UNIVERSIDAD PONTIFICIA COMILLAS

ESCUELA TÉCNICA SUPERIOR DE INGENIERÍA (ICAI)

OFFICIAL MASTER'S DEGREE IN THE ELECTRIC POWER INDUSTRY

Master’s Thesis

Energy management models for shared photovoltaic self-consumption facilities

Author: Alejandro Ruiz Berciano
Supervisor: Mariano Sidrach de Cardona Ortín
Co-Supervisor:

Madrid, July 2019

Master’s Thesis Presentation Authorization

THE STUDENT:

ALEJANDRO RUIZ BERCIANO

…………………………………………………………………………

THE SUPERVISOR

MARIANO SIDRACH DE CARDONA ORTÍN

Signed: Date: 05/07/ 2019

THE CO-SUPERVISOR

Signed: …………………… Date: ……/ ……/ ……

Authorization of the Master’s Thesis Coordinator

Dr. Luis Olmos Camacho

Signed: …………………… Date: ……/ ……/ ……

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Summary

The electricity sector has always been in constant evolution. In recent years, global climate trends and advances in electricity generation technologies have led to a proliferation of clean and renewable energies. These forms of generation are, with the exception of hydroelectric plants, not very mature, generally modular technologies, so that their generation capacity is small in comparison with conventional generation plants, and typically have dispersed location. Thus, distributed renewable energy sources (DER) appear in the panorama, which represent a challenge for the distribution companies and the organizers of the electricity markets, since they break the traditional scheme of the sector and are difficult to dispatch due to the difficult prediction of its power generation. These changes of decentralization and clean energy involve new forms of network management and the operation of electricity markets, challenges that the current regulation is trying to solve. On the other hand, the analysis of data, artificial intelligence, the internet of things, blockchain and other technologies and innovations can suppose great advances in the sector once optimally applied to improve the prediction of the intermittent generation, the sale of energy between peers, the demand management, etc.

Following the recent regulatory changes concerning self-consumption in Spain, with the publication of RD 244/2019 [1], this project seeks to obtain a method of distribution of the energy generated by a shared photovoltaic installation of self-consumption among its owners in an optimal and fair manner so that energy is not wasted and the costs of the users are reduced.

This project simulates the distribution of the energy generated by a self-consumption installation whose ownership corresponds to three different consumers. To develop this model, three annual demand profiles per hour will be generated, as well as a photovoltaic energy generation profile per hour for one year and the prices and other data necessary to evaluate the distribution hypotheses to be studied. These hypotheses will be proposed based on different energy and economic criteria to determine which is the most efficient way to share the energy generated by the photovoltaic installation shared among the different users. In order to obtain the optimum method of distribution of the energy generated, a Matlab program has been developed for the simulation of the different scenarios proposed here.

After analysing the different hypotheses it is observed that those that suppose a greater saving in the electric bill for the clients are those in which the tariffs of the consumers are 2.0DHA, with time discrimination in two periods, and in which the users can exchange of energy between them. The most efficient option is to maximize the consumption of the energy generated by the installation.

If energy transactions between users are not allowed, the best option for distributing the energy generated is the distribution of this according to the hourly consumption of the users, in each hour. This minimizes interactions with the network and optimizes the use of the renewable energy generated. When the purchase and sale of energy between users is allowed, the most efficient hypothesis turns out to be the distribution of the generated energy based on the annual consumption of each client. By varying the price of energy exchanges between users it is observed that the increase of this causes an increase in the final bill of the total of users. A sensitivity study is also carried out with respect to the peak power of the photovoltaic installation. As the peak power of the installation increases the hypothesis that greater savings reported to users is the distribution of energy generated based on the contracted power of the user, since as more self-consumption energy is available and the energy term of the bill decreases, the power term becomes more important, which depends on the contracted power. On the other hand, it can be verified that the possibility of selling energy (to the network or between users) has a role as important as the possibility of self-consuming energy in the savings that users perceive.

Foreword

You rarely have the opportunity to do something for the last time knowing that it is the last. These kinds of occasions are a gift, since they provide the opportunity to do things as you want, because it is the last time. Many things are done in life and never done again. They have an end, a last chance. In fact, all things are done for the last time at some point.

However, few are remembered. These memories are diluted in the cosmos of memory and normally are not visited by the subject (and subject to) in the future. In most cases this is the result of our ignorance of this ephemeris because, did the mother know that she would never carry her son in her arms again, or the friends on the summer evening who, for the last time, went down to the street to play with the ball after school? I hope that the reader agrees with me that the answer is no, because life begins to kill from the moment one is born, and leads the souls by her paths, not always gloomy, but blindly. It is not until time begins to weigh too much when melancholy brings back to consciousness this stolen memory, almost by a pressing feeling of scarcity and guilt, and the soul is filled with yearning. And perhaps for this reason, when one knows that one occasion is the last, he feels that one is not being led by the fate of existence, impotent as the fisherman in the storm, but is clinging to the rudder of his ship and moving towards the happy death, because he covers the cliffs as Sisyphus pushes his rock, aware of the absurdity in which he navigates. And happy because, although he will never hear the anchor slip through the spinner or the sound of the seagulls, that despite being able to fly wherever they wish they will end up on the same ground, this time he knows that it is the last one. The wind and the tide force him because he wants to, and he uses the wind to propel his sails, and the tides to turn his ship. It was told by Norse mythology that a giant deceived the god Thor, by trying to make him fight with an old woman whom he could not even move, because it turned out to be Old Age itself.

Indeed, there are tides that drag thou, therefore, let this project be my flag this last time, because I carry the cellars full of cloves and rum, and as it is my last chance, for the first time I do not fear anything.

To God and the people who made it possible, to Mariano to blow the sails, to my parents for the wifi, to my uncles for the chicken and to my colleagues and friends of the double master and other colleagues of MEPI (Javieres, Nachos, Chelen, Pratto, Carmen, Carlos, Santi, Juan, Jaime, etc.).

Index

SUMMARY **5**

1 INTRODUCTION **15**

2 REVIEW OF DISRUPTIVE TRENDS IN THE ELECTRIC SYSTEM **17**

2.1 DISTRIBUTED GENERATION AND SELF-CONSUMPTION 19
2.2 BLOCKCHAIN AND PEER-TO-PEER POWER EXCHANGE (P2P) 22
2.3 SPANISH REGULATION 27
2.3.1 RD 244/2019 28

3 PROPOSED METHODOLOGY **35**

3.1 LOAD PROFILES 35
3.2 DAY-AHEAD MARKET PRICES 40
3.3 PVPC PRICES OF USERS 41
3.4 CONTRACTED POWER 42
3.5 PROFILE OF ELECTRIC POWER GENERATION OF THE PHOTOVOLTAIC INSTALLATION 43
3.6 POWER SHARING HYPOTHESES 45

4 RESULTS AND DISCUSSION **49**

4.1 USERS WITHOUT SHARED SELF-CONSUMPTION FACILITY 49
4.2 THE ENERGY OBTAINED FROM THE PHOTOVOLTAIC INSTALLATION IS DISTRIBUTED HOURLY ACCORDING TO THE ENERGY CONSUMPTION THE USERS IN EACH HOUR 50
4.3 THE ENERGY OBTAINED FROM THE PHOTOVOLTAIC INSTALLATION IS DISTRIBUTED ACCORDING TO A FIXED PERCENTAGE 53
4.4 THE ENERGY OBTAINED FROM THE PHOTOVOLTAIC INSTALLATION IS DISTRIBUTED ACCORDING TO THE TOTAL ANNUAL CONSUMPTION 55
4.5 THE ENERGY OBTAINED FROM THE PHOTOVOLTAIC INSTALLATION IS DISTRIBUTED ACCORDING TO THE CONTRACTED POWER OF THE USER 57
4.6 COMPARISON OF HYPOTHESES 59
4.7 SENSITIVITY STUDIES 63

5 CONCLUSIONS **69**

6 REFERENCES **71**

Index of figures

Figure 1: Increased penetration of renewable energy sources in European final energy consumption [7] 18
Figure 2: Evolution of global installed PV capacity since the beginning of the century [8] 20
Figure 3: Concept of net metering in self-consumption facilities [9] 21
Figure 4: Scheme of how blockchain transactions are carried out [12] 24
Figure 5: Evolution of the cost of the system based on the price of energy sales between users . 66
Figure 6: Evolution of the total cost of the users according to the factor by which the consumption of the user 1 is multiplied when the generated energy is distributed according to the annual consumption 67
Figure 7: Evolution of the total self-consumption and self-sufficiency according to the factor by which the consumption of the user 1 is multiplied when the generated energy is distributed according to the annual consumption 67

Index of tables

TABLE 1 – TIME PERIODS ACCORDING TO THE HOURS ACCORDING TO [32] 38
TABLE 2 – COEFFICIENTS OF CONSUMPTION PER USER 40
TABLE 3 – RESULTS OBTAINED FOR USERS WITHOUT PV GENERATION AND TARIFF 2.0A 49
TABLE 4 – RESULTS OBTAINED FOR USERS WITHOUT PV GENERATION AND TARIFF 2.0DHA 49
TABLE 5 – RESULTS OBTAINED FOR USERS WITHOUT PV GENERATION AND TARIFF 2.0DHS 50
TABLE 6 – RESULTS OBTAINED FOR THE DISTRIBUTION OF THE GENERATED ENERGY ACCORDING TO CONSUMPTION WITHOUT P2P TRADE AND TARIFF 2.0A 50
TABLE 7 – RESULTS OBTAINED FOR THE DISTRIBUTION OF THE GENERATED ENERGY ACCORDING TO CONSUMPTION WITH P2P TRADE AND TARIFF 2.0A 51
TABLE 8 – RESULTS OBTAINED FOR THE DISTRIBUTION OF THE GENERATED ENERGY ACCORDING TO CONSUMPTION WITHOUT P2P TRADE AND TARIFF 2.0DHA 51
TABLE 9 – RESULTS OBTAINED FOR THE DISTRIBUTION OF THE GENERATED ENERGY ACCORDING TO CONSUMPTION WITH P2P TRADE AND TARIFF 2.0DHA.. 51
TABLE 10 – RESULTS OBTAINED FOR THE DISTRIBUTION OF THE GENERATED ENERGY ACCORDING TO CONSUMPTION WITHOUT P2P TRADE AND TARIFF 2.0DHS.. 52
TABLE 11 – RESULTS OBTAINED FOR THE DISTRIBUTION OF THE GENERATED ENERGY ACCORDING TO CONSUMPTION WITH P2P TRADE AND TARIFF 2.0DHS 52
TABLE 12 – RESULTS OBTAINED FOR THE DISTRIBUTION OF THE GENERATED ENERGY ACCORDING TO CONSUMPTION AND THE SURPLUS ENERGY IN EQUAL PARTS WITH P2P TRADE AND TARIFF 2.0DHS 53
TABLE 13 – RESULTS OBTAINED FOR THE DISTRIBUTION OF THE GENERATED ENERGY IN EQUAL PARTS WITHOUT P2P TRADE AND TARIFF 2.0A 54
TABLE 14 – RESULTS OBTAINED FOR THE DISTRIBUTION OF THE GENERATED ENERGY IN EQUAL PARTS WITH P2P TRADE AND TARIFF 2.0A 54
TABLE 15 – RESULTS OBTAINED FOR THE DISTRIBUTION OF THE GENERATED ENERGY IN EQUAL PARTS WITHOUT P2P TRADE AND TARIFF 2.0DHA 54
TABLE 16 – RESULTS OBTAINED FOR THE DISTRIBUTION OF THE GENERATED ENERGY IN EQUAL PARTS WITH P2P TRADE AND TARIFF 2.0DHA... 55
TABLE 17 – RESULTS OBTAINED FOR THE DISTRIBUTION OF THE GENERATED ENERGY IN EQUAL PARTS WITHOUT P2P TRADE AND TARIFF 2.0DHS... 55
TABLE 18 – RESULTS OBTAINED FOR THE DISTRIBUTION OF THE GENERATED ENERGY IN EQUAL PARTS WITH P2P TRADE AND TARIFF 2.0DHS 55
TABLE 19 – RESULTS OBTAINED FOR THE DISTRIBUTION OF THE ENERGY GENERATED BASED ON ANNUAL CONSUMPTION WITHOUT P2P TRADE AND TARIFF 2.0A.. 56
TABLE 20 – RESULTS OBTAINED FOR THE DISTRIBUTION OF THE ENERGY GENERATED BASED ON ANNUAL CONSUMPTION WITH P2P TRADE AND TARIFF 2.0A 56
TABLE 21 – RESULTS OBTAINED FOR THE DISTRIBUTION OF THE ENERGY GENERATED BASED ON ANNUAL CONSUMPTION WITHOUT P2P TRADE AND TARIFF 2.0DHA.. 56
TABLE 22 – RESULTS OBTAINED FOR THE DISTRIBUTION OF THE ENERGY GENERATED BASED ON ANNUAL CONSUMPTION WITH P2P TRADE AND TARIFF 2.0DHA 57
TABLE 23 – RESULTS OBTAINED FOR THE DISTRIBUTION OF THE ENERGY GENERATED BASED ON ANNUAL CONSUMPTION WITHOUT P2P TRADE AND TARIFF 2.0DHS.. 57
TABLE 24 – RESULTS OBTAINED FOR THE DISTRIBUTION OF THE ENERGY GENERATED BASED ON ANNUAL CONSUMPTION WITH P2P TRADE AND TARIFF 2.0DHS 57
TABLE 25 – RESULTS OBTAINED FOR THE DISTRIBUTION OF THE ENERGY GENERATED AS A FUNCTION OF THE CONTRACTED POWER WITHOUT P2P TRADE AND TARIFF 2.0A........................... 58
TABLE 26 – RESULTS OBTAINED FOR THE DISTRIBUTION OF THE ENERGY GENERATED AS A FUNCTION OF THE CONTRACTED POWER WITH P2P TRADE AND TARIFF 2.0A 58

TABLE 27 – RESULTS OBTAINED FOR THE DISTRIBUTION OF THE ENERGY GENERATED AS A FUNCTION OF THE CONTRACTED POWER WITHOUT P2P TRADE AND TARIFF 2.0DHA 58
TABLE 28 – RESULTS OBTAINED FOR THE DISTRIBUTION OF THE ENERGY GENERATED AS A FUNCTION OF THE CONTRACTED POWER WITH P2P TRADE AND TARIFF 2.0DHA 59
TABLE 29 – RESULTS OBTAINED FOR THE DISTRIBUTION OF THE ENERGY GENERATED AS A FUNCTION OF THE CONTRACTED POWER WITHOUT P2P TRADE AND TARIFF 2.0DHS 59
TABLE 30 – RESULTS OBTAINED FOR THE DISTRIBUTION OF THE ENERGY GENERATED AS A FUNCTION OF THE CONTRACTED POWER WITH P2P TRADE AND TARIFF 2.0DHS 59
TABLE 31 – RESULTS OBTAINED FOR THE DIFFERENT HYPOTHESIS FOR USER 1 WITH ENERGY EXCHANGE BETWEEN USERS AND TARIFF 2.0DHA 60
TABLE 32 – RESULTS OBTAINED FOR THE DIFFERENT HYPOTHESIS FOR USER 2 WITH ENERGY EXCHANGE BETWEEN USERS AND TARIFF 2.0DHA 60
TABLE 33 – RESULTS OBTAINED FOR THE DIFFERENT HYPOTHESIS FOR USER 3 WITH ENERGY EXCHANGE BETWEEN USERS AND TARIFF 2.0DHA 61
TABLE 34 – RESULTS OBTAINED FOR THE DIFFERENT HYPOTHESIS FOR THE TOTAL SYSTEM WITH NO ENERGY EXCHANGE BETWEEN AND TARIFF 2.0DHA 62
TABLE 35 – RESULTS OBTAINED FOR THE DIFFERENT HYPOTHESIS FOR THE TOTAL SYSTEM WITH ENERGY EXCHANGE BETWEEN USERS AND TARIFF 2.0DHA 62
TABLE 36 – RESULTS OBTAINED FOR THE DIFFERENT HYPOTHESIS FOR THE TOTAL SYSTEM WHEN THE PEAK POWER OF THE PV INSTALLATION IS 5 KW WITH ENERGY EXCHANGE BETWEEN USERS AND TARIFF 2.0DHA 64
TABLE 37 – RESULTS OBTAINED FOR THE DIFFERENT HYPOTHESIS FOR THE TOTAL SYSTEM WHEN THE PEAK POWER OF THE PV INSTALLATION IS 14 KW WITH ENERGY EXCHANGE BETWEEN USERS AND TARIFF 2.0DHA 64
TABLE 38 – RESULTS OBTAINED FOR THE DIFFERENT HYPOTHESIS FOR THE TOTAL SYSTEM WHEN THE PEAK POWER OF THE PV INSTALLATION IS 28 KW WITH ENERGY EXCHANGE BETWEEN USERS AND TARIFF 2.0DHA 65
TABLE 39 – RESULTS OBTAINED FOR THE DIFFERENT HYPOTHESIS FOR THE TOTAL SYSTEM WHEN THE PEAK POWER OF THE PV INSTALLATION IS 42 KW WITH ENERGY EXCHANGE BETWEEN USERS AND TARIFF 2.0DHA 65

1 Introduction

The electricity sector has always been in constant evolution. The process of liberalization of the sector that began in the 1980s was only the beginning of a process of changes that modify the structure of this sector as technical and regulatory advances are taking place. In recent years, global climate trends and advances in electricity generation technologies have led to a proliferation of clean and renewable energies. These forms of generation are, with the exception of hydroelectric plants, not very mature, generally modular technologies, so that their generation capacity is small in comparison with conventional generation plants, and typically have dispersed location. Thus, distributed renewable energy sources (DER) appear in the panorama, which represent a challenge for the distribution companies and the organizers of the electricity markets, since they break the traditional generation-transport-distribution-consumption scheme and are difficult to dispatch due to the difficult prediction of its power generation. These changes of decentralization and clean energy involve new forms of network management and the operation of electricity markets, challenges that the current regulation is trying to solve.

Thus, the networks and electrical systems are in constant change due to the continuous technological developments and the existence of an increasingly electrified and changing demand in the use of a good that is considered basic and necessary. Currently there is a long series of disruptive elements in the sector that will make it change in the coming years: RES, climate change policies, demand electrification, etc. The analysis of data, artificial intelligence, the “Internet of things”, blockchain and other technologies and innovations can suppose a great advance in the sector if optimally applied to improve the prediction of intermittent generation, the sale of energy between pairs , demand management, etc.

On the other hand, all these trends in the sector lead to an increasing use of distributed electricity generation resources for self-consumption. In the Spanish case, the use of shared self-consumption has recently been legally approved. However, the need for an efficient and as fair way as possible to distribute the energy generated among the different users is evident.

Self-consumption facilities must play an important role in this energy transformation. After the approval of RD 244/ 2019 [1] the door is open for an unprecedented development of shared self-consumption in Spain.

After the elimination of the “sun tax” and the administrative simplification the legalization of this type of facilities, the situation is very favourable for the proliferation of this type of systems. This is expected to reduce energy costs while contributing to a cleaner and renewable electricity system. However, for this situation to be optimal, algorithms and ways to use this shared energy must be designed so that all parties benefit [2].

Thus, currently, the electric sector is going through substantial changes in its structure that should lead to a more decentralized system and where the operating costs of the different utilities are lower so that their profit margins grow, thus encouraging them to try to give better customer service. The future is also based on a system where clean and renewable energy is very present, helping to eliminate, along with the electrification of demand, the current problems of global warming and climate change. The system is changing and it is the objective of this project to contribute to this change towards a better system by proposing a method of energy management of a shared self-consumption facility that can contribute to this evolution of the system towards a cleaner and more egalitarian future.

In addition, as previously introduced, it is also the objective of this project to determine a fair and efficient way, both economically and energetically, of the distribution of the energy generated by a shared self-consumption facility, applied to a simulated case, based on real data.

First, some of the current trends in the electricity sector will be reviewed to put into context the development and motivation of this project. In particular, this paper will study mechanisms to optimize the energy exchange between individuals and the network in shared self-consumption facilities. A model will be presented to analyse the different energetic and economic impacts of different ways of sharing the energy generated by the shared self-consumption facility between its owners. In order to create this model, in the following sections the hourly data for a year of consumption of three users, energy generation of the PV facility and prices will be obtained. Then, the methodology and the results will be discussed.

The thesis consists of the following sections. This section is a brief introduction to the different topics that will be covered in this project. Section 2 analyses some of the disruptive trends that currently occur in the electricity sector. Section 3 presents the methodology used to generate the simulation model presented in this document. Section 4 presents the results obtained. Finally, section 5 contains the conclusions of the study.

2 Review of disruptive trends in the electric system

The new challenges faced by the electric power industry have been increasing since the liberalization of the industry in many countries. In addition, the pace at which these changes and innovations are occurring is also increasing if we take into account the trends that have been emerging in recent years and the appearance of new systems and technologies with applications in the energy sector with an uncertain but promising future in terms of open possibilities on how these could be applied in the electricity sector.

At present, there is a growing demand for clean and renewable energy, which does not produce greenhouse emissions or waste when using fuels for electricity generation. While it is true that a few decades ago the energy transition began to become a reality after international agreements on Climate Change, the measures adopted have typically been based on incentives and support schemes to make Renewable Energy Sources (RES) profitable, since they could not compete with conventional technologies in terms of costs.

In this context, many countries began to implement policies to promote RES after the signing of the Kyoto Protocol [3] in 1999. The way in which these countries promoted them was through support schemes and financial incentives. The protocol established mandatory objectives related to the reduction of greenhouse gas emissions for those countries involved. However, despite the fact that 38 developed countries participate in the second commitment period of the Kyoto Protocol (which began in 2013 and lasts until 2020), including the 28 Member States of the European Union (EU), this agreement presented important weaknesses. Although it was a step forward in terms of the commitment to reduce emissions and make the beginning of the energy transition a global reality, it was not a complete success because important economic powers such as the United States, Canada, Russia and Japan did not participate in the protocol.

Despite the lack of commitment of some of the most important countries in the Kyoto Protocol, it gave rise to ambitious targets that those countries undertook in order to reduce their emissions. The objective established in the EU for 2020 was to reduce total emissions by at least 20% compared to those of the 1990s, as well as to achieve a RES produced energy ratio in total energy consumption of at least 20%. The countries that committed to the binding targets in the protocol only accounted for around 14% of global emissions, although it is true that more than 70 countries participated in the agreement with non-binding commitments. The directives and regulations approved in the EU since the beginning of the century in terms of energy policy have been aligned with the fulfilment of the objectives established for the beginning of the year 2020.

Another important step taken in the reduction of emissions was the signing of the Paris agreement in December 2015. This agreement consisted of a commitment to keep global warming below 2 °C throughout the century. Once again, all the EU Member States participated in this agreement, as part of the 55 countries that were part of this commitment. This resulted in a representation of around 55% of total global emissions.

The most relevant directives that promoted RES in the EU after the Kyoto Protocol in 1999 were three:

- Directive 2001/77/EC [4]: This directive established individual objectives for each country, which allows them to adopt freely measures to meet the objectives. Therefore, the European Commission did not oblige countries to take concrete measures to achieve the stated objectives, but rather it monitored individual progress and was forced to take more aggressive measures if they were far from the objectives.

- Directive 2009/28/EC [5]: Established the objective of covering 20% of total energy consumption with renewable generation and defines the regulatory framework in which countries must implement their National Plans for the fulfilment of this objective.
- Directive 2018/2001/CE [6]: Following the agreement reached in Paris, this directive updated the targets of renewable energy penetration to 32% by 2030 as part of the package of measures "Clean energy for all Europeans".

With all these policies for the promotion of renewable energies, the penetration of RES in the European energy system has increased continuously since the beginning of the century, as the following graph of the European Environment Agency illustrates.

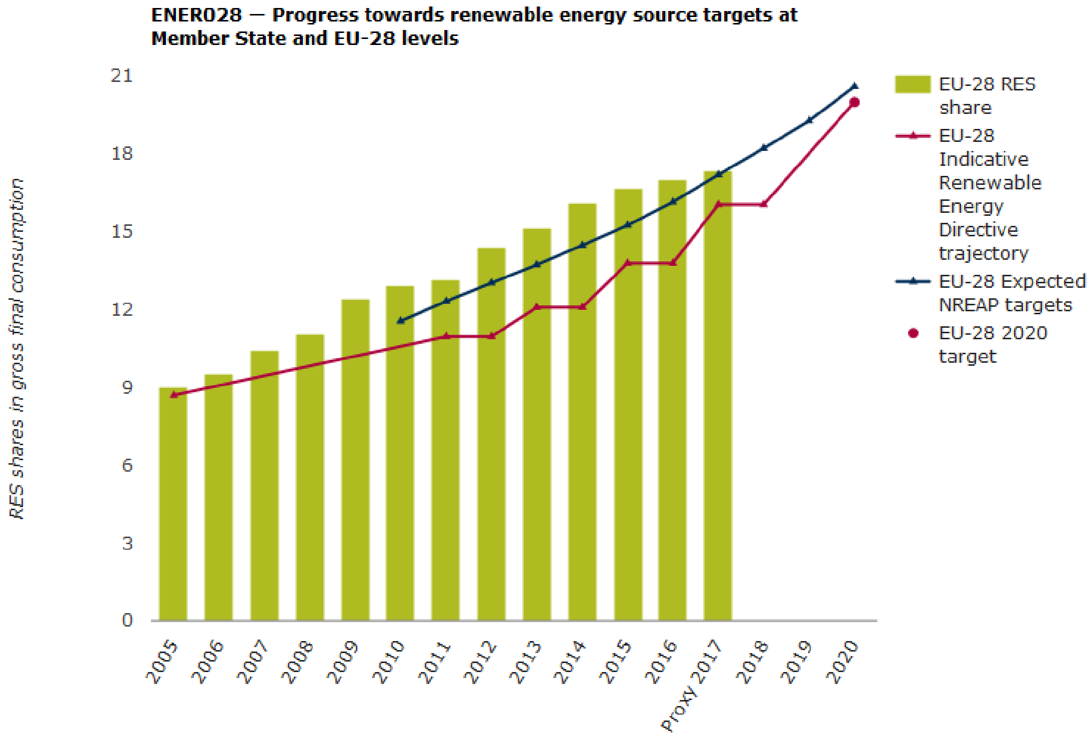


Figure 1: Increased penetration of renewable energy sources in European final energy consumption [7]

Although it is true that the increase in the consumption of renewable energy has occurred since the beginning of the century, as Figure 1: Increased penetration of renewable energy sources in European final energy consumption illustrates, investment in renewable energy sources has undergone great changes. The aid and subsidy systems were of an indispensable nature a few years ago so that investments in this sector could be profitable, but now we are in a moment of changes in which, while technologies are approaching their maturity stages, the costs of exploitation of these are reduced and, therefore, the support schemes implemented in the different countries try to adapt to these cost reductions and are no longer so indispensable.

In this context, the decentralization of the electricity sector is already becoming a reality. The challenges arise not only from distributed generation, but also from the participation of demand and self-consumption. In relation to the latter, the maturation of photovoltaic (PV) technology and the reduction of costs make the investment for self-consumption already profitable in those systems in which a regulation is established to incentivize it. In Spain, Royal Decree 244/2019 not only eliminated the well-known "sun tax", but also established a regulatory framework for the compensation of excess energy and allowed shared self-consumption.

All these new trends in the electricity sector encourage the decentralization of electricity generation. This, together with a regulation such as the case of Spain that favours self-consumption, makes it a real alternative to be considered by consumers who see how they can take advantage of the maturation of photovoltaic technology and the profitability of investing in it. In addition, shared self-consumption can generate economies of scale by reducing the cost per unit of installed capacity. Undoubtedly, the management of these systems will require great efforts in the sector, and we can expect them to be more and more numerous taking into account the evolution that this presents.

In this section we will review some of the changes and challenges that the electricity sector will face in the coming years. Many of these changes have occurred as a result of the promotion, through subsidies, of renewable energies since the beginning of the century. However, in recent years, the maturation of technologies and the reduction of costs have begun to make renewable energies profitable by themselves. This leads us to believe that the near future may be characterized by an increasingly exponential appearance of changes in the conventional electricity sector.

Despite the great advantages that new trends in electricity generation can present in terms of emissions reduction and cleaner energy, renewable technologies present great challenges for the operation of the electrical system. To these challenges are added the alternatives from the perspective of consumption as shared self-consumption or demand management. In the same way, the application of new technologies such as blockchain or trends such as the sale of peer to peer electricity (P2P) in electric power systems must be taken into account.

2.1 Distributed generation and self-consumption

Traditionally, the main disadvantage of renewable energies has been the intermittency in the generation of electricity compared to conventional technologies. The dependence of most renewables on the randomness of atmospheric conditions coupled with the non-existence of large-scale storage technologies in electrical systems were reasons to argue that these technologies could produce at peak times, but they were not reliable enough to be base technologies. To all this was added the need to establish support mechanisms to make investments in these technologies profitable. Therefore, and being its main advantage the clean energy generated, these disadvantages had to be taken into account when investing in RES. With the mentioned evolution in recent years of the maturity of these technologies and the commitment of more and more countries to meet the objectives for 2020 and 2030 of emission reduction and commitment to global warming, the penetration of renewable energies into electric systems is increasingly relevant. This leads to a transformation of the sector in which the traditional generation of high capacity power plants that discharge electricity into the transport network coexists with what is known as distributed generation, in which renewable technologies with smaller capacity and modular plants are connected to the network in a more decentralized sector.

In this context, the great challenges that arise from the installation of renewable energies in the electricity system are no longer the problems of the past, such as the profitability of these, but those related to the operation of the network in this energy transition. This is how intelligent networks, which can automate their operation to maximize efficiency, become essential for the operation of the network. These challenges are even greater if we take into account other factors such as the electric vehicle and facts such as the monitoring of distribution networks in a context of decentralized generation, which means controlling a network that is immensely more complex than it has been until now and which turns the distribution companies in operators of the new distribution system.

On the other hand, with the generation closer to the demand, a large number of possibilities appears related to the active participation of the latter in the electricity markets. In addition to the well-known demand response markets that are beginning to be activated in some European countries, such as Italy, self-consumption systems are one of the main resources for consumers to generate part of the electricity demanded. These systems, not only pose a challenge for the operation of the system due to the greater complexity of the distribution network and discharges to the network, but also jeopardize the economic sustainability of the electrical system as such. This is what is known as the "spiral of death" of electricity companies. With an increase in self-consumption facilities, the income received by the system is reduced, so electricity companies increase the bill to sustain costs. In turn, this would encourage users to invest in self-consumption facilities with greater savings, which would start the process again.

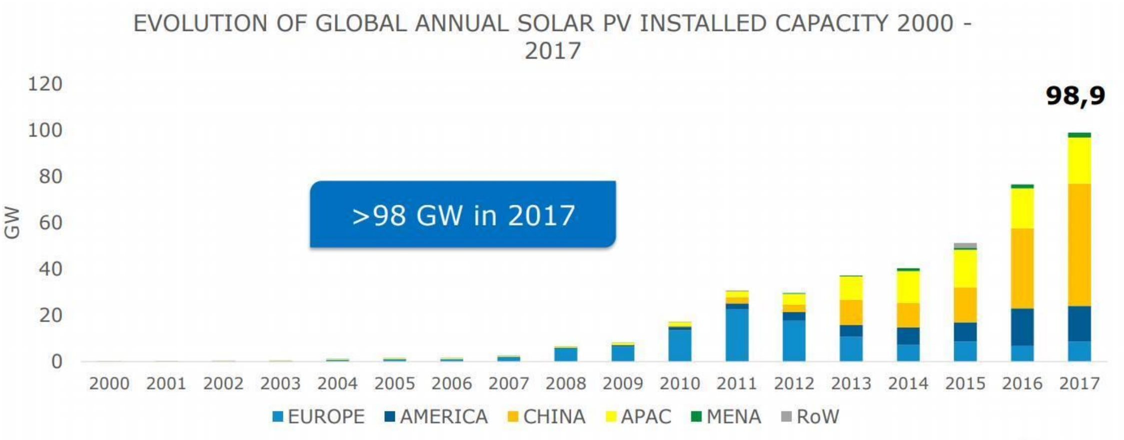


Figure 2: Evolution of global installed PV capacity since the beginning of the century [8]

However, despite all the advantages that the consumer can have to invest in self-consumption facilities, even more taking into account the latest regulatory changes in Spain, the management of the energy generated by the facilities is not simple in this type of facility.

Obviously, the generation of electricity in photovoltaic installations is greater during the day. Although consumer demand is also higher during the day, it is not possible to fully adjust the generation curve of the installation with the demand curve without the help of storage technologies that are not currently sufficiently widespread, although it should be mentioned that in the future this may not be the case. Due to this characteristic, it is essential to differentiate between the concepts of net metering and net billing.

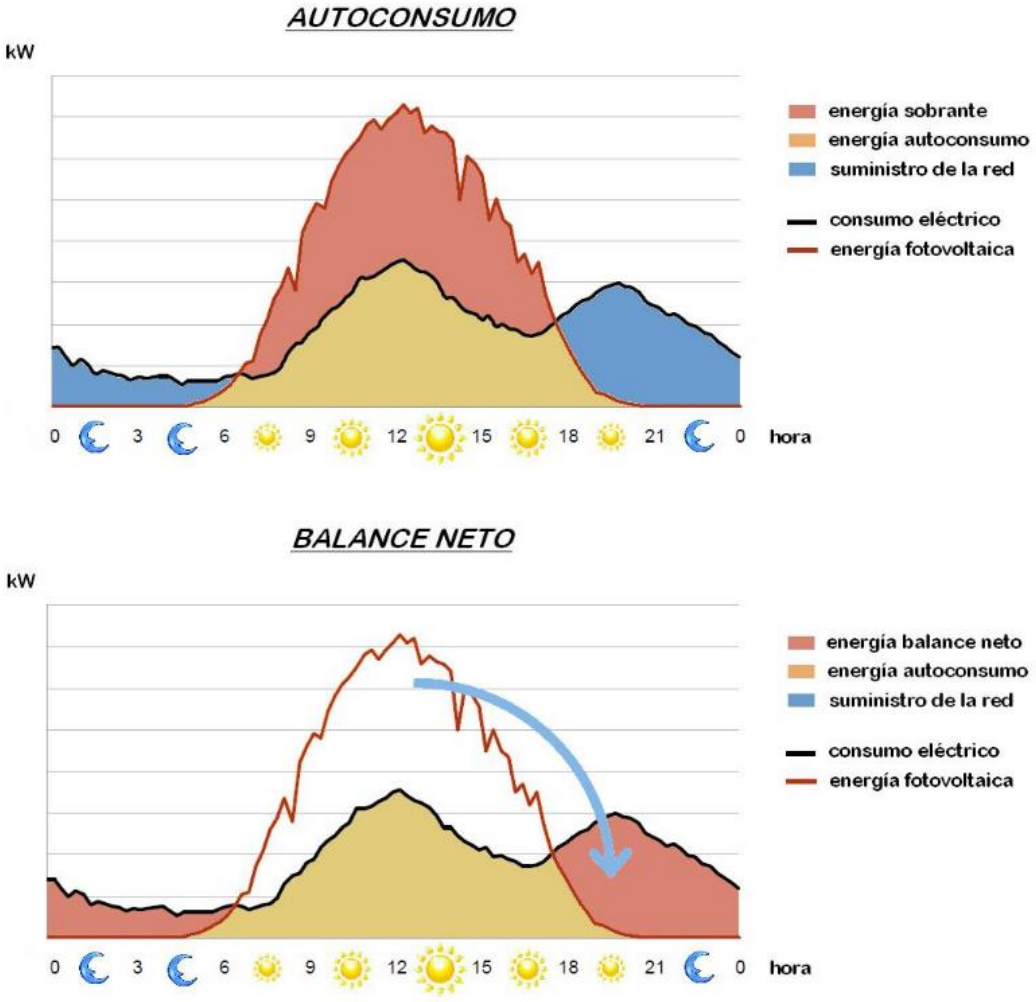


Figure 3: Concept of net metering in self-consumption facilities [9]

If the country's regulation establishes the net billing for self-consumption facilities, the consumer will only pay for the electricity consumed from the grid and not the self-consumption of energy generated during the day, but will not be able to be compensated for the surplus of energy in the hours of greatest photovoltaic generation with the energy consumed at other times of the day. This does not mean that excess energy cannot be remunerated in a net billing regime, but this would be independent.

On the other hand, under a net balance regime, the excess of energy during the hours of the day can be used as compensation for the energy consumed in other periods within the maximum period allowed by regulation.
Although the longer period allowed to use the excess energy to compensate the demand at other times of this period, the greater the incentive granted by the regulation to invest in self-consumption facilities, not limiting this period can lead to investment levels far from maximizing efficiency. If this period is not limited, an energy storage device connected to the network could be very beneficial for the owner, since the consumer would take advantage of having access to the network to consume when the generation in the installation is minimal to absorb the energy of the network and compensate it without cost by injecting the excess energy in hours of maximum generation.

In Spain, the regime established after the approval of Royal Decree 244/2019 is a net billing regime in which compensation for excess energy is recognized. In this way, two modes of self-consumption are established: with surpluses and without surpluses. The details of this regulation will be developed later.

In addition, another of the novelties is the possibility of shared self-consumption in industries or neighbourhood communities. This is especially relevant in terms of savings, since shared self-consumption can be an advantage in terms of energy management generated in different aspects.

In the first place, the aggregate demand curve of several consumers, as in the case of a community of neighbours, presents a consumption peak lower than the sum of the peaks of the individual demand curves of the neighbours. In terms of management of the energy generated in the installation, this is an advantage due to the fact that the aggregate curve presents a lower volatility and, consequently, lower consumption up and down ramps, making it easier to predict and adapt the necessary generation to the demand curve, increase the proportion of self-consumed energy and reduce the excess energy. This is favourable even taking into account the compensations for the surplus of energy. It will always be more profitable for the consumer that the largest possible amount of kWh generated is consumed instead of sold. For example, for a consumer under the PVPC tariff, and with the new regulation in Spain, the compensation for the surplus would be the average daily market price at that hour, which will always be lower than what would be saved if those same kWh were consumed, since the term of energy of the PVPC consists in the cost of acquiring the energy plus other regulated costs.

On the other hand, another of the advantages of shared self-consumption would be to generate economies of scale. This is because the cost per unit of installed energy decreases in a self-consumption facility designed for a community of neighbours compared to the cost per unit of energy that would be the sum of the facilities for each dwelling separately. Therefore, self-consumption facilities have a great potential for growth, especially in Spain after the regulatory change.

2.2 Blockchain and peer-to-peer power exchange (P2P)

A potential force of disruption arose in 2009 when a person or people whose identity is unknown (Satoshi Nakamoto) implemented a system of electronic transactions peer to peer (P2P) that works on a public network. This technology is known as blockchain and was introduced as the base of operation of Bitcoin cryptocurrency. From this moment, the electrical sector has seen potential applications in this technology. The first globally known project was the Brooklyn Microgrid, an initiative launched in New York. This project successfully implemented a peer to peer electricity exchange system based on blockchain. Successive initiatives have been appearing throughout the world in order to improve the functioning of the electricity sector and meet the growing global demand more efficiently and cheaply. Pilot projects and potential applications cover the entire value chain of electricity: P2P [10] and wholesale trade, charge and the possibility of sharing electric vehicles, measurement and billing, and guarantees of origin or certifications.

Blockchain technology [11] is a system in which a record of transactions performed (in bitcoin or another cryptocurrency, for example) is maintained in several computers that are linked in a peer-to-peer network. A chain of blocks is essentially a record, a ledger of digital events that is "distributed" or shared among many different parts. It can only be updated based on the consensus of the majority of system participants and, once entered, the information can never be erased.

Therefore, blockchain is a way of registering information, distributed in a P2P (peer-to-peer) network, where different nodes do not require trust between them, since there is a consensus protocol that certifies the security of transactions. In addition, the chain of blocks is immutable, since modifying it requires the consensus of all nodes. The term blockchain derives from the structure of the aforementioned information record, since the blocks that contain it are ordered chronologically and have an associated number, called “hash”. The blockchain network is peer to peer because each node has the same hierarchical level as the others. Each node is connected to a certain number of the rest, not all, so that when you want to make a transaction, the node sends this information to those connected to it, who replicate it to extend it throughout the network following the same process, provided the transaction is valid

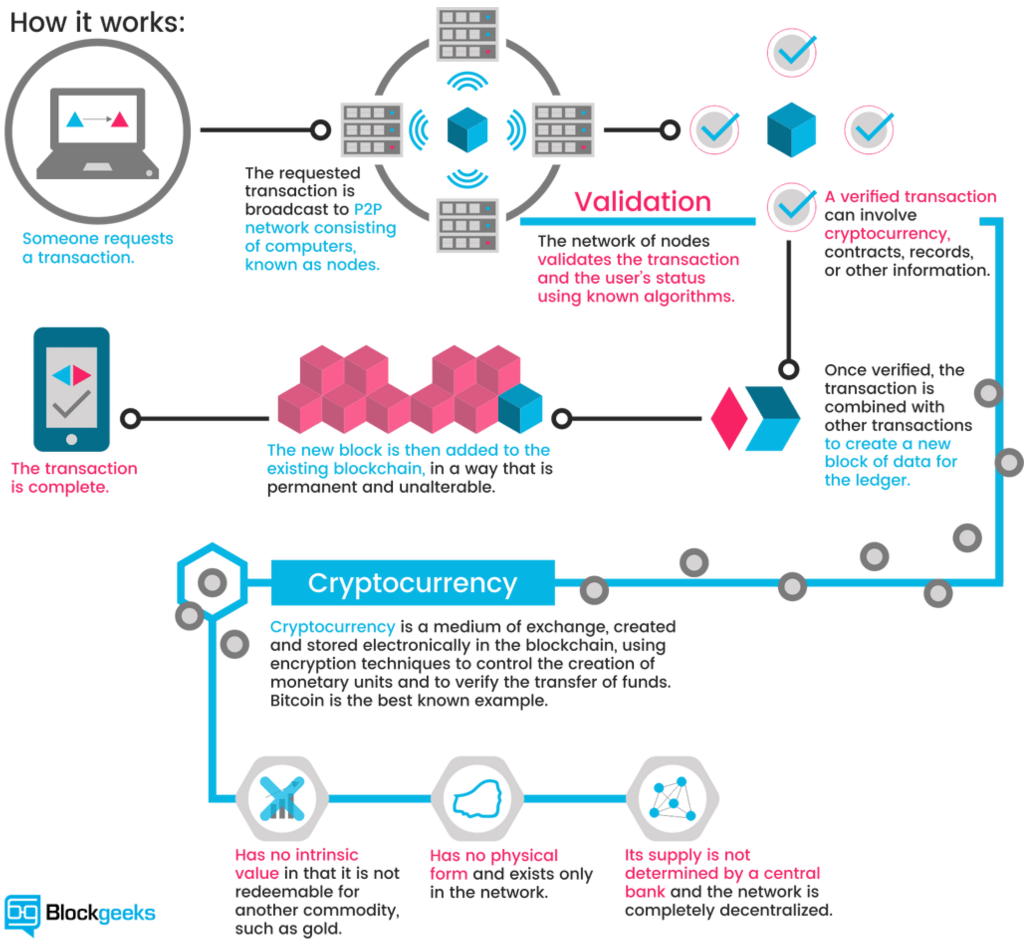
The consensus mechanism most used in blockchain is “Proof of Work” (PoW). It consists in having the system nodes, called miners, solve a mathematical problem before validating the transactions. The miners collect several transactions and need to solve the mathematical problem in order to validate the transaction. The first to find the solution is rewarded with monetary units. This mechanism is used to control the frequency with which transactions are closed by requiring a certain amount of computing time and to protect the system from being attacked, which causes attackers to make a great computational effort to implement their attacks.

Some of the main applications that the blockchain technology can have in the electricity sector are summarized in this section:

- Smart meters: The blockchain applied to smart meters can make them more powerful than existing ones. Using blockchain, smart meters could be used to send data to the Distribution System Operator (DSO) without requiring a direct connection. In addition, the consumer could carry out energy transactions with the other participants, controlling more precisely the sources of the energy that they consume.

- Failure prevention in network installations: Network installations could report failures through blockchain technology and even consumers could report outages.

- Optimization of the energy dispatch: Due to the tendencies of the current energy sector with respect to the decentralized generation of electricity, self-consumption and even the propagation of the electric vehicle, blockchain can have a great impact on the way in which energy is sent. In a network with a high proportion of distributed generation, self-consumption facilities and a highly fluctuating demand with many electric vehicles that demand to be loaded at specific times, blockchain can allow transactions in real time between pairs of similar agents that form a modular network.



Someone requests a transaction.

The requested transaction is broadcast to P2P network consisting of computers, known as nodes.

The network of nodes validates the transaction and the user's status using known algorithms.

A verified transaction can involve cryptocurrency, contracts, records, or other information.

Once verified, the transaction is combined with other transactions to create a new block of data for the ledger.

The new block is then added to the existing blockchain, in a way that is permanent and unalterable.

The transaction is complete.

Cryptocurrency is a medium of exchange, created and stored electronically in the blockchain, using encryption techniques to control the creation of monetary units and to verify the transfer of funds. Bitcoin is the best known example.

Has no intrinsic value in that it is not redeemable for another commodity, such as gold.

Has no physical form and exists only in the network.

Its supply is not determined by a central bank and the network is completely decentralized.

Figure 4: Scheme of how blockchain transactions are carried out [12]

Blockchain can be:

- Public blockchain model: Everyone has access to the network in this case, downloading the corresponding application. The security of this type of networks is based on consensus and hash protocols, with anonymous users.

- Federated blockchain model: A limited number of entities or organizations manage the network and maintain synchronized copies of the block chain. It is considered a useful and effective approach to improve the scalability of distributed systems and to decentralize access to energy markets. The peers in the same layer act to collectively meet the needs for energy and stability and, in turn, receive tokens to sell for their functioning as agents that maintain the network. This layered system extends from regional energy suppliers to neighbourhoods and buildings and even individual homes, all acting to maintain their microcosm of the network.

- Other models: private networks, for example.

Some companies related to energy sale platforms that make use of blockchain technology are presented below:

- Power Ledger [13]: This platform was founded in May 2016 and allows the sale of P2P energy (exchanges of energy between equal agents, for example, between owners of photovoltaic installations) using blockchain technology, recording the production and consumption of electricity in real time. It also has its own cryptocurrency, the POWR, interchangeable by the Sparkz token, which gives access to the Sparkz exchange platform for energy. The POWR tokens are access passes to the platform, which are sold to new users and generate revenue for the platform. The retailers are the "Application Hosts", which execute the application and guarantee a quantity of POWR tokens that are exchanged for Sparkz tokens. The latter are the ones that are finally sold to the users, since they will pay with them the exchanges of energy between equals. Sparkz tokens are destroyed in the application once they have been used in an energy transaction.

- WePower [14]: WePower is a renewable energy exchange platform based on blockchain. It is designed to make green energy producers obtain capital by selling their own energy tokens. It connects buyers with renewable energy producers directly to buy green energy in advance, at prices lower than those of the market.
  The role that blockchain technology plays in this platform is to grant transparency and reliability to transactions, through tokens and smart contracts. This company also launched a pilot project to tokenize all energy transactions in Estonia, which was chosen for being ideal for this project, with 100% smart meters at the demand points.

- Grid+ [15]: Grid+ will operate as an energy retailer that will use the Blockchain technology. Using an Intelligent Agent allows the user to control their consumption and pay his/her energy. This system has two main interests. The first is that it reduces the administrative cost on the Grid+ side. The second is the elimination of default risk, since customers can only buy electricity when their smart agent owns BOLTs (Grid+ cryptocurrency).

In a peer-to-peer (P2P) energy exchange [10] [16], a "peer" is an agent or a group of agents of the energy markets, either generators, consumers or prosumers. The idea of P2P energy exchanges is to make transactions between equal agents possible without the existence of intermediaries.

The exchange of P2P energy is a radical change regarding the conventional functioning of the energy markets. In a conventional electrical system, energy exchange occurs from large capacity generators to consumers, being transported for many kilometres. The flow of capital circulates in the opposite direction to energy.

For its part, the exchange of P2P energy promotes energy transactions between equal agents in the presence of surpluses, being especially useful this type of exchanges between agents within a certain geographical area.

In addition to microgrids in specific geographic regions, P2P exchanges arouse great interest in current trends in the evolution of the electricity sector due to their possible application to distribution networks. In future intelligent networks with a very high demand due to a hypothetical but expected increase in the sales of electric vehicles, and with an increase in distributed generation in the system, P2P energy exchanges could be very useful for the users of electric vehicles, for example. When they have finished loading their car, it could serve as storage system and sell the remaining energy to other consumers who need electricity. Self-consumption systems that exchange energy would also be an example of P2P exchanges.

In this section some examples of P2P energy exchange projects that are currently being developed in the world will be analysed.

The first one mentioned is located in the United Kingdom, the Piclo project [17] is an online platform that executes transactions of energy exchanges between generators and consumer companies. The transparency of these exchanges is manifested in the total visualization of the data to which these consumers have access. Depending on the measurements, the offers of the generators and the preferences of the consumers, supply and demand are matched every half hour. Thus, consumers can request that they prefer to obtain energy from one production technology or from other, for example, renewable technologies.

In Holland, the Vandebron platform [18] allows consumers to buy electricity from producers independently, being able to agree with a photovoltaic plant or a wind farm to acquire the energy produced by the generator. In addition, self-consumption is favoured by offering prosumers that sell their excess energy in the platform the possibility of acquiring their energy consumed at a lower price.

With regard to energy exchanges between equal prosumer agents, the SonnenCommunity [19] in Germany is a great example of this. In this community those prosumers owners of batteries (SonnenBatterie) are able to participate. Agents can exchange surplus self-generated energy with other prosumers. The operation consists in that when the prosumers have surpluses, they discharge it to the batteries for the moments in which the self-generated energy is not enough to cover the demand in the community (for example on non-sunny days). The novelty of this community lies not only in the P2P exchanges of energy, but in the use of electricity storage systems as a fundamental part of the platform.

LO3 Energy [20], a young company from New York, is working with Siemens Digital Grid and Siemens startup, next47, on a project called Brooklyn Microgrid, where neighbours are authorized to produce, consume and buy energy within their community with a chain-enabled platform of blocks (blockchain).

Brooklyn Microgrid was founded in 2016. It started with sales of electricity from neighbours who had installed solar panels to neighbours who did not have facilities in their homes. With the help of LO3 Energy, residents of Park Slope and the surrounding neighborhoods of Gowanus and Boerum Hill founded "Brooklyn Microgrid" [21].

This project was made possible thanks to the coexistence of three factors:

- First, due to the blockchain platform of LO3 Energy, a technology that marks the time of each transaction with a chain of secure blocks, documenting each of the energy transactions.

- Secondly, thanks to the collaboration of the division of digital networks of Siemens, so that technical solutions to install microgrids were offered.

- Lastly, the newly created company of Siemens next47, supported the project by involving potentially disruptive technologies, through financing, project experience and business advice.

However, the project is not limited to being exclusively a micro-grid on a small scale in which energy is exchanged between equal parts. Given the consequences of Hurricane Sandy in 2012, one of the objectives of the project is to incorporate battery storage systems into the network, as is already done in the SonnenCommunity of Germany, to maintain supply in situations of natural disasters such as the mentioned one.

2.3 Spanish regulation

Shared self-consumption is defined as the consumption of electrical energy from generation facilities connected inside a network of several consumers or through a direct line of electrical energy associated with a community of consumers. It comes from the production of energy by several users, in a shared way. It is usually done through a photovoltaic installation. This practice was prohibited as a result of RD900 / 2015 [22]. In 2016, the Generalitat de Catalunya decided to file an appeal with the Constitutional Court against part of the Royal Decree and, a year later, following the 68/2017 judgment of May 25 of the Court, some articles were repealed, those referring to the shared self-consumption [23]. From this moment on, the absence of a legal regulation on the matter that indicated how to proceed in the connection of the facilities became the problem.

In October 2018, RD15 / 2018 [24] was published, which suppressed the aforementioned one. In this the right to shared self-consumption is recognized. In addition, a period of 3 months was announced for the drafting and publication that, from a technical point of view, solved the connection problem.

The Royal Decree-Law is a legal norm of urgency and necessity that emanates from the executive power, which is why it must be endorsed by the parliament in less than a month, thus having a provisional nature. In addition, the aforementioned document gives a period of 3 months for the Government to develop normatively Article 18, referring to self-consumption.

From the RDL15 / 2018 the following points can be highlighted:

- As a result of this the “sun tax” is annulled, since the self-consumed energy with renewable origin does not have to pay tolls or charges. Then the self-consumption energy poured into the network must only pay the tolls for the use of the distribution network (fixed power term in the user's invoice).
- The classification of this type and facilities is simplified with respect to that set forth in Law 24/2013 of the Electricity Sector. Thus, there are two types of facilities: self-consumption without surplus and self-consumption with surplus. Those without legal capacity to deliver power to the network will need the installation of an anti-dumping equipment. In the case of facilities with surpluses, there will be a consumer subject and a producer subject. The greater legal requirements will suppose the disadvantage of this type of installation, whose advantage will be the possibility of monetizing the energetic surpluses.
- Although it is not named as such, the right to self-consumption by one or several consumers (shared) is recognized to take advantage of economies of scale. It is understood that shared

self-consumption facilities will be those in which more than one consumer participates and are connected in low voltage to the network that derives from the same transformation centre.
- It also simplifies the processing and legalization of self-consumption. Specifically, it is stated that in the case of installations without surpluses of less than 100 kW connected in low voltage, only the provisions of the low voltage electrotechnical regulation must be followed. In these installations and in those of self-consumption of up to 15 kW with surpluses, it will not be necessary to request access and connection permits from the distributor, making it much easier to legalize them.
- It is no longer necessary to install standardized measurement equipment to record the net solar generation, with the corresponding cost reduction, it is allowed to install more power of the one contracted, etc…

Therefore, as a result of the approval of RDL15 / 2018, the door opens to the expansion of self-consumption shared in Spain. As we have indicated, in this Royal decree-law the derogation of the so-called "sun tax" is certified in addition to simplifying the administrative procedures to legalize this type of self-consumption facilities. All this supposes a high saving in his costs of installation, favouring still more his use, added to that in many of them it is no longer necessary to install counters of net consumption and generation.

Finally, on April 6, 2019 Royal Decree RD 244/2019 [1] was published, which regulates the administrative, technical and economic conditions of self-consumption in Spain, expanding the regulatory framework of the Royal Decree-Law mentioned above. The most outstanding points of the mentioned RD are summarized below.

2.3.1 RD 244/2019

The purpose of this Royal Decree is to establish the technical, administrative and economic conditions of self-consumption.

This Royal Decree refers to the concept of "simplified compensation of surpluses". The difference regarding the net balance is that the surplus energy of the plates is not counted and compensated per watt poured (in the case of the net balance for each watt discharged to the grid one watt can be recovered when required). In this case the economic compensation per watt poured is reflected in the electric bill in the form of a discount. This discount will depend on the retailer. This RD implies a new definition of self-consumption: consumption by one or several consumers of electricity, coming from generation facilities close to consumption and associated with it.

This document eliminates the limitation of the maximum power generation installed up to the contracted power of the consumer associated and facilitates the measurement configurations. The self-consumption facilities adhered to the modalities reflected in the previous Royal Decree of self-consumption are adapted. The connection to the network of single-phase generation facilities up to 15 kW is also allowed. Beyond, there is a period of 4 years for supplies with a measurement point type 4 (fundamentally access tariffs 3.0 A and 3.1 A with less than 50 kW of contracted power) to be integrated into telemanagement systems to provide hourly measurement of its consumption, which will allow the hourly price signal of the wholesale electricity market to be received and economic efficiency measures implemented in this sense.

Types of self-consumption:

- **Self-consumption without surplus:** The facilities under this type of self-consumption need an anti-pouring equipment, so that no energy is spilled into the network, with minimal administrative procedure.
- **Self-consumption with surplus:** They can send power to the network, being a home or an industry in hours of inactivity, for example. There are two modalities here:
  - **With surpluses receiving compensation:** The electric distributor will compensate the energy discharged to the grid in the electricity bill. All homes and industries with less than 100 kW of installed power can accommodate to this mode. The generation must be renewable, without additional or specific remuneration regime and the total power of the associated production facilities less than or equal to 100 kW. If it becomes necessary to make a supply contract for auxiliary production services, a single supply contract is signed for the associated consumption and for auxiliary services with a retailing company.
  - **With surpluses not subject to simplified compensation:** In principle for installations greater than 100 kW, with surpluses that are delivered to the network under sale regime. The price will be marked by the legislation of electric generators. It can be with single or more than one supply contract.

Thus, the self-consumption with compensation of the surplus can be given in the following ways: selling the energy in the pool market or compensating the surpluses monthly, through the valuation of surplus hourly energy, being called this option simplified compensation. The amount to be compensated may never exceed the monthly value of the hourly energy consumed.

If the consumer is covered by the self-consumption mode without surpluses, they themselves will be the owner of the supply point and of the production facilities connected to their own network. If the self-consumption is collective, all the owners share in solidarity the ownership of the anti-pouring mechanism and the generating facility.

The permanence in the modality chosen for self-consumption will be at least one year, although this time is extendable. Likewise, storage systems may be installed in all cases. In addition, self-consumption is classified in:

- Individual: A single consumer. It can be used in any modality. If self-consumption is through a network, it will necessarily be considered self-consumption with surpluses.
- Collective: More than one consumer associated with the generation facilities, all of whom must belong to the same self-consumption modality and have communicated to the distributor (directly or through their retailer) an equal agreement signed by all the participants that develop this form of self-consumption, depending on the power of the consumers, their economic contribution to the associated generation facility or any other criterion (in the absence of notification of distribution coefficients agreement, the distributor will calculate them according to the contracted powers). It can be used in any modality. If self-consumption is through a network, it will necessarily be considered as self-consumption with surpluses.

All households with self-consumption have the possibility of using the model with compensation of surpluses, this being the most recommended for all installations of less than 15 kW, since the retailer's access point is not required. The compensation received will depend on two things:

- If the contract has a regulated price (PVPC), the economic compensation will be the average daily price of the energy purchased at the time of the spill, which price is set by OMIE.

- If the contract is of the free market, the price will be compensated according to what was negotiated with the retailer.

Industries with self-consumption photovoltaic installations of less than 100 kW may be eligible for self-consumption with surplus compensation. Being mostly installations of more than 15 kW, these will have to perform the procedures of access and connection to the network to be able to pour. The price of compensated energy in solar installations above 10 kW is always the result of negotiation between the client and the retailer.

According to the contracting regulated with PVPC, the Reference Retailer will perform the billing discounting, on the amounts to be invoiced before taxes, the economic term of the surplus hourly energy at a price approximately equal to that of the electricity day ahead market price, while never exceeding the economic value of hourly energy consumed from the network in the monthly billing period. If the social bonus is applicable, the corresponding discount will be applied to the difference between the two previous amounts. Once the final amount has been obtained, the relevant taxes will be applied.

Thus:

- For self-consumption of less than 100kW power, which are connected to the low voltage network and the installation is in low voltage, the access contract will be made ex officio by the Distributor, who will also be in charge of informing the retailer. The procedure will be the following one: The CC.AA. will inform in 10 days to the distributor from the reception of the documentation that accredits the start-up of the installation. With this documentation, the distributor will have 5 days to send the modification of the contract to the retailer and self-consumer. It will also inform about all the characteristics of self-consumption (modality, distribution, etc.). From the reception of this modification, the consumer will have 10 days to notify the distributor of any discrepancy.
- The rest of the self-consumers, or new points of supply, must make a communication to the Distributor or through the retailer so that it modifies ex officio the existing contract. The distributor, then, will have a period of 10 days to modify the contract. In case of discrepancy, the associated consumer will have 10 days from the receipt of the same by the distributor to notify their disagreement.
- The contract with the retailer should reflect the self-consumption modality. Reference retailers may not refuse contract modifications of self-consumers subject to PVPC (voluntary price for the small consumer).

It is not necessary for the consumer to contact their retailer to choose a modality, but it can be the distributor itself that contacts the retailer (once it has received the corresponding information and within a period of 5 working days) to communicate the date of the start of the chosen modality and, if applicable, the agreement of the distribution coefficients and the conditions of the simplified compensation mechanism.

The electric bill can never be compensated 100%, as there are costs assigned to the power term. The costs of the energy term could be completely saved, theoretically. However, the new situation may lead to an adjustment of the contracted power and the reduction of the power term.

As said, there are two ways of monetizing the surplus energy:

- **Sale of energy to the network:** This modality can accommodate all forms of self-consumption, being mandatory in the case of self-consumers not eligible for surplus compensation. Under this regime, the hourly surplus energy is operated as a network installation where the hourly price of the electricity pool is valued or, where appropriate, the Specific Remuneration Regime if it has been granted to the installation. The self-consumers who operate under this modality will have the consideration of producers having to comply with what is established in the regulations (representative, etc.). In addition, the energy sold must satisfy the generation toll (€ 0.5 / MWh) and its economic valuation will be subject to the 7% tax.
- **Simplified compensation mechanism:** Applicable for self-consumers with surpluses receiving compensation. The hourly energy consumed by the network will be valued at the agreed price between the parties (in the case of PVPC it will be valued at the hourly cost of energy for the PVPC). The compensation mechanism is established monthly. And in no case the value of the surplus hourly energy may be greater than that of the consumed one. The surplus energy will not pay the toll to the generation nor its economic value will be subject to the Tax on the Value of the Production of Electric Power (tax of 7%). In the case of "facilities through the network", the self-consumers must satisfy an amount for the use of the distribution network, which will be defined by the CNMC.

In the RD, it is defined: "production facility close to consumption and associated to them" that covers individual and collective consumers, defining the types of facilities that can be put into operation. Production facilities associated with consumption are considered to be close if they meet any of the following conditions:

- Nearby indoor network installation: If they are connected by lines directly or connected in the internal network of the associated consumers.

- Nearby installation through the network (which must satisfy an amount for the use of said network, pending to be established by the CNMC): If they are connected to any of the low voltage networks derived from the same transformation center, the distance between generation and consumptions connected in low voltage is less than 500 meters or if generation and consumption are located in the same cadastral reference taking into account its first 14 digits (or similar circumstance in the autonomous communities of Navarra and País Vasco).

As indicated, collective self-consumption may belong to any of the self-consumption modalities when it is carried out between nearby indoor network installations. However, in the case of nearby installations through the network, it may only belong to self-consumption modalities with surpluses.

If the installations are “Nearby indoor network”, they are renewable energy with installed power of less than 100 kW and, in a year, the energy consumed by the auxiliary services is less than 1% of the energy generated by the generation facility, its Auxiliary services are considered negligible. In this case, a supply contract is not required for them, so that a single access contract for the auxiliary services and the consumption that is associated to them is formalized, if the consumer and the owner of the installation are the same physical / legal person.

There is no limit for self-consumption facilities. The compensation will be made in the period in which the invoicing is made (monthly) and can be negotiated with the retailer regarding the compensation of consumption.

It is allowed to rent a surface (roof) to an external company that invests, installs and maintains the PV modules. The owner consumes the energy that is generated and the saving is shared between the owner and the company that owns the installation.

These facilities can also be shared between industries and homes, neighbourhood communities, etc. The system by which the savings obtained or the photovoltaic production are distributed will be decided among the co-owners.

In solar installations on the free market and below 100 kW, surplus compensation will be carried out through economic compensation. The compensation will be reflected in the vendor's invoice each month, depending this compensation on the price of the energy at the moment of the power injection to the grid. These prices will be offered by the retailers and the client will be able to contract the offer that best suits them.

In the form of self-consumption with surpluses and compensation, where the energy poured into the system will not be considered as energy incorporated into the electrical system (exempt from generation tolls), the retailer is responsible for the balance of that energy.

Therefore, it seems essential an operational development and adaptation of the regulation corresponding to the procedures managed by Red Eléctrica and the CNMC, for the nomination of surplus energy, the economic liquidation between the subjects of the wholesale market involved and the allocation of production measures and consumption.

Regardless of the type of installation, it is required to inform the retailer that there is a self-consumption facility owned. If the installation is without spillage it is not necessary to obtain the access and connection permits to the network, but it is sufficient to deliver a certificate of installation or memory / technical project to the regional body that corresponds.

If the modality is with surplus in installations of more than 15 kW, it will be necessary to carry out the aforementioned procedures. The initiation of these procedures is done at the request of the Autonomous Community (within 10 days of submitting the documentation), and the electricity company is obliged to respond within 5 days to the user of the installation. For connection and access procedures, the provisions of the Law of the Electricity Sector -LSE (Law 24/2013, of December 26 [25]) must be complied with.

These procedures are:

- Send the connection project to the distributor, and the distributor can request changes.
- The Distributor will make a Technical Connection Conditions Report in less than one month.
- Realization of a Technical Access Contract where the access conditions are specified.

The installations of more than 100 kW have two options to which they can benefit:

- The modality of self-consumption without surpluses.

- Self-consumption with surpluses without compensation (the surplus is sold in the electricity market with the conditions for electricity producers). This involves declaring the benefits, enrolling in the IAE as a producer and paying generation taxes and network access toll for the energy sold to the distributor.

It is not required by the self-consumer to install another meter since in the self-consumption mode with surplus compensation only one meter is needed to measure the energy demand and injected into the network, that is, bidirectional. Currently, most Smart Meters have this capability.

In the following cases, the production facilities must have measurement equipment to record the net generation

- If the self-consumption is collective.
- If the generation facility is “Nearby through the network”.
- If the generation is not of a renewable technology, cogeneration or waste.
- If the self-consumption is with surpluses without compensation and also there is no single contract for supply.
- In high power generation facilities (equal to or greater than 12 MVA).

However, for those individual self-consumers in the surplus mode without compensation, and provided that they allow access to the counters by the distributor, there is the possibility of availing themselves of the following measurement configurations:

- Bidirectional measuring equipment with capacity to obtain the net energy generated every hour.
- Measurement equipment with record of the total energy consumed.

The storage systems will share the measurement equipment that registers the net generation, the measure equipment of the border point or the measure equipment of the associated consumer.

In exceptional cases it is allowed for the measurement equipment not to be located at the border point, guaranteeing physical access and informing the owner of the network, provided that it is proven that installing it at the border point would involve an investment greater than 10% of the total investment, or in cases where the facade is a protected area.

The measurement equipment will be located as close as possible to the border point and, depending on their type, will have the following requirements:

- Type 5: they will have to be integrated into the telemanagement and telemetry systems of the entity that is responsible for the reading.
- Type 4: It must comply with the provisions of the unified regulation of points of measurement of the electrical system, as approved by Royal Decree 1110/2007 [26]. In addition, the development rules for type 4 and 5 points must be met, following the most demanding ones.
- Type 3: Devices that allow remote connection with characteristics similar to those for type 3 generation point of measurement are required.

In cases with more than one production facility with different physical / legal titleholders, a measurement equipment is required to record the net production in each installation, being optional in those cases in which the ownership of the generation facilities is the same person.

The distributor will be in charge of reading the energy measurement equipment and of making the net hourly balances, to make them available to the participants in these measures, that is, consumers, retailers, etc. These will be disaggregated so that the energy can be invoiced in an appropriate manner and with the necessary detail to be able to apply the compensation with surpluses if applicable.

For the management and sale of energy from production facilities with renewable technology in self-consumption with surpluses, the existing veto has been lifted in Royal Decree 413/2014 [27], which prevented acting as representatives of the dominant operators in the electricity sector and of those agents with a quota of participation in the supply of the production market superior to 10%.
The self-consumption registry will be telematic and of free access and will contain 2 sections: Section without surpluses and section with surpluses (receiving compensation, not receiving compensation with a single supply contract and not receiving compensation without a single supply contract).

The registration will be ex officio by the Autonomous Communities for low-voltage self-consumers with an installed power of less than 100 kW. The General State Administration may inspect the self-consumers, in particular, the economic conditions of the supplies and the energy sold. Before March 31 of each year, the TSO and the distributors will send aggregate information related to the self-consumption facilities.

This RD gives a period of 6 months to join some of the types of self-consumption described. The RD comes into force on the day following its publication, however it is given to the Autonomous Communities, a period of 3 months to automate the management and communication protocols to the electricity company and a period of 4 months to the electric distributors for make the appropriate changes that allow the compensation of surpluses.
The electric powers that are included in the Royal Decree and that refer to the different modalities, refer to the power of the investor, not the photovoltaic modules.

Thus, the main mission of shared self-consumption will be to provide the owners with free and clean energy to cover as much of their energy needs as possible, this process being economically optimal. This implies not wasting energy that has an economic and social value. Therefore, this raises the need to establish an efficient and fair mechanism of distribution of the energy generated, as well as the management of the electricity that will not be self-consumed.

3 Proposed methodology

This project simulates the distribution of the energy generated by a self-consumption facility whose ownership corresponds to three different consumers, that is, it is a collective self-consumption facility. To develop this model, three annual profiles of hourly demand will be generated, as well as an energy PV generation profile per hour of one year and the prices and other data necessary to evaluate the distribution hypotheses to be studied. These hypotheses will be proposed based on different energetic and economic criteria in order to determine which is the most efficient way of sharing the energy generated by the shared photovoltaic installation among the different users.

In the first place, the necessary data will be obtained to simulate the different scenarios. Then, the different purposed hypotheses are presented.

3.1 Load profiles

Obtaining the demand profiles of the three consumers is sought in this section.

To determine the hourly consumption of each home, standard profiles generated by Red Eléctrica de España will be used. For this, a typical annual power consumption will be assumed for each user and the mentioned profiles will be used in each dwelling to obtain the consumption per hour of the year to be simulated. To obtain these standard profiles, we will use the ones published by Red Eléctrica de España, in its management function of the Electrical Measurement Information System (SIMEL) [28].

Among the functions of the operator of the Spanish electricity system is to ensure the proper functioning of the system of measurements of the Spanish electricity system, with the operator in charge of managing and obtaining the readings of the border points that are established in the regulation, in accordance with Article 30.2 of Law 24/2013, of December 26, of the Electricity Sector. With the aim of developing this function, since 1998 Red Eléctrica de España manages the main concentrator of the Electricity Measurement Information System (SIMEL), independently. This system of electrical measurements is a fundamental element for the functioning of the market and the closing of energy exchanges for their liquidation. Once the information has been validated and, in cases where it is necessary, estimated, it is added per programming unit to be sent to the Settlement Information System (SIL). In addition, the measures received are used for other purposes, such as sending the information required by MINETUR, CNMC, public administrations, and also for the publication of statistics on the electricity system. Thus, SIMEL is an intelligent system in charge of obtaining the hourly energy data registered in the Spanish meters located at border points between electric system activities, directly or through secondary concentrators. These points include generation facilities, international connections, connections between the distribution and transport networks, or between two distributors, and consumer supply points.

In addition, by Article 12 of Royal Decree 1110/2007, of August 24, which approves the unified Regulation of points of measurement of the electrical system, the Operator of the System is in charge of reading almost 7,000 border points (2014). This process consists of receiving the hourly measurements every day (directly or through secondary hubs), comparing the data received from different sources, estimating the gaps according to the corresponding procedures, maintaining and being in charge of updating the structural data and perform the relevant inspections according to the unified regulation of points of measurement.

Thus, the participants of this measurement system have access to the information of their own measuring points in the SIMEL, according to the conditions set to access the measurement concentrator. Each participant, retailer or representative may access only the points of which they participate, in a restricted manner.

To allow this access, Red Eléctrica has developed a secure system to allow each participant to consult and obtain files and forms with the relevant data so that they can perform their functions. In addition, general and free access reports are published on this system of measurements, whose information is generated from these energy data and the registers of the different border and measurement points, which exist in the aforementioned electrical measurement concentrator. Red Eléctrica is the operator of the system and calculates and publishes periodically the final demand profiles of the peninsular system.

The final profile is the consumption profile that will be used to generate, from non-hourly measures records, the hourly consumption profiles of consumers of certain types. The calculation of these profiles is done following the stated in the Resolution of December 21, 2018 of the General Directorate of Energy Policy and Mines. At the end of each month, and with a maximum delay of 5 days, the consumption profiles are published. If corrections in these data occur later, they do not affect the calculated profiles.

The general provisions of the aforementioned Resolution of December 21, 2018, of the General Directorate of Energy Policy and Mines [29], are summarized below. In this the method to calculate the consumption profiles for the purposes of the liquidation of this, for customers type 4 and 5 without registration of consumption per hour, is approved according to Royal Decree 1110/2007, of August 24, which approves the unified regulation of points of measurement of the electrical system, for the year 2019.

General dispositions

Article 9 of Royal Decree 1435/2002, of December 27 [30], stipulates that for the supply points without obligation to have a record of hourly consumption, for the liquidation of energy, the General Directorate of Energy Policy and Mines will determine, to proposal of the National Commission of the Markets and the Competition, the profile of consumption and the method to obtain it according to the type of consumer in function of his access tariff and the equipment of which they have for measurement and control.

On the other hand, in article 32 of the Unified Regulation of Points of Measure of the Electric System approved by Royal Decree 1110/2007, of August 24, it is indicated that, for points of demand type 4 and 5 without hourly record of consumption, the liquidation is done by applying the consumption profile determined by the General Directorate of Energy Policy and Mines mentioned above.

In addition, Royal Decree 216/2014, of March 28 [31], which indicates the methodology to be followed for the calculation of prices affecting consumers under regulated PVPC tariffs, establishes in its sixth article that if a supply hosted by the PVPC does not have telemanaged hourly measurement equipment and with integrated telemetry in an efficient way in the corresponding systems, the invoicing will be done by applying the demand profiles calculated according to the Royal Decree, applied to the real measurements by periods. The eighth article defines the hourly coefficients of these profiles referring to the invoicing of the PVPC.

The profiles have been subject to review by the system operator, according to the fourth additional provision of Royal Decree 216/2014, of March 28, sending this revision to the National Commission of Markets and Competition.

Thus, this general direction resolves to approve the methods to calculate the consumption profiles and these profiles for the purposes of energy settlement, applicable to consumers type 4 and 5 without hourly consumption records.

Method of calculation:

Its purpose is to determine the load profiles that will be used to obtain hourly measurements necessary for the liquidation of energy in the market, based on consumption records obtained from non-hourly measuring equipment. These profiles will, therefore, be applied to those consumers without the obligation to have hourly record of consumption that acquire electrical energy directly or through a retail company.

For the calculation, the following definitions are made:

- Initial profile: Indicative load profile used as the basis for the calculation (values included in Annex III of the Resolution).
- Final profile: it is the demand profile that will be used to generate the hourly measurements of the clients in order to liquidate the energy consumed.
- Reference demand: It is the demand forecast of the Peninsula system that will be used in the calculation of the final profiles starting from the initial ones. These reference values are attached to this General Directorate.
- Demand of the system: the system operator publishes the demand of the electrical system of the Iberian Peninsula to be able to elaborate these profiles.

Consumers are classified into 4 categories according to how their load profiles differ:

- With 2.0A and 2.1A access toll and one-period measuring equipment.
- With access toll 2.0 DHA and 2.1 DHA and measuring equipment with schedule adapted to these rates.
- With access toll 3.0 A and 3.1 A, measured in low voltage and recording in 6 periods.
- With access toll 2.0 DHS and 2.1 DHS and measurement equipment with schedule adapted to these rates.

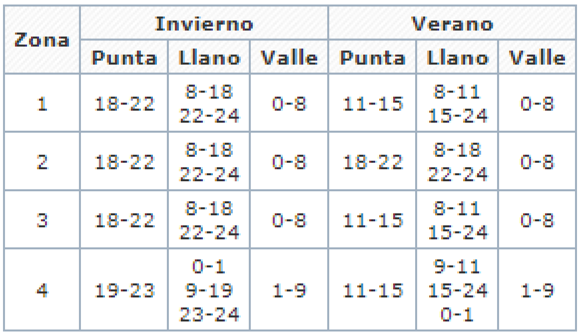
The six periods mentioned in article 9.7 of the unified regulation of points of measurement of the electrical system approved by Royal Decree 1110/2007, of August 24 are (for the access toll of three periods 3.0A based on what is stated in the Annex II of Order ITC / 2794/2007, of September 27, and for the access toll of three periods 3.1A as established in the third additional provision of Order ITC / 3801/2008, of December 26) [32]:

- Period 1: Peak hours of the working days from Monday to Friday.
- Period 2: Plain hours of the working days from Monday to Friday.
- Period 3: Hours of the weekdays from Monday to Friday.
- Period 4: Peak hours on Saturdays, Sundays and national holidays not substitutable by the Autonomous Communities.

- Period 5: Plain hours on Saturdays, Sundays and national holidays not substitutable by the Autonomous Communities.
- Period 6: Valley hours on Saturdays, Sundays and national holidays not substitutable by the Autonomous Communities.

Table 1 shows the hour values used to determine these six periods:

TABLE 1 – TIME PERIODS ACCORDING TO THE HOURS ACCORDING TO *[32]*



Zona	Invierno			Verano		
	Punta	Llano	Valle	Punta	Llano	Valle
1	18-22	8-18 22-24	0-8	11-15	8-11 15-24	0-8
2	18-22	8-18 22-24	0-8	18-22	8-18 22-24	0-8
3	18-22	8-18 22-24	0-8	11-15	8-11 15-24	0-8
4	19-23	0-1 9-19 23-24	1-9	11-15	9-11 15-24 0-1	1-9

For the calculation of the final profiles, the following procedure is followed. The initial profiles are modified depending on the evolution of the demand of the system in relation to the reference (to take into account the different factors that affect consumption). The initial profiles are composed of a relative weight coefficient for each hour of the year. First we define the relative weight of the coefficient of each hour according to the day, dividing, for each day, the coefficient of each hour between the sum of the coefficients of that day. The relative weight of each month of the year is obtained in a similar way. The demand of the system and the reference of each hour of the year are also used, as well as specific coefficients of each category of consumers included in the Resolution.

The operator of the system obtains, therefore, the final profiles adjusting the hourly energy (Demand of the system) with respect to the day, the daily energy with respect to the month and the monthly energy with respect to the year.

The managers of the readings of hourly measures of consumption are the distributors, from the data obtained from the measuring equipment. In order to liquidate the final energy, the final profiles are applied, depending on the category of the customer, to the energy that is registered in the measuring equipment, in each measurement period. If the equipment registers energy in more than one block, the final profile is applied to the hours of each block independently.

The final profiles are supplied by Red Eléctrica through its website. For the development of this document, those corresponding to 2018 have been obtained.

Once the final profiles have been obtained, the hourly consumption profiles of each user are calculated from the annual consumption of each one. Being $MC^{c}_{j,t,J,T,p}$ the incremental measure obtained from the customer counter "c", between the day "t" of the month "j" and the day "T" of the month "J" corresponding to the hour block "p", $MCH^{c,i}_{m,d,h,p}$ the calculated hourly measurement of customer "c" with profile "i", at time "h" of day "d" month of "m" corresponding to the time block "p" recorded by the measuring equipment and D_m the number of days of each month "m", the following formula applies:

$$\mathrm{M}CH_{m,d,h,p}^{c,i} = \frac{P_{j,t,J,T,p}^{i,f}}{\sum_{m=j}^{m=J} \sum_{\substack{d=t\leftrightarrow m=j \\ d=1\forall m\neq j}}^{\substack{d=T\leftrightarrow m=J \\ d=D_m\forall m\neq J}} \sum_{h\in p} P_{m,d,h}^{i,f}} \tag{1}$$

Thus, a Matlab program is developed to obtain consumption profiles following the final profiles. It begins by supposing the annual consumption of each client in kWh, which will depend on the client's characteristics and will be determined later. Although at the time of performing the simulation proposed different rates will be tested, with different types of time discrimination, to obtain the load profiles the coefficients of profile B will be used, because the 2.0DHA is a common rate at the domestic level. This way, a program that takes the coefficient data by hour is elaborated. For each time period (winter / summer, labor / holiday, peak / plain / valley) it adds the hourly coefficients. Then, for each hour, it uses the aforementioned formula to obtain the consumption value in that hour, multiplying the consumption corresponding to the period by the coefficient of final profile in that hour and dividing it by the sum of the coefficients of the corresponding hourly period calculated before. The hours corresponding to each period are obtained from the aforementioned Order ITC / 2794/2007, of September 27, which revises electricity rates as of October 1, 2007. These are shown in the Table 1.

To obtain the consumption per period, the total annual consumption of each client is taken and divided into 6 different periods (peak / level / valley of business days / holidays). For this, in the program, one week of the year of demand in Spain obtained from the website of e-sios (the System Operator Information System (e-sios), developed by Red Eléctrica, which is an information system designed to execute the processes for a safe and economically efficient operation of the Spanish electricity system in real time) [33] is taken and the total consumption is calculated for each of the 6 periods, with the percentage being then the total of consumption that takes place in business days and holidays, and peak, valley and plain periods. With these coefficients, the total annual consumption of each of the load profiles of the project is distributed among the six periods for each client. In this way, there is an annual consumption per block, so that the previously introduced formula can be applied, which requires that the Final Profile has to be applied independently for the hours of each block with the consumption measured in that block. Therefore, 14% is consumed in peak, 25% in valley, and 61% in plain. In addition, 25.5% of the annual total is consumed on a holiday and the rest in the work period.

The clients to simulate are posed as follows:

User 1: Single-family house with average daily consumption of 15 kWh. The members of this family leave the house at 8:00 am and do not return until dinner time, so their consumption is higher in the valley and peak periods in winter and valley and plain in summer, with respect to the standard coefficients obtained previously. In the winter, they rest at home during the weekends, so they consume more than usual. In summer, however, its consumption on holidays goes down a lot, as they spend the weekends out of their home.

User 2: Single-family dwelling with a daily average consumption of 20 kWh, as it is more numerous. This family eats at home every day, although they have breakfast at work / school. Therefore, its consumption is very low in the valley and somewhat higher in the rest of the periods.

User 3: Family with large consumption during all periods. Average daily consumption of 24 kWh. The coefficients calculated during the work week are maintained, but at the weekend they hardly consume electricity.

Therefore, the coefficients to be applied to the annual consumption of each user to distribute it by periods will be those presented in the Table 2:

TABLE 2 – COEFFICIENTS OF CONSUMPTION PER USER

	Peak consumption coefficient		Coefficient of consumption in plain		Coefficient of consumption in valley		Coefficient of consumption in business days		Consumption coefficient in holiday period		Annual consumption (kWh)
	Winter	Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter	Summer	
User 1	22 %	9 %	48 %	64 %	30 %	27 %	27 %	53 %	14 %	6 %	5475
User 2	21 %		69 %		10 %		74,5 %		25,5 %		7300
User 3	14 %		61 %		25 %		90,5 %		9,5 %		8760

Thus, the annual hourly consumption of each of the three generated users is obtained.

3.2 Day-ahead market prices

The hourly data of the daily market price in Spain is obtained from the Esios website. It takes a year of price values corresponding to 2018, as they are considered sufficiently representative.

The daily market in Spain is managed by OMIE [34], operator of the electricity market in Spain and Portugal. This market is the one that sets the prices of electricity daily at 12:00 hours for the following 24. In each hour the price and volume of energy acquired are established according to the supply and demand curves and following a marginalist price model. The EUPHEMIA algorithm approved (by Regulation (EU) 2015/1222 of the European Commission of July 24, 2015) [35] for all markets of the European Union is used. Iberian buyers and sellers send their offers for this market to OMIE, which accepts them in order of economic merit and depending on the available interconnection capacity. If the capacity of interconnection with a country saturates, the price in those countries will become different. Once the daily prices are obtained in this market, they are sent to the system operator, who judges their technical viability. This is the so-called management of the technical restrictions of the system and serves to ensure that the market results are physically feasible in the transport network. These results undergo certain modifications depending on their technical feasibility after the analysis developed by Red Eléctrica, as operator of the system. This results in a viable daily program.

Deviations in production or consumption are managed in other markets, such as intraday.

From RD 244/2019 it is derived that surpluses of self-consumption under regulated tariffs will be compensated at the daily market price, since on the amounts to be invoiced before taxes, the economic term of the surplus hourly energy must be discounted at a price approximately equal to the one the electricity pool, in a way that in no case the economic value of the hourly energy consumed by the network in the monthly invoicing period is exceeded.

3.3 PVPC prices of users

The users proposed in this project will have contracted powers of less than 10 kW, and will be domestic, so that they can benefit from 3 different options for their electricity bill [36].

- Regulated price PVPC (Precio Voluntario del Pequeño Consumidor)

This is the regulated tariff that the reference retail companies have the obligation to offer. Users with voltages lower than 1kV and contracted power of less than 10 kW are eligible for this tariff, this being the default rate that goes into effect if they do not negotiate in the free market.

This type of contracts have certain advantages with respect to the free market, since the contracts are simpler and do not have small print. In addition, the user can change to the free market at any time, being able to return to the regulated tariff whenever the cusstomer wants.

This tariff has two terms, the energy one and the power one.

The term of energy is regulated by Royal Decree 216/2014 published in the BOE on March 29, 2014. This, in turn, consists of the energy term of the toll and the cost of electricity production. This production cost is determined by the price of the electricity market in Spain, which is published on the website of Red Eléctrica de España S.A.

The energy toll is regulated and depends on the type of tariff:

- Tariff 2.0 A (Without time discrimination): This is imposed by the Ministry of Industry, Energy and Tourism in Annex I of Order IET / 2444/2014, of December 19. It is currently € 0.044027 / kWh.
- Tariff 2.0 DHA (Time discrimination in two periods): For the first period is 0.062012 € / kWh and for the second is 0.002215 € / kWh.
- Tariff 2.0 DHS (Time discrimination in three periods): For the first period is 0.062012 € / kWh, for the second is 0.002879 € / kWh and for the third 0.000886 € / kWh.

The power term depends on the power contracted by the user. It is currently set at € 38.043426 / kW per year. To this we must add the marketing margin (€ 4 / kW per year).

- Fixed annual price per kWh consumed

Introduced by RD 216/2014 of March 28 (Title IV), this fee implies a fixed price for energy consumption for 12 months. It is offered by all the reference retailers. The price is set freely by each company, complying with a series of standard and comparable conditions, such as not including additional products / services, lasting one year, etc ... This rate provides greater stability of the price to the consumer although at a higher cost.

- Offers in the free market

The consumer is free to negotiate with any retailer to contract a price with agreed prices and conditions.

Regarding the PVPC, there are different opinions about its utility for the client. Companies in the electricity sector recommend negotiating tariffs in the free market, but consumer groups report that the regulated tariff is beneficial for their long-term savings. The reports of the CNCM reveal that this is true in some periods, but not in others, depending on the price of the energy.

By accepting an offer in the free market, the client knows the price of his energy while it is in force, but when it is time to renew it, if energy prices have changed, so will, in practice, the contract conditions. Therefore, the customer is always exposed to wholesale market prices. There are also trap clauses and small print, which create uncertainty in the consumer. There are fewer complaints from the domestic sector and companies between consumers who are admitted to the PVPC than those who are in the free market.

Thus, since there are many different and more complex tariffs in the free market, users of this project will be hosted by the PVPC. For the simulation presented here, the three different regulated tariff cases will be tested in the different users.

In addition, the payment made by the customer to the retailer each month for the rental of the measuring equipment must be taken into account, since, normally, the meter is owned by the retailer. This is the case in our project. This payment is established by the Ministry of Industry, Commerce and Tourism. For monophasic electronic counters with hourly discrimination and telemanagement for domestic consumers it is 0.81 € / month. The ICP amount must always be included (€ 0.03 / month).

As for the electricity tax, this is regulated by Art. 92, Law 38/1992, of December 28 [37] and is calculated as 5.11269632% of the sum of the two previous terms, power and energy. Once this tax is applied, 21% VAT must be applied to the total invoice [38].

3.4 Contracted power

Power is the energy that can be supplied to the user at any time. It is measured in kW and allows the user to make use of several electrical devices at the same time. However, each client has a contracted power, that is, a limit to this. Therefore, in addition to defining the use of electricity that the customer can make at any time, the contracted power also defines what it pays for electricity for the power term in its electric bill. This term does not depend on the energy consumed, it is regulated and must always be paid to face the fixed costs of the system. In 2006, the Ministry of Industry regulated the electrical power that could be contracted in different power sections or standardized powers. However, as a result of the RD 1164/2001 of October [39], users can contract powers without sticking to these sections, in intervals of 0.1 kW depending on the installation required, provided it does not exceed 15 kW. The users of this project will have different contracted powers, somewhat higher than their maximum hourly consumption during the year.

3.5 Profile of electric power generation of the photovoltaic installation

To obtain the hourly data of generation of the photovoltaic installation, the hourly data of the year 2016 of solar radiation (W/m^2), ambient temperature ($°C$) and wind speed (m/s), are obtained, in addition to other data of the photovoltaic installation as azimuth (0 º) or inclination (30º). These are obtained from the website of the European Commission, in its section PHOTOVOLTAIC GEOGRAPHICAL INFORMATION SYSTEM [40], from a given location. In this case the installation will be in Madrid.

Afterwards, the hourly energy generation of the installation will be obtained from these values.

First, the peak power of the installation will be set. At the time of performing the simulations, different values will be taken, smaller and greater than the one set as reference. This will be the value that approximately meets the average daily demand throughout the year. It will be obtained as:

$$P_{ref} = \frac{Annual\ average\ daily\ consumption\ (\frac{kWh}{day})}{Annual\ average\ daily\ irradiation\ \left(\frac{kw}{m^2}\right) \cdot PR} = \frac{59\ \frac{kWh}{day}}{5{,}41\ \frac{kw}{m^2} \cdot 0{,}8} \approx 14\ kW \tag{2}$$

The cost of this installation is considered a sunk cost in all cases. The PR factor will be explained later.

Based on this peak power of the installation, the power generated by the photovoltaic panels is calculated by means of the Osterwal method [41], being:

- G: Incidental solar irradiation in the module (W/m^2).
- G_{ref}: Incidental solar irradiation in reference conditions (1000 W/m^2).
- γ: Coefficient of losses by temperature, fixed (-0,48 %/$°C$).
- T: Temperature of the photovoltaic installation. In order to obtain the temperature, the King model [42] is applied, used in [43] , which is formulated as follows:

$$T = T_{amb} + G \cdot e^{(m+n \cdot W)} \tag{3}$$

- W: Wind speed (m/s).
- m: Empirical dimension coefficient of impact of irradiation on temperature, with value -3,56 [44].
- n: Empirical coefficient that describes the cooling of the installation due to wind, with value -0,079 s/m [44].
- T_{ref}: Reference temperature of the photovoltaic installation (25 $°C$).

The calculation will be, therefore:

$$P_m = P_{ref} \cdot \frac{G}{G_{ref}} \cdot [1 + \gamma \cdot (T_m - T_{ref})] \qquad (4)$$

However, at this generated power it will be necessary to discount the losses that are caused in the DC circuit, by the efficiency of the inverter and in the AC circuit. Those that are not calculated will be assumed, based on [44]:

- Losses by angular reflectance and variation of the radiation spectrum in the photovoltaic module: 3%.
- Residual losses in the wiring: 2%.
- Losses due to the dispersion of parameters in the generator: 2%.
- Losses due to tracking errors of the maximum power point of the inverter: 2%.
- Losses for inverter's performance: To obtain this performance we apply the Jantsch equation [45].

$$\eta_{inv} = \frac{\frac{P_{DC}}{P_{peak}}}{\frac{P_{DC}}{P_{peak}} + (b_0 + b_1 \cdot (P_{DC}/P_{peak}) + b_2 \cdot (P_{DC}/P_{peak})^2} \qquad (5)$$

Where b_0, b_1 y b_2 are dimensionless parameters of value 0.02, 0.002 and 0.03 respectively. P_{DC} is the input power to the inverter from the DC circuit.
To obtain the inverter's output power:

$$\eta_{inv} \cdot P_{DC} = P_{AC} \qquad (6)$$

- Losess in the AC wiring: 1 %.

This methodology has been shown to be valid for the calculation of hourly photovoltaic generation in [46].

The Performance Ratio (PR), defined in [47] is a magnitude that represents the relation between the real and nominal performance of a photovoltaic generation installation. It is expressed as a percentage and indicates the available proportion of energy for the feeding of the load, with the losses already taken into account. Therefore, the larger it is, the more efficient the installation will be, so it serves to compare efficiencies of different facilities and to track the status of one, if periodic measures are taken of this.

$$PR = \frac{E_{AC}}{E_{sun} \cdot \eta_{STC}} \cdot 100 = (1 - L_1) \cdot (1 - L_2) \cdot \ldots \cdot (1 - L_n) \cdot \eta_{inv} \qquad (7)$$

Being L_n the different losses, η_{inv} the performance of the inverter, η_{STC} the performance of the system in STC (standard conditions of measurement), E_{AC} the energy generated in AC per day and E_{sun} the solar energy received. To obtain it, the Yield value is used [48]. The Yield or productivity is a magnitude, dependent of the radiation, that measures the energy that each kWp of the installation produces. It is obtained by dividing the energy produced per day by the peak power of the installation.

$$Yield = \frac{E_{day}}{P_{nom}} \tag{8}$$

$$PR\ (\%) = \frac{Yield}{G/1000} \cdot 100 \tag{9}$$

Therefore, once the peak power value is obtained using an estimated PR, the real PR is calculated from the power generation of the installation every hour. A Yield of 4.36 kWh / kWp is obtained, which yields a PR of 80.44%. This means that the estimation is valid. Therefore, the peak power of the photovoltaic installation will be 14 kW.

3.6 Power sharing hypotheses

In order to obtain the optimal method of distribution of the energy generated by the shared self-consumption facility, a Matlab program has been developed for the simulation of the different scenarios proposed here. In the simulation environment presented in this project, with the three users introduced in previous sections and the data obtained from the generation, consumption and price profiles explained in the document, the results obtained for each price and energy sharing hypothesis are evaluated in this section.

The program developed to simulate each scenario acts as follows. For each hour of the year, it compares the consumption of each user and the energy generated by the corresponding photovoltaic installation. If the user needs more energy, he obtains it from the network or from other users, if this is possible. If the user has spare power from the photovoltaic installation, he sells it to other users, if they need it or to the network otherwise. For each scenario, the total costs of each user, their consumption from the network or the photovoltaic installation and their discharges to the network are obtained.

Therefore, in each hour, the surplus of energy sold to the grid will be compensated at the daily market price in that hour. The sales between users will be made in such a way that if a user has already used his part of the generated photovoltaic energy and needs more, he will be able to use the surplus of another user, in exchange for a payment equivalent to 20% of the price he would get if he sold it to the network, that is, the daily market price at that hour.

To compare the different scenarios, three criteria will be used: the economic cost of the electricity bill, self-sufficiency and self-consumption. Self-consumption and self-sufficiency are energy parameters that represent the percentage of the energy generated by the photovoltaic installation that is consumed and the percentage of the demand that is satisfied with the energy generated by it, respectively. At the user level, in these parameters the available energy from the photovoltaic installation will depend on the hypothesis analysed and will be the part of the generated energy that corresponds to the user according to the method of distribution proposed. Therefore, the bigger they are, the more efficient use is being made of the installation. The economic cost of the electricity bill represents the total cost (with all the terms and taxes previously defined) for the users that the acquisition of the electricity they need to satisfy their demand supposes, that is, the cost of the part that has not been supplied by the photovoltaic installation. In each scenario, the percentage of savings in this cost will also be compared with the hypothesis in which the users do not have a shared photovoltaic installation.

Self-consumption is defined in this project as:

$$Self - consumption\ (\%) = \frac{Energy\ consumed\ from\ the\ PV\ installation}{Energy\ produced\ by\ the\ PV\ installation} \cdot 100 \tag{10}$$

And self-sufficiency:

$$Self - sufficiency\ (\%) = \frac{Energy\ consumed\ from\ the\ PV\ installation}{Consumed\ energy} \cdot 100 \tag{11}$$

The savings on the invoice is defined as:

$$\text{Economical savings in the electric bill (\%)} = \frac{Payment\ of\ the\ invoice\ without\ photovoltaic\ installation - Bill\ payment}{Payment\ of\ the\ invoice\ without\ photovoltaic\ installation} \cdot 100 \tag{12}$$

Where the bill payment will depend on the hypothesis proposed. This saving will be applied for each client and for the total system using the corresponding payments in each case.

The proposed hypotheses are presented below:

- ***Users without shared self-consumption facility***

In this case there is no photovoltaic installation, then all the consumption is done from the network. This scenario has been simulated three times: with the users covered by the 2.0A tariff, under the 2.0DHA and the 2.0DHS. This hypothesis is proposed to be used as a reference for the payment that users make for their electricity consumption per year.

- ***The energy obtained from the photovoltaic installation is distributed hourly according to the energy consumption the users in each hour***

Every hour, the energy generated by the shared photovoltaic installation is distributed according to the consumption that each user is doing at that time. Again, different tariff are tested. In addition, this case is simulated without exchanges between users and with exchanges between them. In the hours in which a user is consuming less energy than the one produced by the photovoltaic installation that corresponds to it, it is automatically sold to those users who are consuming more energy than the one they can obtain in the form of self-consumption. The price set will be 20% of the price at which the user could sell it to the network.

In each hour of the simulated year, the energy generated is distributed proportionally to the consumption of each user at that hour. Therefore, all the energy generated in each hour is distributed so that the users who consume the most will receive more and those who consume less in that hour, less. If the generated energy surpasses the one that is being consumed by the total number of users, the one that consumes the most will have greater surpluses to sell. However, these surpluses will be mainly sold to the grid, since by dividing the hourly energy according to the consumption at each hour, the consumption made of the energy that the shared photovoltaic installation generates is being maximized. This hypothesis is proposed in order to maximize the use of energy produced as self-consumption, minimizing the acquisition and selling needs from the network for users.

- ***The energy obtained from the photovoltaic installation is distributed according to a fixed percentage***

In this case, the economic contribution of the three users has been the same, so that in each hour a third of the produced energy corresponds to each of them. Again this allocation algorithm is simulated with and without sales between users and for different tariffs. The price set for these exchanges will be 20% of the price at which the user could sell it to the network.

In this case, the effect that the equitable distribution of the energy generated by the photovoltaic installation in each hour has on the energy and economic parameters analysed is proven. This hypothesis assumes that, regardless of their consumption, each user deserves to receive the same amount of energy available in each hour.

- ***The energy obtained from the photovoltaic installation is distributed according to the total annual consumption***

To distribute the energy produced every hour by the shared self-consumption facility, the energy consumed throughout the year is used. This value can be obtained through a prediction, if the current year is used, or through the average consumption value of recent years, for example. In this case, given that the annual consumption for the simulated year is known, the real value will be used. Again this allocation algorithm is simulated with and without sales between users and for different tariffs. The price set for these exchanges will be 20% of the price at which the user could sell it to the network.

Therefore, in each hour the available energy generated by the photovoltaic installation is distributed in proportion to the annual consumption of each user. In this hypothesis, it is intended that the users that will consume the most during the year will receive more energy to satisfy their demand. There is no incentive for the user to make more consumption throughout the year to obtain more energy, as this would increase their economic expenses, since their bill would be higher.

- ***The energy obtained from the photovoltaic installation is distributed according to the contracted power of the user***

To distribute the energy produced every hour by the installation of shared self-consumption, the contracted power of each user is used. Again this allocation algorithm is simulated with and without sales between users and for different tariffs. The price set for these exchanges will be 20% of the price at which the user could sell it to the network.

It is worth mentioning that according to RD 244/2019 this is the default allocation method. This case is similar to distributing the energy in proportion to the user's peak consumption. It is intended here to simulate, therefore, the default case defined by the legislation.

4 Results and discussion

In this section the results of each simulated hypothesis are presented. For the different hypotheses proposed, the different energy and economic criteria set will be evaluated (invoice costs, self-sufficiency and self-consumption), to then compare the different alternatives.

4.1 Users without shared self-consumption facility

It is evident that in this case, since users do not have photovoltaic installations, all the energy consumed is obtained from the grid and this means that it will be the scenario where the highest amounts of money are paid for energy consumption. This scenario serves as a reference of economic costs with respect to the others. The most profitable option from the economic point of view in this case is the one in which users have the tariff 2.0DHA.

TABLE 3 – RESULTS OBTAINED FOR USERS WITHOUT PV GENERATION AND TARIFF 2.0A

	Annual cost of the electricity bill (€)	Consumed PV generated energy (kWh)	Energy bought from the network (kWh)	Energy poured to the network (kWh)	Self-consumption (%)	Self-sufficiency (%)
User 1	1,001.72	0.00	5,475.00	0.00	-	-
User 2	1,336.48	0.00	7,300.00	0.00	-	-
User 3	1,590.17	0.00	8,760.00	0.00	-	-
Total	3,928.37	0.00	21,535.00	0.00	-	-

TABLE 4 – RESULTS OBTAINED FOR USERS WITHOUT PV GENERATION AND TARIFF 2.0DHA

	Annual cost of the electricity bill (€)	Consumed PV generated energy (kWh)	Energy bought from the network (kWh)	Energy poured to the network (kWh)	Self-consumption (%)	Self-sufficiency (%)
User 1	863.50	0.00	5,475.00	0.00	-	-
User 2	1,193.89	0.00	7,300.00	0.00	-	-
User 3	1,379.28	0.00	8,760.00	0.00	-	-
Total	3,436.67	0.00	21,535.00	0.00	-	-

TABLE 5 – RESULTS OBTAINED FOR USERS WITHOUT PV GENERATION AND TARIFF 2.0DHS

	Annual cost of the electricity bill (€)	Consumed PV generated energy (kWh)	Energy bought from the network (kWh)	Energy poured to the network (kWh)	Self-consumption (%)	Self-sufficiency (%)
User 1	877.00	0.00	5,475.00	0.00	-	-
User 2	1,221.82	0.00	7,300.00	0.00	-	-
User 3	1,380.02	0.00	8,760.00	0.00	-	-
Total	3,478.84	0.00	21,535.00	0.00	-	-

4.2 The energy obtained from the photovoltaic installation is distributed hourly according to the energy consumption the users in each hour

This hypothesis supposes the maximum use of the energy generated by the photovoltaic installation and therefore no exchanges of energy between users are required. It is, therefore, the hypothesis in which less energy is sold to the network and less is purchased. However, when in the other hypotheses the sale of energy between users is allowed, again the energy generated is always used in the form of consumption if there is demand to be satisfied, so that in these cases the kWh levels sold and purchased from the grid are the same.

In this case it is verified that the introduction of the possibility of selling energy between users has no repercussion in the system, since there are no hours in which a client prefers to sell it to consume it, since the energy generated is distributed according to of consumption in that hour. On the other hand, and as it will happen in all scenarios, the type of tariff that customers receive only affects the price they pay for electricity, not affecting the distribution of the energy generated by the photovoltaic installation or the energy they consume from the net. It is observed that when the three clients have the tariff with time discrimination in two periods, they pay less than in the other cases. The total self-sufficiency of the system is approximately 37%, with self-consumption levels of 36%.

TABLE 6 – RESULTS OBTAINED FOR THE DISTRIBUTION OF THE GENERATED ENERGY ACCORDING TO CONSUMPTION WITHOUT P2P TRADE AND TARIFF 2.0A

	Annual cost of the electricity bill (€)	Consumed PV generated energy (kWh)	Energy bought from the network (kWh)	Energy poured to the network (kWh)	Self-consumption (%)	Self-sufficiency (%)	Economical savings in the electric bill (%)
User 1	606.03	1,350.67	4,124.33	2,292.08	37.08	24.67	39.50
User 2	495.67	2,838.81	4,461.19	5,784.37	32.92	38.89	62.91
User 3	538.07	3,809.59	4,950.41	6,193.83	38.08	43.49	66.16
Total	1,639.77	7,999.07	13,535.93	14,270.29	35.92	37.14	58.26

Table 7 – Results obtained for the distribution of the generated energy according to consumption with P2P trade and tariff 2.0A

	Annual cost of the electricity bill (€)	Consumed PV generated energy (kWh)	Energy bought from the network (kWh)	Energy poured to the network (kWh)	Self-consumption (%)	Self-sufficiency (%)	Economical savings in the electric bill (%)
User 1	606.03	1,350.67	4,124.33	2,292.08	37.08	24.67	39.50
User 2	495.67	2,838.81	4,461.19	5,784.37	32.92	38.89	62.91
User 3	538.07	3,809.59	4,950.41	6,193.83	38.08	43.49	66.16
Total	1,639.77	7,999.07	13,535.93	14,270.29	35.92	37.14	58.26

Table 8 – Results obtained for the distribution of the generated energy according to consumption without P2P trade and tariff 2.0DHA

	Annual cost of the electricity bill (€)	Consumed PV generated energy (kWh)	Energy bought from the network (kWh)	Energy poured to the network (kWh)	Self-consumption (%)	Self-sufficiency (%)	Economical savings in the electric bill (%)
User 1	498.29	1,350.67	4,124.33	2,292.08	37.08	24.67	42.29
User 2	427.53	2,838.81	4,461.19	5,784.37	32.92	38.89	64.19
User 3	405.76	3,809.59	4,950.41	6,193.83	38.08	43.49	70.58
Total	1,331.58	7,999.07	13,535.93	14,270.29	35.92	37.14	61.25

Table 9 – Results obtained for the distribution of the generated energy according to consumption with P2P trade and tariff 2.0DHA

	Annual cost of the electricity bill (€)	Consumed PV generated energy (kWh)	Energy bought from the network (kWh)	Energy poured to the network (kWh)	Self-consumption (%)	Self-sufficiency (%)	Economical savings in the electric bill (%)
User 1	498.29	1,350.67	4,124.33	2,292.08	37.08	24.67	42.29
User 2	427.53	2,838.81	4,461.19	5,784.37	32.92	38.89	64.19
User 3	405.76	3,809.59	4,950.41	6,193.83	38.08	43.49	70.58
Total	1,331.58	7,999.07	13,535.93	14,270.29	35.92	37.14	61.25

TABLE 10 – RESULTS OBTAINED FOR THE DISTRIBUTION OF THE GENERATED ENERGY ACCORDING TO CONSUMPTION WITHOUT P2P TRADE AND TARIFF 2.0DHS

	Annual cost of the electricity bill (€)	Consumed PV generated energy (kWh)	Energy bought from the network (kWh)	Energy poured to the network (kWh)	Self-consumption (%)	Self-sufficiency (%)	Economical savings in the electric bill (%)
User 1	512.09	1,350.67	4,124.33	2,292.08	37.08	24.67	41.61
User 2	456.74	2,838.81	4,461.19	5,784.37	32.92	38.89	62.62
User 3	412.03	3,809.59	4,950.41	6,193.83	38.08	43.49	70.14
Total	1,380.87	7,999.07	13,535.93	14,270.29	35.92	37.14	60.31

TABLE 11 – RESULTS OBTAINED FOR THE DISTRIBUTION OF THE GENERATED ENERGY ACCORDING TO CONSUMPTION WITH P2P TRADE AND TARIFF 2.0DHS

	Annual cost of the electricity bill (€)	Consumed PV generated energy (kWh)	Energy bought from the network (kWh)	Energy poured to the network (kWh)	Self-consumption (%)	Self-sufficiency (%)	Economical savings in the electric bill (%)
User 1	512.09	1,350.67	4,124.33	2,292.08	37.08	24.67	41.61
User 2	456.74	2,838.81	4,461.19	5,784.37	32.92	38.89	62.62
User 3	412.03	3,809.59	4,950.41	6,193.83	38.08	43.49	70.14
Total	1,380.87	7,999.07	13,535.93	14,270.29	35.92	37.14	60.31

In the absence of the possibility of exchanges of energy between users, this would be the hypothesis that would minimize the cost, although it could generate incentives for users to consume more in the hours of higher photovoltaic production, in order to sell the greater proportion of surplus energy they would receive, to the network, to obtain profit. Therefore, there is the possibility of introducing a variant to this hypothesis, in such a way that the energy generated every hour is distributed according to the hourly consumption of each user, and, if there is surplus energy, it is distributed in equal parts. The data obtained in the most efficient case if this is applied turned out to be more expensive, although this may be due to the fact that the clients do not act perversely seeking to profit, since the hourly consumption is defined in advance in the model. In a real system, it could be an efficient alternative to avoid this event.

TABLE 12 – RESULTS OBTAINED FOR THE DISTRIBUTION OF THE GENERATED ENERGY ACCORDING TO CONSUMPTION AND THE SURPLUS ENERGY IN EQUAL PARTS WITH P2P TRADE AND TARIFF 2.0DHS

	Annual cost of the electricity bill (€)	Consumed PV generated energy (kWh)	Energy bought from the network (kWh)	Energy poured to the network (kWh)	Self-consumption (%)	Self-sufficiency (%)	Economical savings in the electric bill (%)
User 1	352.52	1,351.60	4,123.40	4,756.76	22.13	24.69	59.18
User 2	499.08	2,665.85	4,634.15	4,756.77	35.93	36.52	58.20
User 3	545.02	3,492.36	5,267.64	4,756.88	42.32	39.87	60.49
Total	1,396.63	7,509.81	14,025.19	14,270.42	34.48	34.87	59.36

4.3 The energy obtained from the photovoltaic installation is distributed according to a fixed percentage

Because in this case the energy is distributed in equal parts, users who consume less save more than those who consume more, who will pay more in their electricity bill in this scenario with respect to the others. This way of sharing tries to recreate the case in which all the users have contributed economically the same for the installation of the photovoltaic modules and wish to have the same amount of generated energy available. When energy exchanges between users are not allowed, this hypothesis is the one in which there are more exchanges of energy with the network, because the generated energy is used less to satisfy the consumption needs of the users, with an inefficient distribution from the energy point of view. Therefore, in these cases, this hypothesis has the lowest values of self-consumption and self-sufficiency.

In this scenario, due to the distribution algorithm, there are hours with energy sales between users. The existence of this possibility causes the total cost of energy acquisition to decrease, since the user who buys this energy does so at a lower price than if he had to buy it from the network, and the user who sells it is receiving a lower price than what it would earn if he sold it to the network, but it continues to earn money and the benefits of the former outweigh this “loss”. Again, the tariff with best prices for the users is the 2.0DHA. As expected, in the cases in which there are energy sales between users, the energy consumption of the network is reduced, the consumption from the PV installation increases and self-consumption and self-sufficiency increase for all customers and the system in general. For the user with lower consumption, having to buy more energy from their neighbours, the existence of sales between users is an additional expense that makes his bill increase, although the group of neighbours together pay less, as it has to sell to the network a lower amount of energy produced in the photovoltaic modules.

TABLE 13 – RESULTS OBTAINED FOR THE DISTRIBUTION OF THE GENERATED ENERGY IN EQUAL PARTS WITHOUT P2P TRADE AND TARIFF 2.0A

	Annual cost of the electricity bill (€)	Consumed PV generated energy (kWh)	Energy bought from the network (kWh)	Energy poured to the network (kWh)	Self-consumption (%)	Self-sufficiency (%)	Economical savings in the electric bill (%)
User 1	366.76	1,438.48	4,036.52	5,984.64	19.38	26.27	63.39
User 2	560.56	2,797.03	4,502.97	4,626.09	37.68	38.32	58.06
User 3	733.74	3,570.19	5,189.81	3,852.93	48.10	40.76	53.86
Total	1,661.05	7,805.70	13,729.30	14,463.66	35.05	36.25	57.72

TABLE 14 – RESULTS OBTAINED FOR THE DISTRIBUTION OF THE GENERATED ENERGY IN EQUAL PARTS WITH P2P TRADE AND TARIFF 2.0A

	Annual cost of the electricity bill (€)	Consumed PV generated energy (kWh)	Energy bought from the network (kWh)	Energy poured to the network (kWh)	Self-consumption (%)	Self-sufficiency (%)	Economical savings in the electric bill (%)
User 1	373.91	1,439.17	4,035.83	5,833.54	19.39	26.29	62.67
User 2	551.67	2,849.29	4,450.71	4,599.10	38.38	39.03	58.72
User 3	706.41	3,710.62	5,049.38	3,837.65	49.99	42.36	55.58
Total	1,631.99	7,999.07	13,535.93	14,270.29	35.92	37.14	58.46

TABLE 15 – RESULTS OBTAINED FOR THE DISTRIBUTION OF THE GENERATED ENERGY IN EQUAL PARTS WITHOUT P2P TRADE AND TARIFF 2.0DHA

	Annual cost of the electricity bill (€)	Consumed PV generated energy (kWh)	Energy bought from the network (kWh)	Energy poured to the network (kWh)	Self-consumption (%)	Self-sufficiency (%)	Economical savings in the electric bill (%)
User 1	265.24	1,438.48	4,036.52	5,984.64	19.38	26.27	69.28
User 2	486.81	2,797.03	4,502.97	4,626.09	37.68	38.32	59.22
User 3	600.03	3,570.19	5,189.81	3,852.93	48.10	40.76	56.50
Total	1,352.08	7,805.70	13,729.30	14,463.66	35.05	36.25	60.66

TABLE 16 – RESULTS OBTAINED FOR THE DISTRIBUTION OF THE GENERATED ENERGY IN EQUAL PARTS WITH P2P TRADE AND TARIFF 2.0DHA

	Annual cost of the electricity bill (€)	Consumed PV generated energy (kWh)	Energy bought from the network (kWh)	Energy poured to the network (kWh)	Self-consumption (%)	Self-sufficiency (%)	Economical savings in the electric bill (%)
User 1	272.15	1,439.17	4,035.83	5,833.54	19.39	26.29	68.48
User 2	480.12	2,849.29	4,450.71	4,599.10	38.38	39.03	59.79
User 3	573.99	3,710.62	5,049.38	3,837.65	49.99	42.36	58.38
Total	1,326.27	7,999.07	13,535.93	14,270.29	35.92	37.14	61.41

TABLE 17 – RESULTS OBTAINED FOR THE DISTRIBUTION OF THE GENERATED ENERGY IN EQUAL PARTS WITHOUT P2P TRADE AND TARIFF 2.0DHS

	Annual cost of the electricity bill (€)	Consumed PV generated energy (kWh)	Energy bought from the network (kWh)	Energy poured to the network (kWh)	Self-consumption (%)	Self-sufficiency (%)	Economical savings in the electric bill (%)
User 1	279.13	1,438.48	4,036.52	5,984.64	19.38	26.27	68.17
User 2	516.35	2,797.03	4,502.97	4,626.09	37.68	38.32	57.74
User 3	605.63	3,570.19	5,189.81	3,852.93	48.10	40.76	56.11
Total	1,401.12	7,805.70	13,729.30	14,463.66	35.05	36.25	59.72

TABLE 18 – RESULTS OBTAINED FOR THE DISTRIBUTION OF THE GENERATED ENERGY IN EQUAL PARTS WITH P2P TRADE AND TARIFF 2.0DHS

	Annual cost of the electricity bill (€)	Consumed PV generated energy (kWh)	Energy bought from the network (kWh)	Energy poured to the network (kWh)	Self-consumption (%)	Self-sufficiency (%)	Economical savings in the electric bill (%)
User 1	286.05	1,439.17	4,035.83	5,833.54	19.39	26.29	67.38
User 2	509.52	2,849.29	4,450.71	4,599.10	38.38	39.03	58.30
User 3	580.04	3,710.62	5,049.38	3,837.65	49.99	42.36	57.97
Total	1,375.61	7,999.07	13,535.93	14,270.29	35.92	37.14	60.46

4.4 The energy obtained from the photovoltaic installation is distributed according to the total annual consumption

In this case, unlike the previous one, the user who consumes the most will save the most. This does not suppose an incentive to increase the consumption and to obtain profits selling the extra surplus energy that would correspond to him, since although it saves more money it will continue increasing his absolute invoice, incurring in more cost. In this case it is verified that, as in previous cases, the existence of energy sales between users decreases energy costs, increases self-sufficiency and self-consumption and reduces energy consumption from the grid. Again, the cheapest tariff is the 2.0DHA.

TABLE 19 – RESULTS OBTAINED FOR THE DISTRIBUTION OF THE ENERGY GENERATED BASED ON ANNUAL CONSUMPTION WITHOUT P2P TRADE AND TARIFF 2.0A

	Annual cost of the electricity bill (€)	Consumed PV generated energy (kWh)	Energy bought from the network (kWh)	Energy poured to the network (kWh)	Self-consumption (%)	Self-sufficiency (%)	Economical savings in the electric bill (%)
User 1	478.87	1,392.49	4,082.51	4,269.21	24.59	25.43	52.20
User 2	552.02	2,804.50	4,495.50	4,744.43	37.15	38.42	58.70
User 3	618.25	3,703.96	5,056.04	5,354.76	40.89	42.28	61.12
Total	1,649.15	7,900.95	13,634.05	14,368.41	35.48	36.69	58.02

TABLE 20 – RESULTS OBTAINED FOR THE DISTRIBUTION OF THE ENERGY GENERATED BASED ON ANNUAL CONSUMPTION WITH P2P TRADE AND TARIFF 2.0A

	Annual cost of the electricity bill (€)	Consumed PV generated energy (kWh)	Energy bought from the network (kWh)	Energy poured to the network (kWh)	Self-consumption (%)	Self-sufficiency (%)	Economical savings in the electric bill (%)
User 1	481.15	1,395.18	4,079.82	4,212.37	24.64	25.48	51.97
User 2	543.97	2,848.23	4,451.77	4,730.36	37.73	39.02	59.30
User 3	608.40	3,755.66	5,004.34	5,327.56	41.46	42.87	61.74
Total	1,633.52	7,999.07	13,535.93	14,270.29	35.92	37.14	58.42

TABLE 21 – RESULTS OBTAINED FOR THE DISTRIBUTION OF THE ENERGY GENERATED BASED ON ANNUAL CONSUMPTION WITHOUT P2P TRADE AND TARIFF 2.0DHA

	Annual cost of the electricity bill (€)	Consumed PV generated energy (kWh)	Energy bought from the network (kWh)	Energy poured to the network (kWh)	Self-consumption (%)	Self-sufficiency (%)	Economical savings in the electric bill (%)
User 1	371.12	1,392.49	4,082.51	4,269.21	24.59	25.43	57.02
User 2	479.37	2,804.50	4,495.50	4,744.43	37.15	38.42	59.85
User 3	486.43	3,703.96	5,056.04	5,354.76	40.89	42.28	64.73
Total	1,336.92	7,900.95	13,634.05	14,368.41	35.48	36.69	61.10

TABLE 22 – RESULTS OBTAINED FOR THE DISTRIBUTION OF THE ENERGY GENERATED BASED ON ANNUAL CONSUMPTION WITH P2P TRADE AND TARIFF 2.0DHA

	Annual cost of the electricity bill (€)	Consumed PV generated energy (kWh)	Energy bought from the network (kWh)	Energy poured to the network (kWh)	Self-consumption (%)	Self-sufficiency (%)	Economical savings in the electric bill (%)
User 1	373,54	1,395,18	4,079,82	4,212,37	24.64	25.48	56.74
User 2	473,28	2,848,23	4,451,77	4,730,36	37.73	39.02	60.36
User 3	477,07	3,755,66	5,004,34	5,327,56	41.46	42.87	65.41
Total	1,323,89	7,999,07	13,535,93	14,270,29	35.92	37.14	61.48

TABLE 23 – RESULTS OBTAINED FOR THE DISTRIBUTION OF THE ENERGY GENERATED BASED ON ANNUAL CONSUMPTION WITHOUT P2P TRADE AND TARIFF 2.0DHS

	Annual cost of the electricity bill (€)	Consumed PV generated energy (kWh)	Energy bought from the network (kWh)	Energy poured to the network (kWh)	Self-consumption (%)	Self-sufficiency (%)	Economical savings in the electric bill (%)
User 1	385.00	1,392.49	4,082.51	4,269.21	24.59	25.43	56.10
User 2	508.91	2,804.50	4,495.50	4,744.43	37.15	38.42	58.35
User 3	492.16	3,703.96	5,056.04	5,354.76	40.89	42.28	64.34
Total	1,386.07	7,900.95	13,634.05	14,368.41	35.48	36.69	60.16

TABLE 24 – RESULTS OBTAINED FOR THE DISTRIBUTION OF THE ENERGY GENERATED BASED ON ANNUAL CONSUMPTION WITH P2P TRADE AND TARIFF 2.0DHS

	Annual cost of the electricity bill (€)	Consumed PV generated energy (kWh)	Energy bought from the network (kWh)	Energy poured to the network (kWh)	Self-consumption (%)	Self-sufficiency (%)	Economical savings in the electric bill (%)
User 1	387.42	1,395.18	4,079.82	4,212.37	24.64	25.48	55.82
User 2	502.69	2,848.23	4,451.77	4,730.36	37.73	39.02	58.86
User 3	483.07	3,755.66	5,004.34	5,327.56	41.46	42.87	65.00
Total	1,373.17	7,999.07	13,535.93	14,270.29	35.92	37.14	60.53

4.5 The energy obtained from the photovoltaic installation is distributed according to the contracted power of the user

In this case, the energy generated by the photovoltaic installation is distributed according to the contracted power, which depends for each user on the peak of consumption throughout the year. As in the previous case, the higher the user's consumption, the greater the savings, since typically the power contracted will be higher in those users with higher consumption throughout the year.

The results in this scenario are similar to the previous ones. The option with lower economic costs, greater self-consumption and better self-sufficiency is given for the case with tariffs 2.0DHA and sale of energy between users.

TABLE 25 – RESULTS OBTAINED FOR THE DISTRIBUTION OF THE ENERGY GENERATED AS A FUNCTION OF THE CONTRACTED POWER WITHOUT P2P TRADE AND TARIFF 2.0A

	Annual cost of the electricity bill (€)	Consumed PV generated energy (kWh)	Energy bought from the network (kWh)	Energy poured to the network (kWh)	Self-consumption (%)	Self-sufficiency (%)	Economical savings in the electric bill (%)
User 1	480.81	1,391.52	4,083.48	4,239.82	24.71	25.42	52.00
User 2	543.19	2,812.02	4,487.98	4,867.07	36.62	38.52	59.36
User 3	625.18	3,697.18	5,062.82	5,261.75	41.27	42.21	60.68
Total	1,649.18	7,900.72	13,634.28	14,368.64	35.48	36.69	58.02

TABLE 26 – RESULTS OBTAINED FOR THE DISTRIBUTION OF THE ENERGY GENERATED AS A FUNCTION OF THE CONTRACTED POWER WITH P2P TRADE AND TARIFF 2.0A

	Annual cost of the electricity bill (€)	Consumed PV generated energy (kWh)	Energy bought from the network (kWh)	Energy poured to the network (kWh)	Self-consumption (%)	Self-sufficiency (%)	Economical savings in the electric bill (%)
User 1	483.06	1,394.22	4,080.78	4,183.52	24.76	25.47	51.78
User 2	535.83	2,853.08	4,446.92	4,850.79	37.15	39.08	59.91
User 3	614.57	3,751.77	5,008.23	5,235.98	41.88	42.83	61.35
Total	1,633.46	7,999.07	13,535.93	14,270.29	35.92	37.14	58.42

TABLE 27 – RESULTS OBTAINED FOR THE DISTRIBUTION OF THE ENERGY GENERATED AS A FUNCTION OF THE CONTRACTED POWER WITHOUT P2P TRADE AND TARIFF 2.0DHA

	Annual cost of the electricity bill (€)	Consumed PV generated energy (kWh)	Energy bought from the network (kWh)	Energy poured to the network (kWh)	Self-consumption (%)	Self-sufficiency (%)	Economical savings in the electric bill (%)
User 1	373.04	1,391.52	4,083.48	4,239.82	24.71	25.42	56.80
User 2	471.68	2,812.02	4,487.98	4,867.07	36.62	38.52	60.49
User 3	493.25	3,697.18	5,062.82	5,261.75	41.27	42.21	64.24
Total	1,337.96	7,900.72	13,634.28	14,368.64	35.48	36.69	61.07

TABLE 28 – RESULTS OBTAINED FOR THE DISTRIBUTION OF THE ENERGY GENERATED AS A FUNCTION OF THE CONTRACTED POWER WITH P2P TRADE AND TARIFF 2.0DHA

	Annual cost of the electricity bill (€)	Consumed PV generated energy (kWh)	Energy bought from the network (kWh)	Energy poured to the network (kWh)	Self-consumption (%)	Self-sufficiency (%)	Economical savings in the electric bill (%)
User 1	375.44	1,394.22	4,080.78	4,183.52	24.76	25.47	56.52
User 2	466.15	2,853.08	4,446.92	4,850.79	37.15	39.08	60.96
User 3	483.15	3,751.77	5,008.23	5,235.98	41.88	42.83	64.97
Total	1,324.74	7,999.07	13,535.93	14,270.29	35.92	37.14	61.45

TABLE 29 – RESULTS OBTAINED FOR THE DISTRIBUTION OF THE ENERGY GENERATED AS A FUNCTION OF THE CONTRACTED POWER WITHOUT P2P TRADE AND TARIFF 2.0DHS

	Annual cost of the electricity bill (€)	Consumed PV generated energy (kWh)	Energy bought from the network (kWh)	Energy poured to the network (kWh)	Self-consumption (%)	Self-sufficiency (%)	Economical savings in the electric bill (%)
User 1	386.92	1,391.52	4,083.48	4,239.82	24.71	25.42	55.88
User 2	501.21	2,812.02	4,487.98	4,867.07	36.62	38.52	58.98
User 3	498.97	3,697.18	5,062.82	5,261.75	41.27	42.21	63.84
Total	1,387.10	7,900.72	13,634.28	14,368.64	35.48	36.69	60.13

TABLE 30 – RESULTS OBTAINED FOR THE DISTRIBUTION OF THE ENERGY GENERATED AS A FUNCTION OF THE CONTRACTED POWER WITH P2P TRADE AND TARIFF 2.0DHS

	Annual cost of the electricity bill (€)	Consumed PV generated energy (kWh)	Energy bought from the network (kWh)	Energy poured to the network (kWh)	Self-consumption (%)	Self-sufficiency (%)	Economical savings in the electric bill (%)
User 1	389.31	1,394.22	4,080.78	4,183.52	24.76	25.47	55.61
User 2	495.56	2,853.08	4,446.92	4,850.79	37.15	39.08	59.44
User 3	489.15	3,751.77	5,008.23	5,235.98	41.88	42.83	64.55
Total	1,374.02	7,999.07	13,535.93	14,270.29	35.92	37.14	60.50

4.6 Comparison of hypotheses

Therefore, the most efficient cases of each scenario are compared in the following tables to determine the best distribution algorithm based on the aforementioned criteria. For each user, and then for the system as a whole, the results of the best scenario of each hypothesis are shown, with 2.0DHA tariffs and energy sales among users.

TABLE 31 – RESULTS OBTAINED FOR THE DIFFERENT HYPOTHESIS FOR USER 1 WITH ENERGY EXCHANGE BETWEEN USERS AND TARIFF 2.0DHA

User 1	Users without PV	Distribution of the generated energy according to hourly consumption	Distribution of the generated energy in equal parts	Distribution of the energy generated based on annual consumption	Distribution of the energy generated as a function of the contracted power
Annual cost of the electricity bill (€)	1,001.72	498.29	272.15	373.54	375.44
Self-consumption (%)	-	37.08	19.39	24.64	24.76
Self-sufficiency (%)	-	24.67	26.29	25.48	25.47
Economical savings in the electric bill (%)	-	42.29	68.48	56.74	56.52

It can be verified that in the case of user 1 the best case of self-consumption occurs when the energy is divided equally. This hypothesis supposes a lower economic cost for this user, since his annual and average daily consumption are lower than that of the other users, so he receives a higher percentage of energy in proportion to his consumption, with respect to the rest of users. Therefore, it also means greater savings. Regarding self-sufficiency, the values are very similar in all cases, but in the distribution hypothesis according to hourly consumption, the self-consumption parameter is much greater than in the rest of the hypotheses. This is a consequence of the fact that the higher the consumption in each hour, the greater percentage of the generation of the photovoltaic installation corresponds to the user.

TABLE 32 – RESULTS OBTAINED FOR THE DIFFERENT HYPOTHESIS FOR USER 2 WITH ENERGY EXCHANGE BETWEEN USERS AND TARIFF 2.0DHA

User 2	Users without PV	Distribution of the generated energy according to hourly consumption	Distribution of the generated energy in equal parts	Distribution of the energy generated based on annual consumption	Distribution of the energy generated as a function of the contracted power
Annual cost of the electricity bill (€)	1,336.48	427.53	480.12	473.28	466.15
Self-consumption (%)	-	32.92	38.38	37.73	37.15
Self-sufficiency (%)	-	38.89	39.03	39.02	39.08
Economical savings in the electric bill (%)	-	64.19	59.79	60.36	60.96

This user consumes more energy generated by the photovoltaic installation than the previous user, since their consumption is concentrated in sunny hours and is greater. Therefore, their values of self-consumption and self-sufficiency are on average higher than the case of user 1. It is observed that the values of self-sufficiency are very similar in each hypothesis while the best self-consumption value is given by distributing the energy generated by the photovoltaic installation in equal parts. The most economical option for this user is the distribution of the energy generated based on consumption. The savings of this consumer are greater than that of user 1, among other things, because his consumption is higher.

TABLE 33 – RESULTS OBTAINED FOR THE DIFFERENT HYPOTHESIS FOR USER 3 WITH ENERGY EXCHANGE BETWEEN USERS AND TARIFF 2.0DHA

User 3	Users without PV	Distribution of the generated energy according to hourly consumption	Distribution of the generated energy in equal parts	Distribution of the energy generated based on annual consumption	Distribution of the energy generated as a function of the contracted power
Annual cost of the electricity bill (€)	1,590.17	405.76	573.99	477.07	483.15
Self-consumption (%)	-	38.08	49.99	41.46	41.88
Self-sufficiency (%)	-	43.49	42.36	42.87	42.83
Economical savings in the electric bill (%)	-	70.58	58.38	65.41	64.97

User 3, with higher consumption, has self-sufficiency and self-consumption values greater than those of user 2. This is a consequence of user 3 having higher annual and instantaneous (average) consumptions and contracted power. Therefore, the hypothesis of distributing photovoltaic generation in equal parts economically supposes the worst scenario. Economically, the most beneficial option is the distribution of the energy generated by the photovoltaic installation each hour based on hourly consumption, where his savings are maximum. By having the highest consumption of the three, this user is the one who saves the most with the installation of the photovoltaic modules.

Below is the table with the values obtained for the different hypotheses, with tariffs 2.0DHA and without energy exchanges between users.

TABLE 34 – RESULTS OBTAINED FOR THE DIFFERENT HYPOTHESIS FOR THE TOTAL SYSTEM WITH NO ENERGY EXCHANGE BETWEEN AND TARIFF 2.0DHA

Total	Users without PV	Distribution of the generated energy according to hourly consumption	Distribution of the generated energy in equal parts	Distribution of the energy generated based on annual consumption	Distribution of the energy generated as a function of the contracted power
Annual cost of the electricity bill (€)	3,436.67	1.331,58	1,352.08	1,336.92	1,337.96
Self-consumption (%)	-	35.91	35.05	35.47	35.48
Self-sufficiency (%)	-	37.14	36.24	36.68	36.69
Economical savings in the electric bill (%)	-	61.25	60.66	61.10	61.07

It is observed that the most economical option is to distribute the energy generated according to hourly consumption, in each hour. This means minimizing exchanges with the network and maximizing the use of the energy generated, resulting in lower costs for the electricity bill for users and greater savings. In addition, it also means greater self-consumption and self-sufficiency than other hypotheses.

Next, the same table but allowing the energy exchange between users, is presented:

TABLE 35 – RESULTS OBTAINED FOR THE DIFFERENT HYPOTHESIS FOR THE TOTAL SYSTEM WITH ENERGY EXCHANGE BETWEEN USERS AND TARIFF 2.0DHA

Total	Users without PV	Distribution of the generated energy according to hourly consumption	Distribution of the generated energy in equal parts	Distribution of the energy generated based on annual consumption	Distribution of the energy generated as a function of the contracted power
Annual cost of the electricity bill (€)	3,436.67	1,331.58	1,326.27	1,323.89	1,324.74
Self-consumption (%)	-	35.92	35.92	35.92	35.92
Self-sufficiency (%)	-	37.14	37.14	37.14	37.14
Economical savings in the electric bill (%)	-	61.25	61.41	61.48	61.45

When comparing the different alternatives for the total of users, it can be verified that the values of the different energy parameters are the same in all the hypotheses with photovoltaic production, since the generated energy available and the total consumption do not vary, taking into account that it is allowed the exchange of energy between users. However, for each client these values are different according to the hypothesis. Economically speaking, there is no great difference between the different hypotheses, being slightly better to distribute the energy based on the total annual consumption. Although in two users the best option is to distribute it based on hourly consumption, the expenses incurred by the user of lower consumption in this scenario makes this option globally not the most attractive.

Except in the case of distribution of the hourly energy generated based on hourly consumption, in which the exchange of energy between users does not take place since no client will have surpluses if another has not yet satisfied its demand, including the possibility of the energy exchange between customers makes the savings of users in the electricity bill increase and the total cost of this decrease, increasing self-sufficiency and self-consumption.

4.7 Sensitivity studies

In order to deepen this analysis, different sensitivity studies are carried out:

- ***Variation of the total results of the system when varying the peak power of the photovoltaic installation***

This section presents the results obtained by varying the peak power of the photovoltaic installation, for the different hypotheses, with 2.0 DHA tariffs and energy exchanges between users. Again, although distributed differently among the users in each hypothesis, the energy purchased from the network is constant, so that the total consumption of the energy generated by the photovoltaic installation is also constant. Being the total annual consumption of the users a fixed value, the values of self-sufficiency and self-consumption in all the hypotheses with sale of energy between users are identical.

In the following tables, it can be seen how the variation of the peak power of the installation affects the economic cost values of the simulated system. For all peak powers, the most efficient option in each scenario is one in which the tariff adopted is 2.0DHA and there is sale of energy from the photovoltaic installation between users.

TABLE 36 – RESULTS OBTAINED FOR THE DIFFERENT HYPOTHESIS FOR THE TOTAL SYSTEM WHEN THE PEAK POWER OF THE PV INSTALLATION IS 5 KW WITH ENERGY EXCHANGE BETWEEN USERS AND TARIFF 2.0DHA

Total	Users without PV	Distribution of the generated energy according to hourly consumption	Distribution of the generated energy in equal parts	Distribution of the energy generated based on annual consumption	Distribution of the energy generated as a function of the contracted power
Annual cost of the electricity bill (€)	3,436.67	2,388.28	2,366.94	2,369.81	2,369.79
Self-consumption (%)	-	79.09	79.09	79.09	79.09
Self-sufficiency (%)	-	29.21	29.21	29.21	29.21
Economical savings in the electric bill (%)	-	30.51	31.13	31.04	31.04

TABLE 37 – RESULTS OBTAINED FOR THE DIFFERENT HYPOTHESIS FOR THE TOTAL SYSTEM WHEN THE PEAK POWER OF THE PV INSTALLATION IS 14 KW WITH ENERGY EXCHANGE BETWEEN USERS AND TARIFF 2.0DHA

Total	Users without PV	Distribution of the generated energy according to hourly consumption	Distribution of the generated energy in equal parts	Distribution of the energy generated based on annual consumption	Distribution of the energy generated as a function of the contracted power
Annual cost of the electricity bill (€)	3,436.67	1,331.58	1,326.27	1,323.89	1,324.74
Self-consumption (%)	-	35.92	35.92	35.92	35.92
Self-sufficiency (%)	-	37.14	37.14	37.14	37.14
Economical savings in the electric bill (%)	-	61.25	61.41	61.48	61.45

TABLE 38 – RESULTS OBTAINED FOR THE DIFFERENT HYPOTHESIS FOR THE TOTAL SYSTEM WHEN THE PEAK POWER OF THE PV INSTALLATION IS 28 KW WITH ENERGY EXCHANGE BETWEEN USERS AND TARIFF 2.0DHA

Total	Users without PV	Distribution of the generated energy according to hourly consumption	Distribution of the generated energy in equal parts	Distribution of the energy generated based on annual consumption	Distribution of the energy generated as a function of the contracted power
Annual cost of the electricity bill (€)	3,436.67	535.04	471.87	465.29	464.51
Self-consumption (%)	-	19.47	19.47	19.47	19.47
Self-sufficiency (%)	-	40.27	40.27	40.27	40.27
Economical savings in the electric bill (%)	-	84.43	86.27	86.46	86.48

TABLE 39 – RESULTS OBTAINED FOR THE DIFFERENT HYPOTHESIS FOR THE TOTAL SYSTEM WHEN THE PEAK POWER OF THE PV INSTALLATION IS 42 KW WITH ENERGY EXCHANGE BETWEEN USERS AND TARIFF 2.0DHA

Total	Users without PV	Distribution of the generated energy according to hourly consumption	Distribution of the generated energy in equal parts	Distribution of the energy generated based on annual consumption	Distribution of the energy generated as a function of the contracted power
Annual cost of the electricity bill (€)	3,436.67	216.91	173.76	164.68	161.87
Self-consumption (%)	-	13.37	13.37	13.37	13.37
Self-sufficiency (%)	-	41.47	41.47	41.47	41.47
Economical savings in the electric bill (%)	-	93.69	94.94	95.21	95.29

Obviously, prices are reduced by increasing the peak power of the photovoltaic installation, since this allows a greater generation of solar energy, supposing greater economic savings because less energy is needed from the network and more is being sold. However, this savings would have to be compared with the cost of the installation and its maintenance, a cost that is beyond the scope of this project. On the other hand, by increasing the peak power of the installation, self-consumption decreases, as there is greater production of solar energy, but its consumption is limited by the consumption of the users in the hours in which they are produced. Therefore, the energy poured into the network increases with the peak power of the installation. Self-sufficiency

also increases with the peak power, as users have greater availability of energy generated by the photovoltaic installation.
By increasing the peak power of the installation and, with it, the energy generated by it, the difference in the cost of acquiring the energy according to the proposed hypothesis increases, being the most economical for the higher peak power the corresponding to the distribution according to the contracted power, since the electric bill depends more on the fixed term in proportion with respect to the energy term, due to a lower consumption of the network. In fact, this is the default option according to the current regulation.

- ***Variation in the total bill payment of the system by varying the price of energy sales between users***

For each scenario, the selling price between users is varied in a range between 10 and 120 % of the sale price of surplus energy to the market, which coincides with the daily market price in each hour. This supposes a change in the cost of the energy for the users, which increases when increasing this price. The parameters of self-sufficiency and self-consumption are not affected by the change in this price. In the hypothesis of distribution based on hourly consumption, there was no sale among users at any time. However, in the hypotheses where this possibility did affect the consumption of energy produced by the shared self-consumption facility, it is observed that when the price of this exchanges increases among users, the total cost of the system increases slightly.

Being hypothesis 2 the distribution of the energy generated in equal parts, the hypothesis 3 the distribution of this energy according to the annual consumption and the 4 according to the contracted power, it is observed that the hypothesis most affected by this parameter is the distribution of energy in equal parts, since generated energy is not being distributed on the basis of energy consumption, and there are more sales among users to efficiently distribute the solar energy. Hypotheses 3 and 4 depend more or less on the user's consumption.

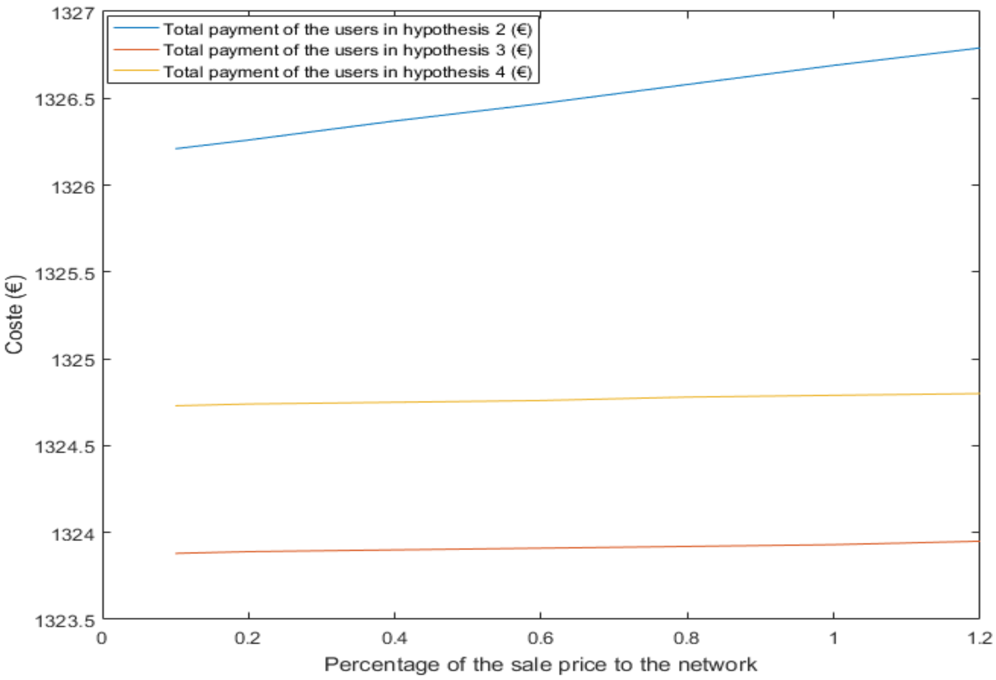


Figure 5: Evolution of the cost of the system based on the price of energy sales between users

- ***Variation of the results when varying the level of demand of user 1***

In this section, the energy consumed by this first user is modified, without changing the shape of its curve, varying its demand profile between 40 % and 140 % of it, to see how this affects the results.

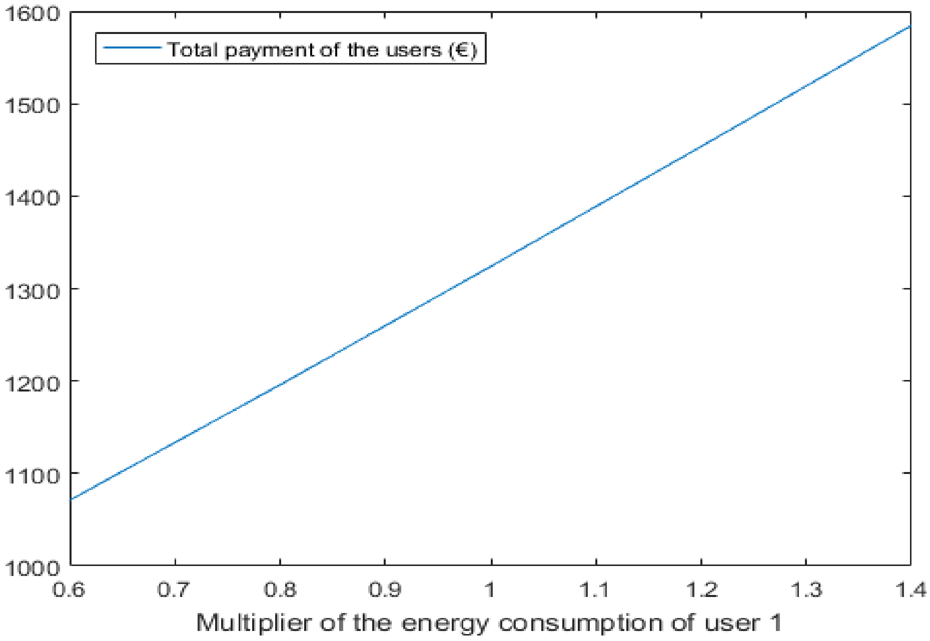


Figure 6: Evolution of the total cost of the users according to the factor by which the consumption of the user 1 is multiplied when the generated energy is distributed according to the annual consumption

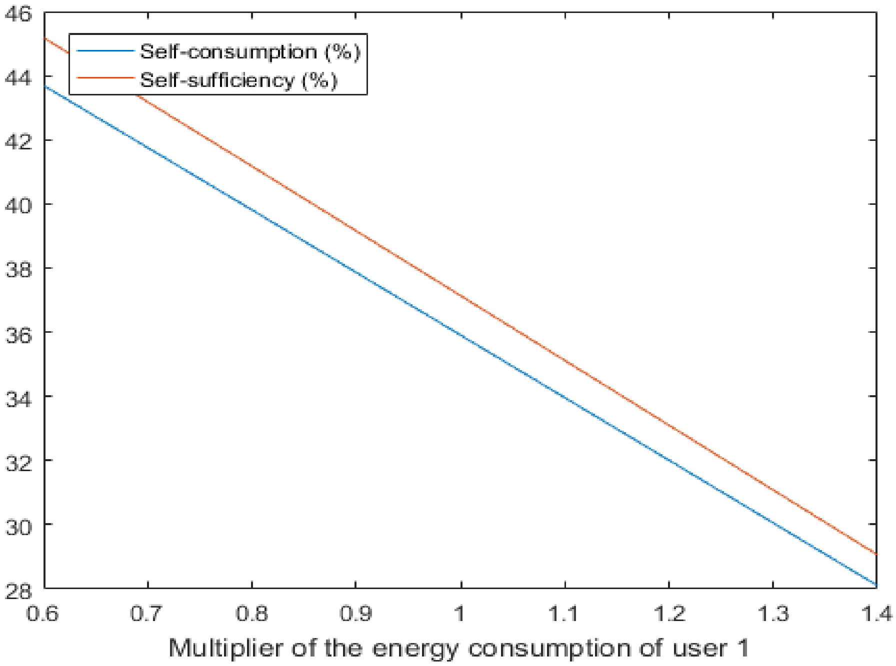


Figure 7: Evolution of the total self-consumption and self-sufficiency according to the factor by which the consumption of the user 1 is multiplied when the generated energy is distributed according to the annual consumption

In all scenarios, a similar effect is seen when varying this parameter. Self-consumption and self-sufficiency decrease as consumption of this user increases. These two parameters vary depending on the consumption that is actually made of the energy generated by the photovoltaic installation. As the consumption of the first user increases, the use made of this generated energy is greater and, therefore, less is sold to the network. As for the cost of the electricity bill, as more energy is acquired, it increases. Of all the hypotheses, the most profitable is the one corresponding to the distribution of the energy generated by the photovoltaic installation based on annual consumption.

5 Conclusions

In this section the conclusions of the project are presented.

After analysing the different hypotheses it is observed that those that suppose a greater saving in the electric bill for the clients are those in which they have the tariff DHA 2.0, with time discrimination in two periods, and in which the exchange of energy among users is allowed. This is logical, since it allows to maximize the use of the energy generated by the photovoltaic installation. The most efficient option is to maximize the consumption of the energy generated by the installation, since it supposes a saving in the invoice superior to the profit of sale of surplus energy to the network. On the other hand, the parameters of self-consumption and self-sufficiency increase. Therefore, the purchase/sale of energy between users means that every hour the generated energy is optimally used, thus minimizing the purchase/sale of energy from the network. A situation in which a user has to buy energy from the network at the same time in which another sells to the network, because its corresponding part of the energy generated by the shared photovoltaic installation is superior to its consumption needs, is undesirable and increases the expenses of the users as a whole.

In the event that energy transactions between users are not allowed, the best option for distributing the energy generated is the distribution of this according to the hourly consumption of the clients, in each hour. This minimizes interactions with the network and optimizes the use of the renewable energy generated, reducing the costs of acquiring energy for the customers throughout the year and increasing the relative savings of users. However, in this case the user could increase their consumption in the production hours to receive larger energy surpluses that they could sell to increase their profits. This would be solved if the surplus energy is distributed in equal parts, although the user would still be able to move loads at hours of higher photovoltaic production.

When the purchase and sale of energy between users is allowed, the most efficient hypothesis turns out to be the distribution of the generated energy based on the annual consumption of each client, although with little difference with respect to other options. The equal distribution hypothesis is the least efficient and greatly benefits those users with lower consumption, seriously damaging those who have more. It has the lowest energy and economic efficiency, since its values of savings, self-consumption and self-sufficiency are lower than those of other options, this effect being somewhat mitigated by including the purchase/sale of energy between users. The distribution hypothesis based on annual consumption is the one that generates the greatest savings in the electricity bill for users, since those that consume the most throughout the year receive more energy from photovoltaic source. Unlike in the case of the distribution of hourly generated energy according to the consumption of each client hour by hour, in this case there is no incentive for the user to consume more throughout the year, as this would increase his total electricity bill.

By varying the price of energy exchanges between users it is observed that the increase of it causes an increase in the final bill of the total of users. Although those who sell more energy will earn more, those who have to buy it (both will be in one and another situation according to their consumption and solar production in each hour) will incur in higher expenses that, taken together, will result in an economic loss of the total of consumers.

A sensitivity study is also carried out with respect to the peak power of the photovoltaic installation. When increasing it the production of photovoltaic installation energy increases, reducing the cost of the electricity bill of the users and thus increasing the parameters of self-sufficiency and economic saving, lowering the percentage of self-consumption. This reduction in cost would have to be compared with the corresponding cost of installation and maintenance of the photovoltaic modules, analysis that is beyond the scope of this project. The higher the consumption of the user, the more savings he will get, relative to what he would pay if the shared self-consumption facility did not exist. As the peak power of the installation increases the hypothesis that greater savings reported to users is the distribution of energy generated based on the contracted power of the user, since as more self-consumption energy is available, the energy term of the bill decreases and the fixed term becomes more important, which depends on the contracted power. Therefore, the user with more contracted power will have greater expenses, and will be proportionally more benefited from having a greater amount of energy generated available in each hour.

Finally, taking into account that there is a fixed term of power and other regulated elements in the electricity bill of consumers, the savings in the invoice that consumers perceive in relation to the energy generated by the shared self-consumption facility they consume and, therefore, they do not have to buy, supposes always a lower value in percentage than the value of self-sufficiency that they record, since, as explained, the invoice does not depend only on the energy consumed. With this in mind, and taking into account that in cases with tariff 2.0 DHA and energy exchanges between consumers the savings received by users are around 60%, with self-sufficiencies that do not reach 40% (whose impact on the percentage of savings, as it has been deduced before, is inferior to this value), it can be verified that the possibility of selling energy (to the network or between users) has a role as important as the possibility of self-consuming energy in the savings that users perceive.

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