2P, as it allows the Community-Based P2P market design (the community manager would assure that the grid constraints are respected) and the full P2P (possibility to trade energy directly community to community) to interact.

6.2 Future Works

After concluding this Thesis, there are three topics that deserve further attention.

The first one consists of incorporating storage units, as they would make the prosumers rely less on importing energy from the grid and also having energy available to export for a higher number of periods. A study would have to be made, in order to find out on how long it would take for the initial investment on the storage unit to be amortized, consequently obtaining how much time it would take to start profiting after investing on a storage unit.

The second one consists of including grid constraints. In fact, by including grid constraints, the most beneficial P2P market design might change according to the location of the peers on the grid. If the peers are all close to each other, for instance all of them connected to the same LV grid, the most beneficial market would most likely still be the Full P2P for the reasons mentioned before. However, for a real test case with the peers connected in different LV grids, that is, having to use MV grids to exchange their energy, the Hybrid P2P would be, presumably, the most beneficial market design, since it allows an interaction between the other two market designs.

The third and final one is related with the inclusion of product differentiation to the study of these P2P market designs. To clarify, product differentiation enables, an agent belonging to the P2P electricity market being able to choose from which generator to buy energy from. This choice may be because the consumer wants to buy energy from a certain technology or wants to buy energy from the neighbourhood to avoid a grid congestion. Including this possibility increases the model flexibility and it also provides the model a feature that will be most likely considered in the near future power system designs.

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