MÁSTER UNIVERSITARIO EN INGENIERÍA INDUSTRIAL (MII)

TRABAJO FIN DE MÁSTER

MODELADO DEL EQUILIBRIO EN UN MERCADO P2P LOCAL DE ENERGÍA

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Madrid

Agosto de 2021

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Madrid

Agosto de 2021

Modelado del equilibrio en un mercado P2P local de energía

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Entidad Colaboradora: ICAI – Universidad Pontificia Comillas

RESUMEN DEL PROYECTO

Introducción

La Estrategia Energética de la Unión Europea (UE) y los Planes Nacionales Integrados de Energía y Clima (PNIEC) de los países europeos incluyen diferentes **estrategias de descarbonización** con el objetivo de alcanzar la neutralidad climática en 2050 [1]. Estos planes establecen objetivos ambiciosos para el sector energético, ya que representa más del 75% de las emisiones de gases de efecto invernadero de la UE.

Para mitigar las emisiones de carbono, la UE pretende aumentar la presencia de energías renovables en su mix energético hasta el 32% en 2030. Este fuerte incremento de energías renovables se alcanzará más fácilmente si se emplean todos los medios disponibles, desde nueva capacidad instalada centralizada hasta distribuida. De ahí que una estrategia importante para la descarbonización sea la **descentralización de la energía**, donde el consumidor final se convierte en un participante clave del futuro mercado de la electricidad.

Hoy en día, cada vez más consumidores se convierten en pequeños generadores, los llamados "prosumidores", con capacidades de producción de energía renovable (por ejemplo, de autoconsumo solar) y de almacenamiento. Asimismo, se observa una creciente preocupación medioambiental por parte de muchos consumidores, que buscan satisfacer su demanda de electricidad con energía obtenida de recursos renovables. En este sentido, las **comunidades de energía renovable**, consistentes en la asociación de prosumidores y consumidores para producir, consumir, almacenar y compartir energía renovable, están surgiendo para promover la generación distribuida y los intercambios locales de energía [2].

En estas comunidades energéticas, los prosumidores pueden compartir su excedente de energía con otros consumidores vendiéndolo a un precio competitivo. Esto puede suponer un beneficio económico para ambas partes, en comparación con el modo tradicional de consumo de energía, y dependiendo de las tarifas vigentes en la red. Los **mercados peer-to-**

peer (P2P) de energía aparecen como una posible estructura de mercado local para organizar los intercambios energéticos dentro de estas comunidades, donde los participantes negocian libremente los intercambios entre sí [3]. El desarrollo de estos mercados locales puede contribuir a la integración de las energías renovables en distintos niveles de la red, siguiendo así la estrategia de descarbonización de los países europeos.

Por todo ello, en cuanto la normativa evolucione para regularlos de forma adecuada, se espera un aumento progresivo de las comunidades energéticas y de los mercados locales P2P de energía, impulsado por los aspectos sociales anteriormente mencionados y las políticas europeas hacia la descarbonización de la economía.

Metodología

El objetivo de este proyecto es profundizar en el modelado de los mercados locales P2P de energía para estudiar de qué manera se pueden organizar los intercambios y cómo establecer un precio dentro de este nuevo mercado. De este modo, se pretende facilitar el estudio de cómo se comportan y pueden evolucionar estos mercados locales, para ayudar a evaluar su impacto en la evolución del mercado eléctrico por la expansión de la generación distribuida.

En primer lugar, este proyecto presenta una **revisión y estudio de la literatura existente sobre el modelado de mercados P2P**, con especial atención a la definición del precio de la energía dentro de este nuevo mercado.

Se han identificado tres enfoques para el modelado de un mercado P2P local de energía. Los tres establecen un precio interno en el mercado local, cuyo valor se encuentra entre los precios de compra y venta de energía a la red, que incentiva el consumo de energía renovable en la comunidad.

Dos de estos enfoques, los mecanismos de fijación de precios basados en precios calculados ([4], [5] y [6]) y los modelos basados en agentes ([7]), simulan un mercado P2P de tipo pool. La particularidad de este mercado es que sus participantes sólo realizan ofertas de energía. El precio interno se calcula según unas reglas previamente acordadas por la comunidad, y sólo depende de la energía disponible en la comunidad y los precios de la red. Este precio es el mismo para todos los participantes de la comunidad.

El tercer enfoque se basa en la teoría de juegos ([8]) y simula un mercado energético P2P de tipo pool, pero con resultados bilaterales. Estos precios bilaterales se obtienen asignando un coste a cada transacción entre participantes.

Tras esta revisión de la literatura, se propone un **modelo matemático para un mercado P2P local de energía**. Este modelo representa un mercado P2P en el que sus participantes pueden intercambiar energía entre sí y con la red, para mantener el balance de energía dentro de la comunidad. El modelo determina la capacidad fotovoltaica y de baterías óptima que debe instalar cada participante, así como su potencia contratada, para minimizar el coste de energía en la comunidad. El precio interno en el mercado local se determina utilizando el mecanismo de precio SDR sin compensación.

Este modelo se ha aplicado a un **caso de estudio** de una comunidad energética en Madrid. Esta comunidad está formada por 4 participantes, tres de los cuales son prosumidores, con posibilidad de invertir en paneles solares y baterías.

El caso de estudio presenta cuatro casos diferentes para analizar el impacto en la comunidad energética de incluir intercambios de energía P2P o capacidad de almacenamiento. Los cuatro casos considerados son:

- **Caso Base:** Comunidad energética sin inversiones en paneles solares ni en baterías. Todos sus participantes deben satisfacer su demanda de energía con la red.
- **Caso 1:** Mercado local de energía P2P con inversiones en paneles solares, pero sin capacidad de almacenamiento.
    - *Caso 1.1: Coste de inversión actual en paneles solares.*
    - *Caso 1.2: Coste de inversión en paneles solares un 10% mayor.*
- **Caso 2:** Mercado local de energía P2P con inversiones en paneles solares y baterías.
    - *Caso 2.1: Coste de inversión actual en baterías.*
    - *Caso 2.2: Coste de inversión en baterías un 10% menor.*

Resultados

Los resultados del caso de estudio muestran que, con el coste de inversión inicial considerado para los paneles solares, cada prosumidor instala la máxima capacidad fotovoltaica permitida, ya que el coste de inversión actual es muy competitivo (caso 1.1). Con el coste de inversión en baterías seleccionado, la capacidad instalada de baterías es muy pequeña, lo que indica que este coste empieza a ser competitivo (caso 2.1). A medida que el coste de inversión de las baterías disminuye, la capacidad instalada de las mismas aumenta (caso 2.2). Los costes de inversión iniciales se basan en la estimación de su valor actual según [9].

Por otro lado, los resultados muestran que la inversión en paneles fotovoltaicos y baterías reduce el coste anual de la energía para la comunidad hasta un 13%, en comparación con el consumo tradicional de energía de la red. La Figura 1 muestra el resultado de los términos incluidos en el coste anual para cada uno de los casos analizados.

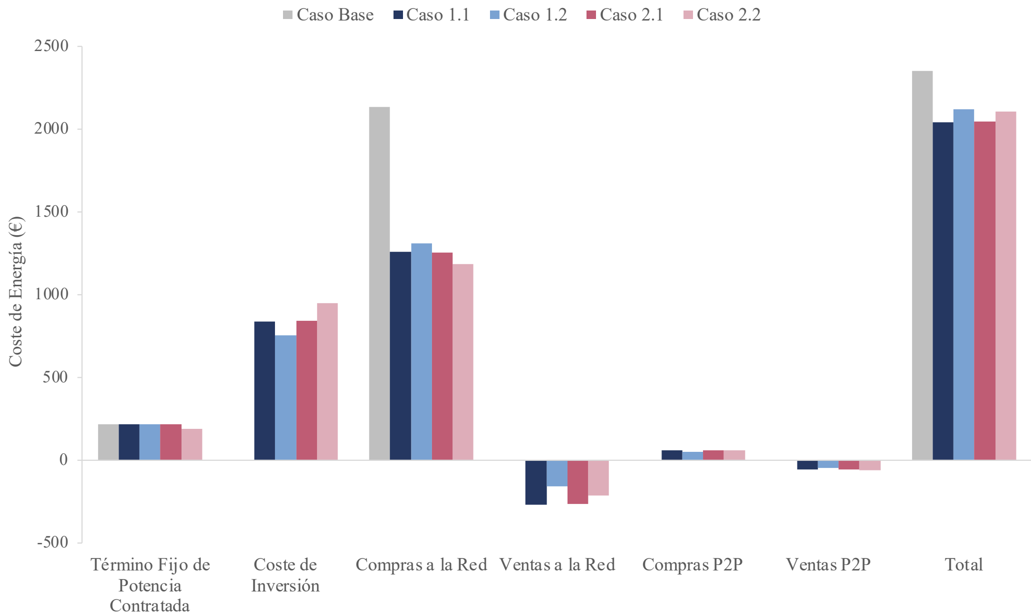

Figura 1. Comparación del coste anual de la energía de la comunidad

La instalación de baterías reduce el término fijo potencia contratada, ya que la comunidad disminuye su dependencia de la red.

Cuanto mayor es la capacidad instalada de las tecnologías, mayor es el coste de la inversión. Sin embargo, este se compensa con la menor dependencia de la red, que se refleja en el resto de los términos.

La instalación de paneles fotovoltaicos reduce el coste de compra de energía a la red. Además, cuanto mayor es la capacidad instalada de baterías, menor es este coste, ya que las baterías aportan más flexibilidad al consumo de la energía generada por los paneles fotovoltaicos.

La instalación de baterías reduce el beneficio obtenido por las ventas a la red. En el caso 2, parte del excedente de energía de los paneles solares durante el día se utiliza para cargar las baterías en lugar de venderse a la red.

Los intercambios en el mercado P2P aumentan a medida que hay más energía disponible en la comunidad. Cuanto mayor es la capacidad fotovoltaica instalada, mayor es el excedente de energía y mayores son los intercambios P2P. Cuanto mayor es la capacidad instalada de baterías, mayor es la flexibilidad para el consumo de la energía generada por los paneles fotovoltaicos, lo que permite también más intercambios P2P.

Conclusiones

A partir de este proyecto se puede concluir que los mercados locales de energía P2P pueden ser una estructura factible para organizar las comunidades energéticas. Con la regulación adecuada, pueden contribuir a la expansión de la generación renovable distribuida, incentivando a los miembros de una comunidad energética a colaborar entre sí, maximizando su consumo renovable. Sin embargo, si la generación distribuida sigue expandiéndose y la potencia contratada de estas comunidades disminuye, es posible que sea necesario revisar las tarifas eléctricas para continuar financiando el mantenimiento del sistema eléctrico.

En cuanto al modelo propuesto, minimiza el coste energético de la comunidad. Por lo tanto, los intercambios de energía entre los participantes quedan indeterminados. Para futuros estudios, se propone resolver el modelo utilizando teoría de juegos, minimizando el coste energético de cada participante individualmente, o incluir reglas para distribuir el beneficio de la comunidad entre los participantes. Por otra parte, también es interesante incluir la posibilidad de flexibilidad de la demanda en la comunidad, para maximizar el consumo de su generación renovable.

En cuanto al precio interno en el mercado P2P, se puede concluir que el método de SDR incentiva de forma efectiva el consumo de energía renovable en la comunidad. En el caso de estudio, el participante que no instala paneles fotovoltaicos compra su demanda de energía en el mercado local siempre que haya disponible. No obstante, una contribución importante al modelo sería calcular el precio interno utilizando el método de SDR con compensación. En el modelo propuesto, cuando hay un excedente de energía en la comunidad, los prosumidores obtienen el mismo beneficio vendiendo su excedente a la red o en el mercado local. Añadiendo esta compensación, el beneficio de los que están consumiendo cuando hay exceso de generación fotovoltaica se repartiría también entre los que están generando.

Por último, en base a los resultados del caso de estudio, se demuestra que este proyecto contribuye a los Objetivos de Desarrollo Sostenible (ODS) propuestos por la ONU, más concretamente a los ODS 7, 11 y 13. Impulsa con éxito la expansión de la generación renovable distribuida con un impacto positivo tanto para el medio ambiente como para la sociedad. Este impacto se mide mediante la reducción de las emisiones de CO_2 derivadas del consumo de energía y la reducción del coste de la energía.

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Modeling the equilibrium in a local P2P energy market

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Collaborating Entity: ICAI – Universidad Pontificia Comillas

ABSTRACT

Introduction

The EU Energy Strategy and the National Energy and Climate Plans (NECPs) of European countries include different **decarbonization strategies** with the aim of becoming a climate-neutral economy by 2050 [1]. These plans propose ambitious targets for the energy sector since it accounts for more than 75% of the EU's greenhouse gas emissions.

To mitigate carbon emissions, the EU aims to increase the presence of renewable energy sources (RES) in its energy mix to 32% by 2030. This high increment of RES will be more easily reached if all available means are used, from centralized to distributed new installed capacity. Therefore, an important strategy for decarbonization is the **decentralization of energy**, where the final consumer becomes a key participant in the future electricity market.

Nowadays, more and more consumers are becoming small generators, the so-called "prosumers", with renewable energy production (ex. from a rooftop solar panel) and storage capabilities. Besides, there is an increasing environmental concern of many consumers in satisfying their electricity demand through energy obtained from RES. In this sense, **renewable energy communities** (RECs) consisting in the association of prosumers and consumers for producing, consuming, storing and sharing renewable energy, are emerging to promote distributed RES and local energy exchanges [2].

In RECs prosumers can share their surplus generated energy with other consumers by selling it at a competitive price. This could provide an economic benefit to all parties, compared with the traditional way of energy supply, and depending on the grid tariffs in place. In this sense, **peer-to-peer (P2P) energy markets** appear as a feasible local market structure to organize the energy exchanges inside these communities, where the peers freely negotiate

the energy exchanges with each other [3]. The development of local markets could contribute to the integration of renewable energies at different levels of the grid, thereby following the decarbonization strategy of European countries.

All in all, driven by the social aspects previously mentioned and the European policies towards the decarbonization of the economy, it seems that there will be an unstoppable and progressive increase of RECs and local P2P energy markets as soon as regulation evolves to regulate them in a proper way.

Methodology

This thesis aims to go deeper into the modeling of local P2P markets to study how energy exchanges and energy prices could be conducted within this new market. This will facilitate the study of how these local markets behave and could evolve, to help assessing their impact on the electricity market evolution due to the expansion of distributed generation.

To do so, this thesis presents a **review and study of the existing literature on P2P market modeling**, with a special focus on the energy price definition inside this new market structure.

Three approaches to model a local P2P energy market have been identified. The three of them establish an internal price in the local market, which is between the buying of and selling prices to the grid, that incentivizes the consumption of renewable energy in the community.

Two of them, pricing mechanisms based on price computation ([4], [5] and [6]) and agent-based models ([7]), simulate a P2P energy market with a pool-type market clearing. In this market there are only energy bids, and the internal price is calculated from the energy available in the community and the grid prices. This price is the same for all the participants in the community.

The third approach is based on game theory ([8]) and simulates a P2P energy market with also a pool-type market clearing, but with bilateral results. These bilateral prices are obtained by assigning a cost to each transaction between participants.

Following this literature review, a **mathematical model for a P2P energy market** has been proposed. This model represents a local P2P energy market where its participants can trade energy among each other and with the grid, to maintain the energy balance within the community. It computes the optimal PV and battery capacity to be installed by each participant, as well as their contracted power, to minimize the community energy cost. The internal price in the local market is determined using the SDR pricing mechanism without compensation.

This model has been applied to the case of a hypothetical energy community in Madrid. This community consists of 4 participants, three of them are prosumers, with the possibility of PV and storage investment.

The case study presents four different cases to analyze the impact and the results when P2P energy exchanges or storage capabilities are considered. The four cases considered are:

- **Base Case:** Energy community without PV nor batteries investments. All participants must satisfy their energy demand with the grid.
- **Case 1:** Local P2P energy market with PV investments but no storage capabilities.
    - *Case 1.1: PV initial investment cost.*
    - *Case 1.2: PV investment cost a 10% higher.*
- **Case 2:** Local P2P energy market with PV and batteries investments.
    - *Case 2.1: Batteries initial investment cost.*
    - *Case 2.2: Batteries investment cost a 10% lower.*

Results

The results of the case study show that with the initial PV investment cost considered, each prosumer install the maximum PV capacity allowed since today's PV investment cost is highly competitive (case 1.1). With the selected batteries investment cost, the installed capacity of batteries is very small which indicates that it is starting to be competitive, although it is not yet (case 2.1). As the battery investment cost decreases, the installed capacity of batteries is higher (case 2.2). The initial investment costs are based on its current value estimation [9].

Moreover, the results show that the investment in PV panels and batteries reduces the annual energy cost for the community up to 13% compared to the traditional energy supply from the grid. Figure 1 compares each of the terms included in the annual cost for each of the cases analyzed.

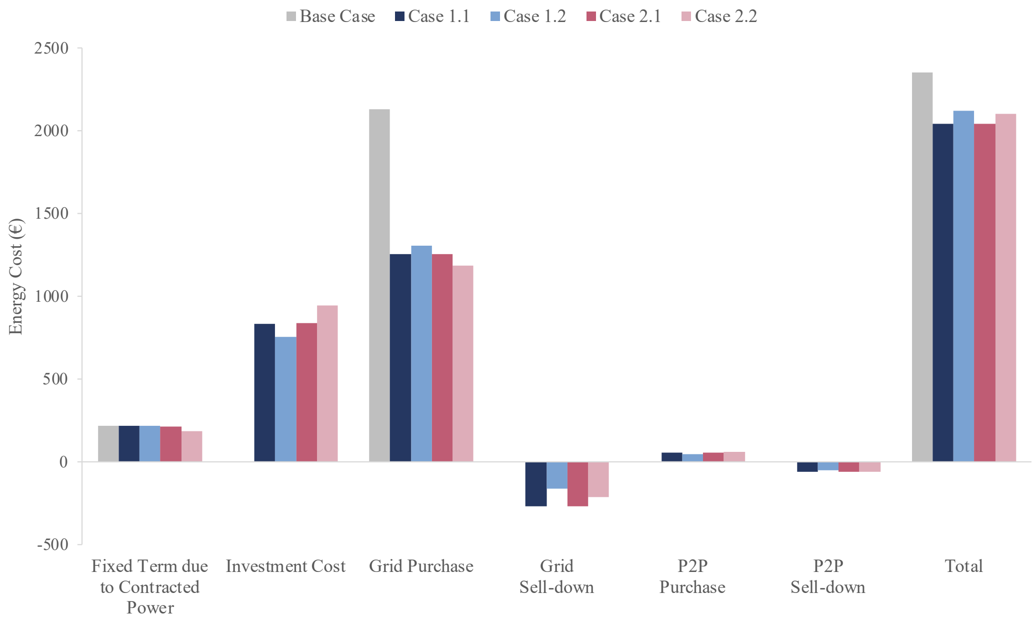

Figure 1. Community annual energy cost comparison

The addition of batteries reduces the fixed term due to contracted power as the community becomes more independent from the grid.

The more installed capacity of the technologies, the higher the investment cost. But it is compensated by the lower dependence of the grid, reflected in the rest of the terms.

The installation of PV panels reduces the cost of purchasing energy from the grid. Moreover, the higher the installed capacity of batteries, the lower is this cost, as they provide more flexibility to the consumption of the energy generated by the PV panels.

The installation of batteries reduces the benefit obtained for the sell-downs to the grid. In case 2, the surplus energy during the day is partly used to charge the batteries instead of selling it to the grid.

The exchanges in the P2P market increase as more energy is available in the community. The more PV capacity installed, the more surplus energy and the more P2P exchanges. The more battery capacity installed, the more flexibility, allowing also more P2P exchanges.

Conclusions

All in all, from this thesis it can be concluded that local P2P energy markets may be a feasible structure to organize energy communities. With the proper regulation, they can contribute to the expansion of renewable distributed generation, incentivizing the members of an energy community to collaborate among each other, maximizing their renewable consumption. However, if decentralization of energy continues expanding and the contracted power of these energy communities decreases, it may imply that there is a need to revise the electricity tariffs to keep financing the maintenance of the electricity system.

Regarding the proposed model, it minimizes the energy cost of the community. Therefore, the internal energy exchanges between participants are undetermined. Future researchers are oriented to solve the model using game theory, minimizing the energy cost for each participant individually, or to include rules to distribute the benefit of the community among participants. Also, it can be interesting to include the possibility of demand-response in the community, to maximize the energy consumption from renewable technologies.

Regarding the internal price in the P2P market, it can be concluded that the SDR method effectively incentivizes the consumption of renewable energy in the community. In the case study, the participant who does not install PV panels always buys its energy demand in the local market, as long as it is available. However, an important contribution to the model would be computing the internal price using the SDR with compensation. In the proposed model, when there is energy surplus in the community, prosumers obtain the same benefit either by selling their surplus to the grid or in the local P2P market. Adding the compensation, the benefit of those that are consuming when there is excess PV generation would be partially shared with those that are generating.

Finally, based on the results from the case study, it is demonstrated that this thesis effectively contributes to the Sustainable Development Goals (SDGs) proposed by the UN, more precisely to SDGs 7, 11 and 13. It successfully promotes the expansion of distributed renewable generation, with positive impact for both the environment and society. This impact is measured by the reduction of CO_2 emissions from energy consumption and the reduction of the energy cost.

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Nomenclature

Indexes

n	Participants in the P2P local market, $n \in N$
h	Hours
t	Technologies (Photovoltaic or Battery), $t \in \{PV, B\}$
k	Iterations, $k \in K$

Parameters

$D_{n,h}$	Energy demand [kWh]
PB_h	Price of energy bought from the grid (from trader) [€/kWh]
PS_h	Price of energy sold to the grid (feed-in-tariff) [€/kWh]
TP	Fixed tariff for contracted power [€/kW]
SR_h	Solar radiation profile of PV panel [%]
CH	Hours to charge the battery [hours]
$SOC_{n,0}$	Initial state of charge (SOC) of the battery [kWh]
ηc_n	Charging efficiency of battery [%]
ηd_n	Discharging efficiency of battery [%]
$IC_{t,n}$	Investment cost of each technology [€/kW]
$Q_{t,n}^{max}$	Maximum installed capacity allowed [kW]
$Q_{t,n}$	Capacity installed before investments [kW]
$UCONV$	Convergence threshold
λ	Compensating factor [€/kWh]
α_n	Sensitivity coefficient [-]
$\beta_{n,m}$	Bilateral trading coefficient imposed by participant n to participant m [-]

Positive Variables

$e_{t,n,h}$	Energy generated from each technology [kWh]
$e_{n,m,h}$	Energy sold by participant n to participant m [kWh]
dq_h	Energy deficit in the community [kWh]
$dq_{n,h}$	Energy deficit (total energy bought by each participant) [kWh]
$dqg_{n,h}$	Energy bought from the grid [kWh]
$dql_{n,h}$	Energy bought from the P2P local market [kWh]
eq_h	Energy surplus in the community [kWh]
$eq_{n,h}$	Energy surplus (total energy sold by each participant) [kWh]
$eqg_{n,h}$	Energy sold to the grid [kWh]

$eql_{n,h}$	Energy sold to the P2P local market [kWh]
ps_h	Internal energy price in the P2P local market [€/kWh]
pb_h	Weighted average price of energy purchases [€/kWh]
sdr_h	Supply-Demand Ratio [-]
$c_{n,h}$	Energy charging the battery [kWh]
$soc_{n,h}$	SOC of the battery [kWh]
$soc_{n,h}^{max}$	Maximum SOC of the battery [kWh]
$q_{t,n}$	Installed capacity of each technology [kW]
$iq_{t,n}$	Increase in the installed capacity of each technology [kW]
qc_n	Contracted power [kW]
$x_{n,h}$	Adjusted demand [kWh]
$ps_{n,m,h}$	Bilateral trading price between participants n and m in the P2P local market in hour h [€/kWh]
$\mathrm{ebid}_{\mathrm{n,h}}$	Energy bid [kWh]
$\mathrm{pbid}_{\mathrm{n,h}}$	Price bid [€/kWh]

Functions

U_n	Utility function
$\tilde{C}_n$	Trading cost function

Chapter 1. Introduction

This chapter presents a description of the European Union's strategy for the energy transition and how the energy decentralization plays an important role in it. More specifically, the current situation of energy communities and local energy markets is analyzed to justify the motivation and objectives of this thesis. Finally, the structure of the rest of the document is presented.

1.1 EU Energy Strategy

The Energy Strategy of the European Union (EU) define energy and climate targets for 2050 to ensure safe, affordable, and sustainable energy for Europe [1]. Through this strategy, the EU aims to become a climate-neutral economy by 2050, as stated in the European Green Deal and in line with its commitment to global climate action under the Paris Agreement [2].

To this end, EU countries have agreed on common standards and objectives to achieve this target, and they are required to develop integrated national energy and climate plans (NECPs) [3]. These plans include different **decarbonization strategies** with ambitious targets for the energy sector, since this sector accounts for more than 75% of the EU's greenhouse gas emissions [4]. To mitigate carbon emissions, the EU aims to increase the presence of renewable energy sources (RES) in its energy mix to 32% by 2030, towards being climate-neutral by 2050. In particular, the Spanish NECP expects to achieve a 42% share of renewable energies in the final energy use by 2030 [5]. This high increment of RES will be more easily reached if all available means are used, from centralized to distributed new installed capacity. Therefore, an important strategy for decarbonization is the **decentralization of energy**, where the final consumer becomes a key participant in the future electricity market.

1.2 Energy Communities and P2P Local Energy Markets

Nowadays, more and more consumers are becoming small generators, the so-called "prosumers", with renewable energy production (ex. from a rooftop solar panel) and storage capabilities. Besides, there is an increasing environmental concern of many consumers in satisfying their electricity demand through energy obtained from RES. In this sense, **renewable energy communities** (RECs) consisting in the association of prosumers and consumers for producing, consuming, storing and sharing renewable energy, are emerging to promote distributed RES and local energy exchanges [6].

In RECs prosumers can share their surplus generated energy with other consumers by selling it at a competitive price. This could provide an economic benefit to all parties, compared with the traditional way of energy supply, and depending on the grid tariffs in place. In this sense, **peer-to-peer (P2P) energy markets** appear as a feasible local market structure to organize the energy exchanges inside these communities, where the peers freely negotiate the energy exchanges with each other [7]. The development of local markets could contribute to the integration of renewable energies at different levels of the grid, thereby following the decarbonization strategy of European countries.

This new market structure encourages the deployment of distributed renewable generation. It can combine together two different profiles of participants, such as passive consumers willing to consume renewable energy and active consumers (prosumers) willing to produce their own renewable energy [8]. Besides, P2P energy markets could offer greater flexibility to consumers, providing them with efficient economic signals so that they can adapt their consumption according to the energy price and the local availability of renewable energy. Since it is a local market, energy is generated close to where it is consumed, which contributes to larger reliability and resilience of the grid as well as, in general, to a reduction of energy losses [7].

However, this new market structure also presents some drawbacks. Among others, 1) grid access tariffs should encourage investment in distributed RES without endangering the sustainability of the electricity system; 2) it raises the issue of to what extent individual distributed RES is more profitable than utility generation, which allows for economies of scale; and 3) large additions of distributed RES can cause problems to the grid such as voltage changes or lower power quality, which can increase the complexity of the operation of the distribution grids [7].

All in all, driven by the social aspects previously mentioned and the European policies towards the decarbonization of the economy, it seems that there will be an unstoppable and progressive increase of RECs and local P2P energy markets as soon as regulation evolves to regulate them in a proper way.

Several works, such as [7] and [9], identify different **P2P energy market structures** depending on the degree of decentralization and the interaction among participants. They propose three types of structures: full P2P market, community-based P2P market, and hybrid P2P.

- **Full P2P market:** Peers directly negotiate with each other without the supervision of a centralized third party (see Figure 1.1). Prosumers and consumers negotiate among themselves the price of the energy exchanged and could express their preferences when choosing the type of energy to buy. To balance the overall energy surplus or deficit in the REC, the community is connected to retailer who will allow exchanges with the main grid to solve these imbalances. This network connection can be either unique for the entire community or independent for each participant, in which case each participant would have its own retailer.

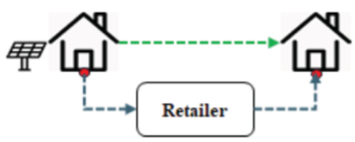


Figure 1.1. Full P2P market [7]

- **Community-based P2P market:** More organized structure where there is a community manager who manages the energy exchanges inside the REC and who balances the deviations inside the community with the main grid (see Figure 1.2).

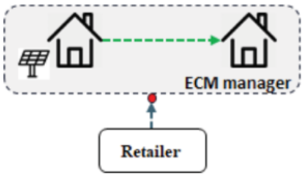


Figure 1.2. Community-based P2P market [7]

- **Hybrid P2P market:** Combination of the two previous structures (see Figure 1.3). It presents different levels of energy exchange. There are different communities, some of them with a manager, which can interact among themselves and with the main grid.

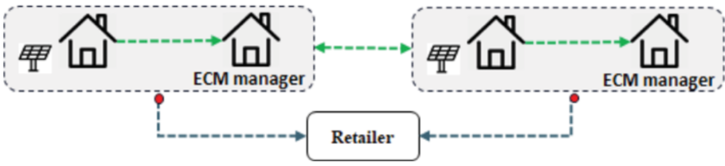


Figure 1.3. Hybrid P2P market [7]

This thesis focuses on the study of full P2P markets where prosumers and consumers can trade electricity at an agreed price [8]. In this way, with proper regulation, consumers can save costs while prosumers can make a profit while contributing to the penetration of RES into the existing electricity market.

1.3 Current Situation of P2P Energy Markets

To date, local P2P energy markets are still at an early stage. Nevertheless, a growing number of **P2P energy trading projects** are being developed worldwide, especially in areas where electricity trading is deregulated [10]. In UK, Piclo is an electricity trading platform where business consumers can select and buy electricity directly from local renewable suppliers. In the Netherlands, Vanderbron is another electricity trading platform where consumers can buy electricity directly from local independent producers. In USA, Yeloha is another project where consumers can pay for a portion of the solar energy generated by the owner of a solar installation. In Germany, SonnenCommunity is a community where its members completely cover their energy needs on sunny days from their RES and batteries [11].

Among existing pilot projects, the Brooklyn Microgrid project (BMG project) stands out. It is the first project worldwide where the members of an energy community can trade the energy generated locally with their neighbors over a blockchain platform [12]. In this project, an electrical microgrid is built in addition to the existing distribution network. The energy exchanges inside the community are done within the distribution grid while the physical microgrid network is only used for emergencies. Besides, the community interaction is carried out in a private blockchain platform. There, consumers constantly bid their price limits and preferred sources for the consumed energy, whereas prosumers bid their minimum energy selling price. Regularly, the energy transactions are cleared, and energy exchanges are allocated to the participants trying to maximize their economic benefit. According to [12], the rate of participation in the BMG project and the positive social acceptance of the community can be considered as an evidence of the market potential of local energy communities based on distributed RES generation.

In Spain there are no significant local P2P energy market projects, but in recent years there has been an increase in the interest in self-consumption and distributed generation. Figure 1.4 presents the evolution of installed self-consumption capacity in Spain, where a notable increase has been observed in the last years.

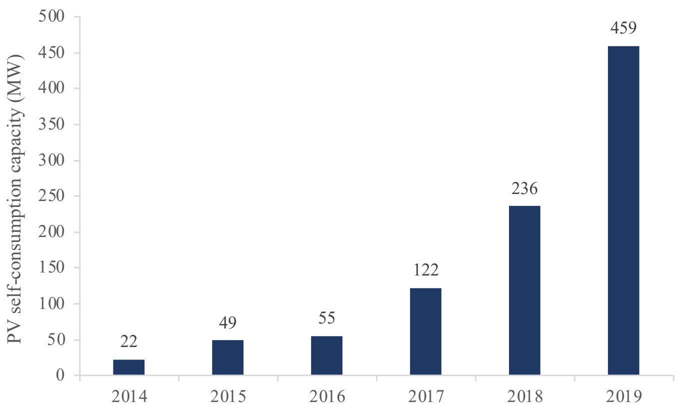


Figure 1.4. Estimated installed capacity of PV self-consumption in Spain [13]

1.4 Motivation

The growth of energy communities and the expansion of distributed generation reveal the need for proper modeling of these local markets. This will enable better studies of their behavior, evolution, and the analysis of their interactions with the wholesale market. Evidence of this need is the success of some pilot projects. It represents the beginning of the expansion of these initiatives and, therefore, the need for further study and new regulations, already under elaboration in many countries.

This thesis aims to go deeper into the modeling of local P2P markets to study how energy exchanges and energy prices could be conducted within this new market. This will facilitate the study of how these local markets behave and could evolve, to help assessing their impact on the electricity market evolution due to the expansion of distributed generation.

1.5 Objectives

This thesis aims to review and study the existing literature on P2P market modeling, with a special focus on the energy price definition inside this new market structure. The goal is to propose a mathematical model for a P2P energy market.

To achieve this goal, the following partial objectives must be addressed:

1. Review of the state of art. Analyze the different approaches to P2P market modeling in the literature, classify them, and eventually identify the main modeling tendencies.
2. Propose a mathematical model for P2P energy markets based on the analysis conducted and the conclusions derived.
3. Implementation of the proposed model and design of different scenarios to test and validate the resulting model.
4. Analysis and discussion of the results from the previous point.

1.6 Document structure

This thesis is structured as follows. Chapter 2 presents a review of existing literature and an analysis of the main modelling approaches for P2P energy markets. Chapter 3 describes the model proposed for simulating a P2P energy market with PV panels and batteries investments. Finally, Chapter 4 presents the analysis of a case study and Chapter 5 presents the conclusions and the future lines of research.

Chapter 2. State of Art

This chapter presents a review of the existing literature to model a local P2P energy market. The first section presents a brief description of a P2P energy market design. The second section classifies different articles modeling a P2P energy market according to their considerations. The third section presents a detailed description of three approaches found in the literature to model and determine the energy price in a local P2P market. Finally, the last section summarizes in a table the analysis of the different articles.

2.1 Design of Local P2P Energy Markets

A local P2P energy market is a new market structure to organize the exchanges inside a renewable energy community. These communities consist in a group of prosumers and consumers, where everyone negotiates their energy purchase or sale needs within the community. If there is a surplus or deficit of energy after the negotiation, it is somehow compensated with the main grid by the involved retailers. In this way, it ensures the maximum possible benefit for all the community.

The design of an energy market can be defined according to several criteria, but for the study that follows, we will focus on the type of **market clearing**. In a truly local P2P energy market, participants submit buying and selling bids of their demand and generation respectively, as well as the maximum price at which they are willing to buy, or the minimum price at which they are willing to sell, and the market clearing provides the energy price. There are two types of market clearing:

- **Continuous and bilateral**: As soon as a selling and a buying bid can be matched, the trade becomes effective.
- **Pool type system**: A unique price is set by clearing together all selling and buying bids with the objective of, for example, minimizing the energy cost or maximizing the social welfare of the community. Although the result is usually a single price, it

may not always happen, and the market clearing could have as a solution bilateral price agreements.

2.2 Considerations for Local P2P Energy Market Model

To begin with, we examine various considerations taken from the literature to model a local P2P energy market, as well as how these considerations influence the model.

According to the definition of REC, the **energy generated by the prosumers** is always obtained from RES. However, some articles only consider prosumers with solar panels, such as [14], while others consider prosumers with different generation profiles, with solar and wind energy generation, such as [15]. The generation from solar panels is always maximum during the day and null during the night, so the trading price in the local market decreases during the day as a consequence of the higher availability of renewable energy. On the other hand, energy from wind resources is generally more stable throughout the day. Therefore, the increase in demand during the day in a community based on wind generation, as its production is less variable, will raise the trading price in the local market during the day. Furthermore, [15] studies how the number of participants in the local market influence the benefit obtained by the different prosumers and consumers. Other articles present new possible generation profiles for prosumers. For example, [16] proposes the utilization of the batteries of electric vehicles. The more renewable energy resources considered, the more flexibility and cost reduction for these local markets will be obtained in the future, but also, more complexity will be added to its model.

The possibility of **energy storage** with batteries in local markets is studied in [17], [18], [19], [20], [21] and [22]. Due to the difficulty of forecasting renewable energy generation, these authors choose to include batteries to reduce this uncertainty. Storage provides greater flexibility to communities and helps to reduce the intermittency of renewable energy. Moreover, as presented in [19], the combination of P2P exchange and the use of storage reduces the cost of electricity by half compared to the traditional way of energy supply, excluding the investment cost of the technologies. This saving is primarily due to the reduction of dependency on the main grid, limited just to the peaks of demand periods of the day. Also, this article presents a study of the economic viability of residential storage, considering their investment costs, and concludes that participation in the local market is still worthwhile. In [21], authors analyze the role of battery flexibility in a P2P energy market with batteries owned by each participant versus a central battery shared by the community.

Another consideration introduced by some authors is **network constraints**. In [20], the authors include the possibility of line congestion. In [23], the authors analyze the active power losses and voltage variations in an energy community over a day. It turns out that grid problems mainly occur when there is a large PV solar energy production, and generation and demand are not distributed uniformly along the grid. In [24], a case study of a P2P market is conducted. It shows that local P2P energy exchanges do not violate technical constraints, and the community benefits from an energy cost reduction. All these models present a more comprehensive analysis of local P2P energy markets, trying to assess their impact on the grid, but accordingly, complexity increases.

One of the characteristics of a P2P market is that it can provide efficient price signals, so participants can adapt their consumption to reduce their energy cost by taking advantage of the moments of high renewable generation in the community. Thus, the authors in [20], [25], [26] and [27] include the possibility of **demand response**. In this way, P2P market participants can reschedule the consumption of specific electronic devices and appliances to take advantage of periods with higher availability of renewable energy. In all these models the energy cost of each participant decreases.

Lastly, it is worth mentioning some authors who try to study the impact of local P2P markets on the current electricity market. In [19], a market model is presented in which a local P2P energy market is integrated with the day-ahead and intraday electricity markets. The model considers generation and consumption forecasts in the day-ahead market, as well as deviations in the intraday market caused by the difficulty of forecasting renewable generation. The results of the model show a significant energy cost reduction for the community, especially when combining local P2P trading with batteries to store energy.

2.3 Approaches for Local P2P Energy Market Model

In this section, we discuss different approaches in the literature to model P2P electricity markets to determine the energy trades and the resulting local price.

Extensive literature is available for modeling local P2P energy markets. Most models are based on the economic benefit obtained by the participants from the P2P energy trading in a local market, compared to trading energy in the traditional centralized electricity market [7]. This benefit arises when the feed-in-tariffs of injecting electricity to the grid are lower than the wholesale energy price, or when access tariffs discounts are applied due to a reduced usage of the grid, that is supposed to decrease losses. Therefore, prosumers can sell their surplus energy within the community at prices lower than the wholesale price and still have profits. Prosumers benefit from their selling, and consumers benefit from their energy cost reduction and lower access tariffs. This suggests the importance of establishing correct pricing schemes in the local market, which ensure a fair share of revenues within the community as well as provide incentives to the participants for remaining in the community.

Several articles, such as [17], highlight the challenge of modeling P2P markets as it involves modeling the decision-making process of each participant. Their objective is to maximize their economic benefit but, at the same time, human factors should be considered such as their motivation, their commitment to the environment, or their commitment to the local exchange. These may cause that some of them will be willing to pay more if the energy comes from renewable resources or from a neighbor instead of an energy company.

In the review of the literature, we have observed several approaches to modeling a local P2P energy market. However, the energy pricing definition inside this new market is still a matter of research. The problem with modeling a local P2P energy market is that it cannot be solved by a traditional Nash equilibrium or cost minimization problem because the marginal cost of energy, being all renewable, is zero. Apart from articles [19] and [21], in which the authors consider the price in the local market to be the grid price discounted by a certain % to account for the reduced grid usage, we have identified three different methods to determine this price:

pricing mechanisms based on price computation, game theory with consumer preferences and agent-based models with auction mechanisms.

The following sections present a mathematical integrated description of these three methods to represent P2P energy markets. To do so, here we present a brief description of the variables involved.

Being $D_{n,h}$ the energy demand and $e_{n,h}$ the energy generated by participant n in hour h, we will denote the energy bought or sold by a participant in an hour by $dq_{n,h}$ or $eq_{n,h}$ respectively:

$$dq_{n,h} = \max(0, D_{n,h} - e_{n,h}) \tag{2.1a}$$

$$eq_{n,h} = \max(0, e_{n,h} - D_{n,h}) \tag{2.1b}$$

Moreover, variables $dq_{n,h}$ and $eq_{n,h}$ can be divided in two, the energy exchanged with the grid ($dqg_{n,h}$ and $eqg_{n,h}$) or within the local P2P market ($dql_{n,h}$ and $eql_{n,h}$), i.e:

$$dq_{n,h} = dqg_{n,h} + dql_{n,h} \tag{2.2a}$$

$$eq_{n,h} = eqg_{n,h} + eql_{n,h} \tag{2.2b}$$

The energy exchanged by each participant in the P2P market ($dql_{n,h}$ and $eql_{n,h}$) comes from the energy generated in the community. Being $e_{m,n,h}$ the energy generated by participant m sold to participant n, we can define $dql_{n,h}$ and $eql_{n,h}$ as:

$$dql_{n,h} = \sum_{m \neq n} e_{m,n,h} \tag{2.3a}$$

$$eql_{n,h} = \sum_{m \neq n} e_{n,m,h} \tag{2.3b}$$

Finally, the energy bought or sold by the community in an hour will be denoted by dq_h or eq_h respectively. These variables can also be divided in two, the energy exchanged with the grid (dqg_h and eqg_h) or within the local P2P market (dql_h and eql_h).

$$dq_h = \sum_n dq_{n,h} \tag{2.4a}$$

$$eq_h = \sum_n eq_{n,h} \tag{2.4b}$$

$$dqg_h = \sum_n dqg_{n,h} \tag{2.4c}$$

$$eqg_h = \sum_n eqg_{n,h} \tag{2.4d}$$

$$dql_h = \sum_n dql_{n,h} = \sum_n eql_{n,h} = eql_h \tag{2.4e}$$

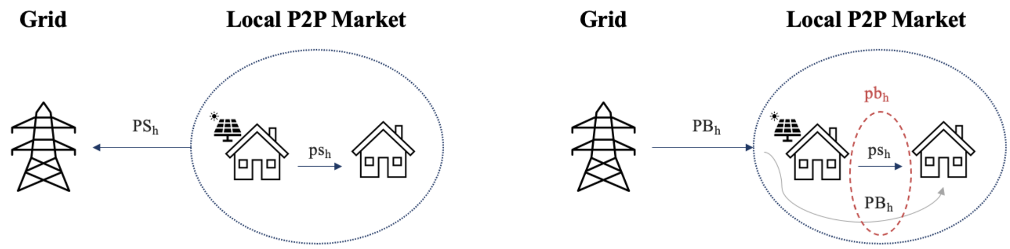
2.3.1 Approach 1. Pricing Mechanisms based on Price Computation

Introduction

Pricing mechanisms are used to determine the price at which participants of a local P2P market trade energy with each other. When based on REC price computation, the local electricity price is calculated, for a certain delivery time, only from the energy available in the community (based on the energy generation and demand of its participants) and the buying and selling prices of the grid.

To clarify the different prices involved in a local P2P market,

Figure 2.1 summarizes the possible energy exchanges and the price at which they are made. Being PB_h and PS_h the energy buying and selling prices to the grid, ps_h the internal energy price in the local market and pb_h the weighted average buying price, then:



(a) Local energy community with surplus generation

(b) Local energy community with deficit of generation

Figure 2.1. Overview of energy exchanges in a local P2P market

To ensure that all participants benefit from being part of the P2P market, the internal price must be a value between the energy selling and buying prices to the grid.

$$\boxed{PS_h < ps_h < PB_h} \tag{2.5}$$

Types

Some common ways to compute the P2P market price depend on how the benefit obtained is distributed among participants. These are: Bill Sharing (BS), Mid-Market Rate (MMR) and Supply-Demand Ratio (SDR).

<u>Bill Sharing (BS)</u>

The BS pricing mechanism is a cost sharing method. It is based on calculating the electricity bill of the entire energy community and distribute it among its participants depending on their energy consumption or export [28]. Thus, the resulting internal energy price ensures that the total cost or benefit of the community is distributed evenly among all its participants.

$$ps_h = PS_h \cdot \frac{\sum_h eql_h}{\max\left(0, \sum_{n,h}(e_{n,h} - D_{n,h})\right)} \tag{2.6a}$$

$$pb_h = PB_h \cdot \frac{\sum_h dql_h}{\max\left(0, \sum_{n,h}(D_{n,h} - e_{n,h})\right)} \tag{2.6b}$$

Mid-Market Rate (MMR)

The MMR pricing mechanism assumes that the internal energy price (ps_h) is the average between the energy buying of and selling prices to the grid [28].

$$ps_h = \frac{PB_h + PS_h}{2} \tag{2.7}$$

Depending on whether there is generation surplus or deficit in the community, the final weighted average price of energy sales or purchase will depend on the quantity exchanged with the grid. In [14] and [28], authors analyze how the exchanges with the grid influence the final energy cost.

Supply-Demand Ratio (SDR)

The SDR is a variable that measures the relation between the energy available in the P2P market, offered by the prosumers, and the energy demand in the community. According to [25], the SDR is defined as:

$$sdr_h = \frac{eq_h}{dq_h} \tag{2.8}$$

Depending on the value of the SDR, the community would have to exchange energy with the grid. When SDR > 1, surplus energy is generated in the community that must be sold to the grid. When SDR = 1, the energy generated in the community is the same as the energy demand, so there is no energy exchange with the grid. When 0 < SDR < 1, there is a deficit of energy generation in the community, thus it is necessary to buy energy from the grid. When SDR = 0 all the energy is bought from the grid, as there is no energy available in the community.

The SDR pricing mechanism is based on one of the fundamental laws of economics. It assumes that the relation between the internal energy price and the SDR is inverse-proportional [25]. Therefore, the higher the SDR (more energy available), the lower the internal price will be, and the lower the SDR (less energy available), the higher the internal price will be.

Following, the internal energy price (ps_h) and the weighted average buying price (pb_h) are defined depending on the energy availability in the community and the SDR [25]:

- If **SDR ≥ 1** (excess generation in the community)

  The internal energy price is the same as the selling price to the grid. If the price was lower, prosumers would not sell the energy in the local market and would sell it directly to the grid. All the consumers buy their energy in the local P2P market.

$$ps_h = pb_h = PS_h \quad if\ sdr_h \geq 1 \tag{2.9}$$

- If **0 < SDR < 1** (deficit generation in the community)

  The internal energy price is inversely proportional to the SDR. Therefore,

$$ps_h = \frac{1}{a \cdot sdr_h + b} \tag{2.10a}$$

To calculate the coefficients a and b, the boundary conditions are evaluated:

1. If SDR = 0, there is no energy surplus in the community and all the energy is bought from the grid, therefore $ps_h = PB_h$.
2. If SDR = 1, the energy generated in the community is the same as the energy demand, so there is no energy exchange with the grid, the internal energy price is the lowest possible, therefore $ps_h = PS_h$.

By substituting the two points into the equation (2.10a), we obtain the following equation set:

$$\begin{cases} PB_h = \dfrac{1}{b} \\ PS_h = \dfrac{1}{a+b} \end{cases} \rightarrow \begin{cases} a = \dfrac{PB_h - PS_h}{PB_h \cdot PS_h} \\ b = \dfrac{1}{PB_h} \end{cases} \tag{2.10b}$$

Therefore, the internal energy price in the P2P local market is:

$$ps_h = \frac{PB_h \cdot PS_h}{(PB_h - PS_h) \cdot sdr_h + PS_h} \quad if\ 0 < sdr_h < 1 \tag{2.10c}$$

Consumers will buy energy from both the grid and the local P2P market. Therefore, the resulting average energy buying price is the weighted average between the amount of energy purchased from the grid and from a prosumer. The final buying price can be obtained from the following economic balance:

$$dq_h \cdot pb_h = eq_h \cdot ps_h + (dq_h - eq_h) \cdot PB_h \tag{2.10d}$$

And therefore, the final buying price in the P2P local market is:

$$pb_h = ps_h \cdot sdr_h + PB_h \cdot (1 - sdr_h) \quad if\ 0 < sdr_h < 1 \tag{2.10e}$$

To sum up, the internal energy price and average buying price in the local P2P market are defined as a function of the SDR:

$$ps_h = \begin{cases} \dfrac{PB_h \cdot PS_h}{(PB_h - PS_h) \cdot sdr_h + PS_h}, & 0 < sdr_h < 1 \\ PS_h, & sdr_h \geq 1 \end{cases} \tag{2.11a}$$

$$pb_h = \begin{cases} ps_h \cdot sdr_h + PB_h \cdot (1 - sdr_h), & 0 < sdr_h < 1 \\ PS_h, & sdr_h \geq 1 \end{cases} \tag{2.11b}$$

Note that these prices only depend on the energy selling and buying prices from the grid and the generation and demand in the community. Figure 2.2 represents the relationship between these prices and the SDR.

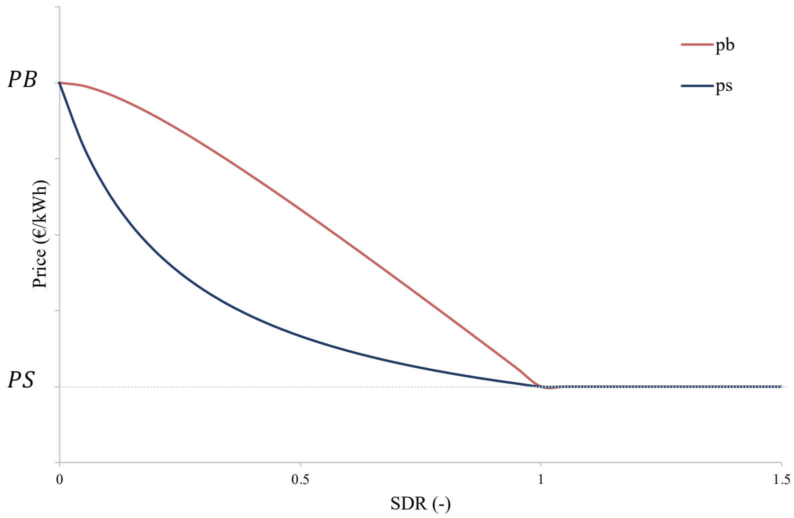


Figure 2.2. Relationship between ps, pb and SDR

<u>SDR Compensated</u>

According to (2.11), when there is surplus generation in the community (SDR > 1), prosumers obtain the same benefit either by selling their surplus to the grid or in the local P2P market. To incentivize prosumers to participate in the P2P market in this situation, a compensating factor λ is added in [22]. In this way, the benefit of those that are consuming when there is excess PV generation is partially shared with those that are generating.

The internal energy price and average buying price in the local P2P market are then defined as a function of the SDR and the compensating factor.

$$ps_h = \begin{cases} \dfrac{PB_h \cdot (PS_h + \lambda)}{(PB_h - PS_h - \lambda) \cdot sdr_h + PS_h + \lambda}, & 0 < sdr_h < 1 \\ PS_h + \dfrac{\lambda}{sdr_h}, & sdr_h \geq 1 \end{cases} \tag{2.12a}$$

$$pb_h = \begin{cases} ps_h \cdot sdr_h + PB_h \cdot (1 - sdr_h), & 0 < sdr_h < 1 \\ PS_h + \lambda, & sdr_h \geq 1 \end{cases} \tag{2.12b}$$

$$0 < \lambda < (PB_h - PS_h) \tag{2.12c}$$

Figure 2.3 represents the relationship between these prices, the SDR and the compensating factor λ.

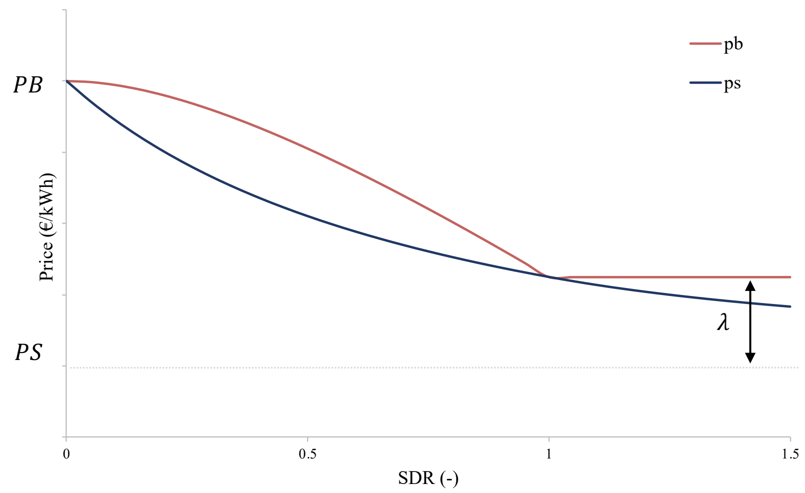


Figure 2.3. Relationship between ps, pb, SDR and λ

Despite this compensation and the resulting increase in the internal energy price, consumers still make a profit versus buying their entire energy demand from the grid. Consumers are always going to pay for their energy less than PB_h and prosumers are always going to get paid for their energy more than PS_h. This ensures that all P2P market participants receive an economic benefit by staying in the community.

Implementation Example

An example of the application of this first approach based on articles [18] and [25] is shown below. The main characteristics are:

- The market clearing is a *pool* type but with some singularities. Participants submit buying and selling bids of their demand and generation respectively, but not about their buying or selling prices. The price is calculated according to some rules previously agreed upon in the community (like BS, MMR or SDR).
- A *common* internal energy price is established for the community, so all participants trade their energy at the same price in the local P2P market.

- It is assumed that *all* the energy generated by prosumers is exchanged in the P2P market before being exchanged with the grid. This means that no participant will be buying energy from the grid when another is selling to the grid.

Table 2.1 shows the prices considered in this first approach.

Inputs	PB_h	Price of energy bought from the grid in hour *h* (from trader) [€/kWh]
	PS_h	Price of energy sold to the grid in hour *h* (feed-in-tariff) [€/kWh]
Outputs	$\boldsymbol{ps_h}$	Internal price of energy in the P2P local market in hour *h* [€/kWh]
	$\boldsymbol{pb_h}$	Weighted average price of energy purchases in hour h [€/kWh]

Table 2.1. Prices considered in approach 1

The most extended pricing mechanism based on price computation is the SDR, as in [18] and [25]. These articles define a formula to compute the internal price in a community depending on whether the participants sell or buy energy.

$$p_{n,h} = \begin{cases} ps_h, & eq_{n,h} > 0 \\ pb_h, & dq_{n,h} > 0 \end{cases} \tag{2.13}$$

The problem is then solved by computing the internal energy price using equation (2.11), given the demand and generation of the participants in a local market. In addition, participants flexibility can be added by considering new assumptions, such as the possibility of demand elasticity [25] or the use of batteries [18].

In [25] authors formulate a P2P market where its participants have the possibility of changing their initial demand depending on energy prices, in order to reduce their energy cost. The decision variable is $x_{n,h}$ which represents the adjusted demand of a participant, corresponding to its final energy consumption. The objective function is presented in equation (2.14) where α_n represents the sensitivity coefficient of a participant, which quantifies the participant's willingness to change its consumption pattern.

$$\min \sum_{h} \left[p_{n,h} \cdot \left(\boldsymbol{x_{n,h}} - e_{n,h}\right) + \alpha_n \cdot \left(\boldsymbol{x_{n,h}} - D_{n,h}\right)^2 \right] \quad \forall\, n \tag{2.14}$$

In [18] authors formulate a P2P market where its participants also have battery storage capabilities. The decision variable is $c_{n,h}$ which represents the energy charging (if $c_{n,h} > 0$) and discharging (if $c_{n,h} < 0$) of a participant's battery. The objective function is presented in equation (2.15).

$$\min \sum_{h} \left[p_{n,h} \cdot \left(\boldsymbol{c_{n,h}} + \left(D_{n,h} - e_{n,h} \right) \right) \right] \quad \forall\, n \tag{2.15}$$

Conclusion

This first approach of pricing mechanisms is the simplest method and results in a single price for each delivery time for the energy traded in the local P2P market. This price provides incentives to participants to modify their consumption to reduce their energy costs, taking advantage of periods of higher renewable generation in the community and thus with a lower internal energy price. Besides, this price allows to allocate the benefits obtained by the community among its participants.

Considering the 3 different types of pricing mechanisms based on price computation presented above, in [29] the performance of each of them is evaluated. They define a performance index to evaluate the potential of each mechanism. This potential is measured according to the ability to incentivize participants to modify their consumption and how benefits are distributed. From the analysis of a case study, the following conclusions are derived [29]:

- The performance index is very low for the BS mechanism. This mechanism only averages the electricity bill of all the participants, so the incentives for demand response are low.
- The performance index is higher for the MMR and SDR mechanisms. These mechanisms provide a more dynamic internal price, that depends on the energy availability in the community, and thus provide better incentives for demand response.

- The performance of these mechanisms is different if we consider a flat or a variable rate for grid prices. A flat rate considers grid prices to be constant throughout the day, while a variable rate considers different price segments. With a flat rate, MMR and SDR perform similarly whereas with a variable rate, the SDR outperforms the MMR.

In the end, MMR and SDR perform better than BS, with SDR performing slightly better than MMR.

2.3.2 Approach 2. Game Theory

Introduction

Game theory is a mathematical tool for simulating how people with conflict interests interact with each other, in which each participant's gain or losses are compensated by those of the other participants. It allows analyzing the strategies of the game players when each players' outcome depends on all players' decisions [17]. The proposed models allow participants to address their energy objectives: maximize the profit of those participants that are generating or minimize the cost of those that are consuming, maintaining a constant balance between generation and demand [30].

Types

Game theory can be divided into two main groups: cooperative game theory and non-cooperative game theory.

<u>Cooperative Game Theory</u>

Prosumers and consumers are considered as a unit, and the decisions of the participants are oriented to maximize the benefit of the community. A series of incentives should be given to keep participants in the group. The benefit of the community is shared among the participants according to different distribution techniques. Some examples of models using cooperative game theory are found in [14], [15], [18] or [31]. The authors in [14] explain that a local P2P energy market could be modeled using a cooperative game because to make local energy-trading possible, a group of prosumers need to cooperate and be willing to sell their surplus energy on the market. The authors in [15] formulate a local P2P energy market through a cooperative game where the community benefit is distributed among the participants according to their contribution. An energy price for the local market is obtained according to the Shapley value (measures the contribution of each participant to the local market).

Non-Cooperative Game Theory

Participants interact with each other trying to maximize their own benefit. The result does not have to be optimal for the community. These models are based on finding the optimal decision that makes none of the participants want to change their strategy since they would lose. This decision is called the Nash equilibrium. Some examples of models in the literature that use non-cooperative game theory are [20] and [30]. In particular, the authors in [20] compare the results between a cooperative and a non-cooperative game. On the one hand, they study a centralized model that tries to maximize social welfare. On the other hand, a P2P model is studied where each participant tries to maximize his benefit.

Implementation Example

An example of the application of this second approach based on article [20] is shown below. The main characteristics are:

- The market clearing is a *pool* type with bilateral results. There is not a single internal price, and the bilateral prices of each transaction are dual variables resulting from the optimization problem.
- There is *not* a *common* internal energy price for the community. Participants trade their energy at different prices in the local P2P market.
- It is *not* assumed that *all* the energy generated by prosumers is exchanged in the P2P market before being exchanged with the grid. There could be a situation where two participants do not reach an agreement and exchange their energy with the grid instead of between them.

Table 2.2 shows the prices considered in this second approach.

Inputs	PB_h	Price of energy bought from the grid (from trader) [€/kWh]
	PS_h	Price of energy sold to the grid (feed-in-tariff) [€/kWh]
	$\beta_{n,m}$	Bilateral trading coefficient imposed by participant *n* to *m* [€/kWh]
Output	$ps_{n,m,h}$	Bilateral trading price between participants *n* and *m* in the P2P local market [€/kWh]

Table 2.2. Prices considered in approach 2

To assign a cost to the local transactions, the P2P market model in [20] consider that its participants have preferences to exchange their energy with each other, depending on different factors such as distance or emissions. These preferences are expressed by a bilateral trading coefficient $\beta_{n,m}$ which represents participant *n* desire to exchange energy with participant *m*. The higher $\beta_{n,m}$ is, the less interesting it is for *n* to buy energy from *m* but the most interesting it is for *n* to sell energy to *m*.

From this parameter it can be calculated the energy trading cost of each participant. Being $e_{m,n,h}$ the energy bought by participant *n* from participant *m* in the local market, then $\beta_{n,m} \cdot e_{m,n,h}$ represents the cost of participant n for buying energy in the local market ($\beta_{n,m} \cdot e_{m,n,h} > 0$). And being $e_{n,m,h}$ the energy sold by participant *n* to participant *m* in the local market, then $\beta_{n,m} \cdot e_{n,m,h}$ represents the earnings for selling energy in the local market ($\beta_{n,m} \cdot e_{n,m,h} < 0$). Thus, the energy trading cost of participant *n* is:

$$\tilde{C}_n(e_n) = \sum_{\substack{h \\ m \neq n}} \beta_{n,m} \cdot (e_{m,n,h} - e_{n,m,h}) \tag{2.16}$$

Considering this cost, in [20], the authors formulate and compare both a cooperative and non-cooperative game problem with product differentiation to model a P2P local market with storage capabilities, demand response and grid restrictions. The objective function for the non-cooperative game is presented in equation (2.17). If $U_n(d_n)$ is the final demand (considering batteries and its response), the objective function for each individual participant *n* is as follows:

$$\max \Pi_n(d_n, e_n) = U_n(d_n) - \widetilde{C_n}(\boldsymbol{e_n}) \quad \forall\, n \tag{2.17}$$

And subject to (2.1), (2.2), (2.3) and (2.4), being the dual variable associated to equation (2.4) the bilateral trading price between two participants in a local P2P market ($ps_{n,m,h}$).

In [32], the authors formulate a multi-bilateral economic dispatch problem with product differentiation to model a P2P market. Although it is not a game theory problem, they assign a cost to local exchanges also using product differentiation.

Conclusion

This second approach of game theory, in particular the implementation example modeling a bilateral P2P market, results in different internal prices, for each delivery time, for each pair of participants. These differences come from product differentiation, allowing participants to express their preferences to exchange energy with each other through bilateral trading coefficients $\beta_{n,m}$.

The initial problem of modeling a P2P energy market tries to be solved through product differentiation. Since all the energy comes from RES, its variable cost is theoretically zero, being impossible to solve the optimization problem using the traditional method of Nash equilibrium. Therefore, by adding the bilateral trading coefficients $\beta_{n,m}$. it appears a cost associated to the local energy exchanges that can be minimized. As a consequence, the results strongly depend on the values assigned to these coefficients.

2.3.3 Approach 3. Agent-Based Models

Introduction

Agent-based models simulate different agents which interact, negotiate, and cooperate to achieve their objectives, and then, these models try to assess the effects of their decisions on the system as a whole [27]. In these models, each agent solves its own optimization problem to maximize its individual benefit to determine its bidding strategy. From the bidding strategies of all the agents, an internal energy price can be determined.

Implementation Example

An example of the application of this third approach based on article [27] is shown below. The main characteristics of this approach are:

- The market clearing is a *pool* type. Depending on the pricing mechanism selected, there are two possibilities. On the one hand, participants submit buying and selling bids of their demand and generation respectively, but not about their buying or selling prices. The internal price is calculated according to some rules previously agreed upon in the community (like BS, MMR or SDR). On the other hand, participants submit buying and selling bids of their demand and generation respectively, as well as about their buying or selling prices.
- A *common* internal energy price is established for the community, so all participants trade their energy at the same price in the local P2P market.
- It requires the existence of an *energy coordinator* in the local P2P market.

Table 2.3 shows the prices considered in this third approach. Note that the price bid is put into brackets to show its optional, depending on the pricing mechanism selected.

Inputs	PB_h	Price of energy bought from the grid (from trader) [€/kWh]
	PS_h	Price of energy sold to the grid (feed-in-tariff) [€/kWh]
Outputs	$\boldsymbol{ps_h}$	Internal price of energy in the P2P local market [€/kWh]
	$\boldsymbol{pb_h}$	Weighted average price of energy purchases [€/kWh]
	$\boldsymbol{ebid_{n,h}}$	Energy bid [kWh]
	$\boldsymbol{[pbid_{n,h}]}$	Price bid [€/kWh]

Table 2.3. Prices considered in approach 3

In [27], the authors present a multiagent-based model for a local P2P market with the possibility of demand response and battery storage capabilities. In this article, the authors describe a multiagent-based simulation framework that includes three types of agents:

- **Prosumer Agents.** Participants in the P2P market with energy demand and PV generation capacities. They have to decide how to schedule their consumption and produce the energy bids.

- **Coordinator Agent.** A representative of the community who trades with the retailer and manages the prosumers' bids. It has to determine the internal energy price based on the energy bids and maintain the energy balance in the community through the grid.
- **Retailer Agent.** The trading company. It acts as a passive agent as it only gives the buying and selling energy prices to the grid, which are not considered dynamic.

Figure 2.4 presents an overview of this framework: the three types of agents, the interaction among them, and their corresponding models.

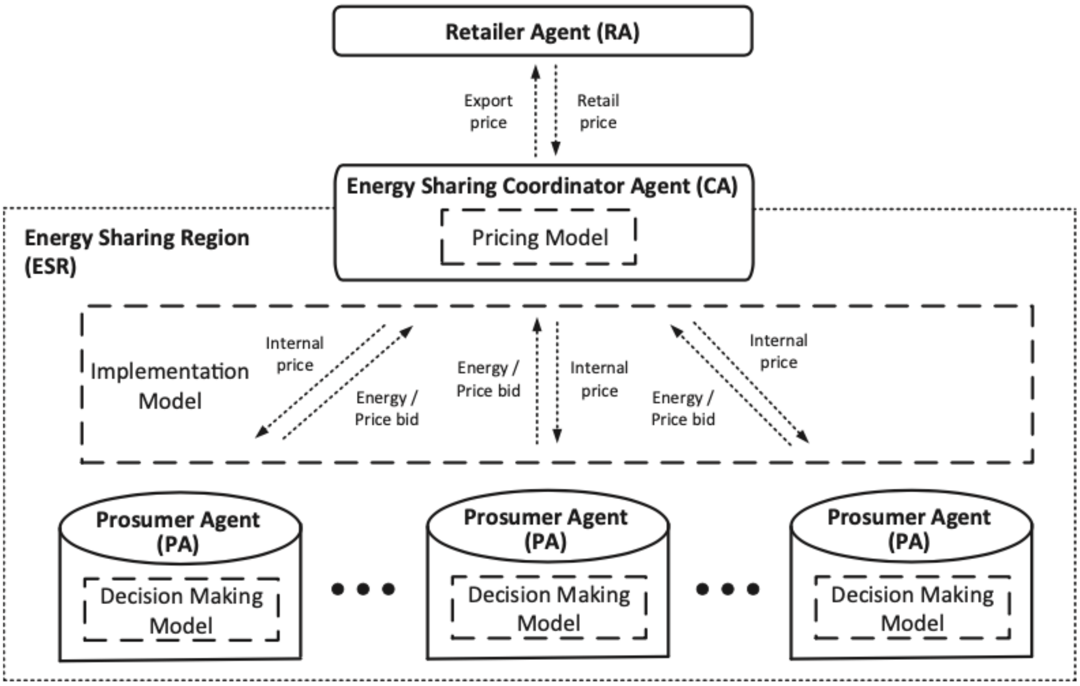


Figure 2.4. Overview of the multiagent-based simulation framework [27]

The agent-based P2P market model is solved using two algorithms. First, a decision-making algorithm is solved in which each agent individually solves its optimization problem and provides its energy bids based on the energy prices. In this article, price bids are not considered. Second, the coordinator agent solves the pricing algorithm to obtain the energy price in the local market from the energy bids of each agent. Both algorithms are described below.

Decision-making model

The decision-making model is the process by which prosumers modify their demand to minimize their energy cost.

The inputs of the model are the internal energy trading price and the weighted average internal buying price in the local P2P market. In the initial bid, these prices are the buying and selling prices to the grid. Other inputs are the energy demand, the renewable energy generation, and the set of electrical devices of the participant.

$$ps_h^{k=0} = PS_h \tag{2.18a}$$

$$pb_h^{k=0} = PB_h \tag{2.18b}$$

From these inputs an optimization problem is formulated. The objective function is the minimization of the prosumer's energy cost considering that the demand for some of his electronic devices may vary. Prosumers can change their scheduled consumption depending on the internal trading price, to take advantage of lower prices in the P2P market. Finally, each prosumer shares its energy bid with the coordinator. If the energy bid is positive, the prosumer is a buyer, and if it is negative, the prosumer is a seller.

This process is described in Figure 2.5 and it is implemented by all the participants individually.

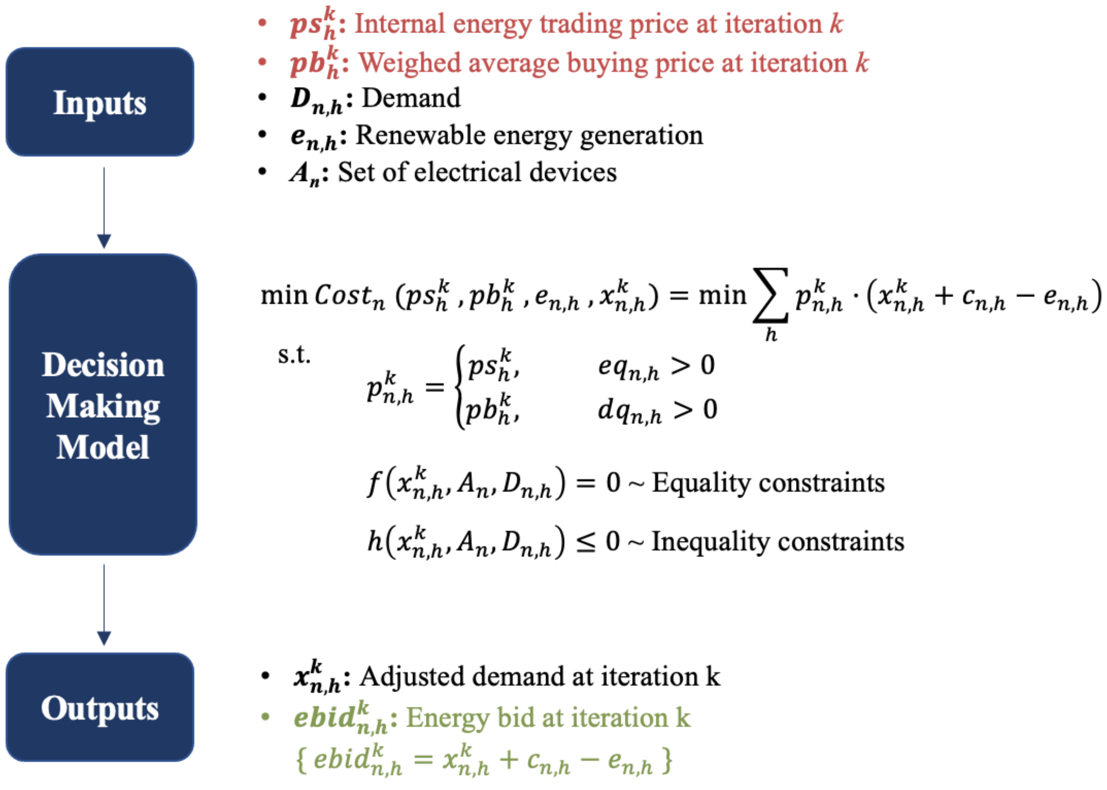


Figure 2.5. Overview of a prosumer's decision-making model [27]

<u>Pricing model</u>

The pricing model is the process by which the coordinator allocates all the prosumers' bids and determines the internal energy price.

The inputs of the model are the buying and selling energy prices from the grid as well as the energy bid of each prosumer. From these inputs, the method to allocate the bids and determine the internal energy price used in the article [27] is price computation. The three types of BS, MMR and SDR pricing mechanism are described and compared. Here, we will focus on the SDR mechanism. First, the SDR is calculated from the energy bids and then, the internal energy price is determined from equation (2.11). Finally, the coordinator shares the resulting internal energy price with the prosumers and the energy exchange with the retailer.

This process is described in Figure 2.6 and it is only implemented by the coordinator.

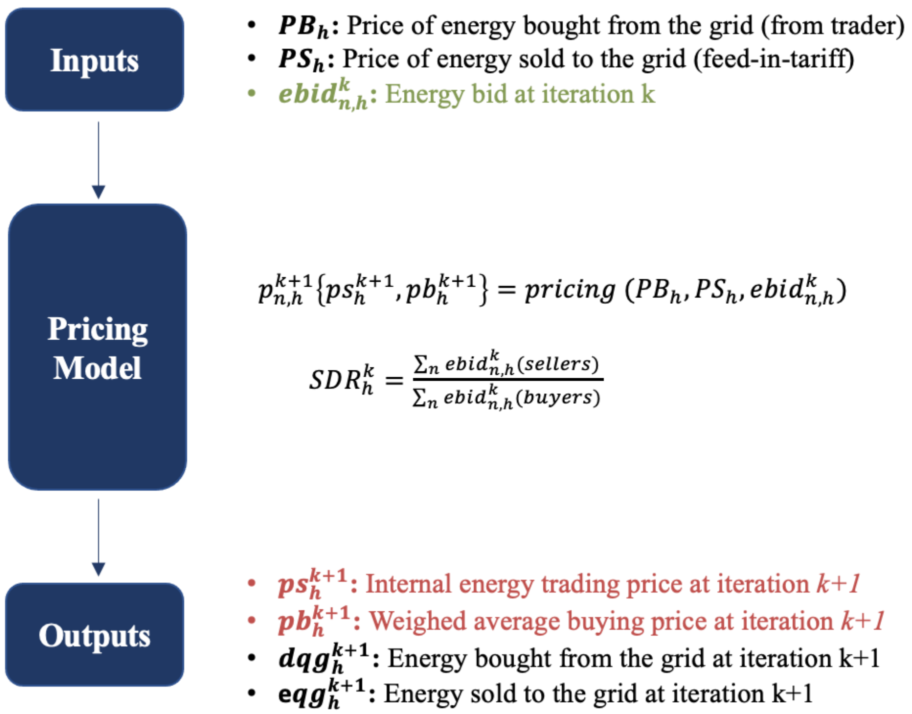


Figure 2.6. Overview of the coordinator's pricing model [27]

Another possibility to determine the internal energy price, considering both energy and price bids, is presented in [28], where the authors formulates matching algorithm.

<u>Implementation</u>

These two models are implemented iteratively until energy bids and the internal energy price converge. To guarantee the convergence of this process, the authors in [27] apply two techniques (step length control and learning process involvement) and a last-defense mechanism in case it is not achieved.

Conclusion

This third approach simulates the behavior of a group of prosumers and consumers trying to reach an agreement on the energy selling while maximizing their own benefit. In the implementation example studied, the result is a single price for energy in the local P2P market obtained after several iterations from energy bids. The internal price is calculated similarly to the approach 1. The difference between both is the way the model is resolved.

The main problem with this approach is that sometimes it is necessary to add more constraints to ensure that the problem converges. Moreover, it is not always possible to reach a Nash equilibrium, the point at which each agent would lose out if he changed his strategy.

2.4 Classification

Table 2.4 classifies the articles previously analyzed based on their considerations and model approach considered.

DESIGN			CONSIDERATIONS					MATHEMATICAL MODEL	
Reference	**Market clearing**	**Renewable Generation Resources**	**Exchange with the grid**	**Grid constraints**	**Storage**	**Demand response**	**Other**	**Objetive Function**	**Internal P2P Market Price Calculation**
[14]	Pool	Solar PV	✓	✕	✕	✕	-	Maximize the benefit of the coalition	MMR
[15]	Pool	Solar PV & Wind	✓	✕	✓	✕	The batteries are EV	Maximize the benefit of the coalition	Shapley value
[18]	Pool	Solar PV	✓	✕	✓	✕	-	Maximize the individual income of participants	Shapley value
[19]	Pool	Solar PV	✓	✕	✓	✕	Interaction between the day-ahead and intraday markets	Minimize costs of electricity for the community (split into the day-ahead and intradat market objectives)	Electricity grid consumption prices minus the transmission networks charges
[20]	Bilateral	Solar PV	✓	✓	✓	✓	-	Maximize individual utility function of participants	Dual variable (product differentiation)
[21]	Pool	Solar PV	✓	✕	✓	✕	Individual vs Centralized battery storage	Minimize the cost for grid consumption	Electricity grid consumption prices minus grid usage costs
[22]	Pool	Solar PV	✓	✕	✓	✕	-	Minimize the total energy cost of the community	SDR compensated
[24]	Pool	Solar PV	✓	✓	✓	✓	-	Minimize individual energy cost	Multi-agent (Matching bids algorithm)
[25]	Pool	Solar PV	✓	✕	✕	✓	-	Minimize individual energy cost	SDR
[26]	Pool	Solar PV	✓	✕	✓	✓	-	Maximize social welfare of buyers and sellers	Multi-agent (SDR)
[27]	Pool	Solar PV	✓	✕	✓	✓	-	Minimize individual energy cost	Multi-agent (BS, MMR and SDR)
[28]	Pool	Solar PV	✓	✕	✕	✕	-	N/A	BS, MMR and Matching bids algorithm
[29]	Pool	Solar PV	✓	✕	✕	✕	-	N/A	BS, MMR and SDR
[30]	Pool	Solar PV & Wind	✓	✕	✕	✕	-	Minimize the energy bill of consumers	Algorithm
[32]	Bilateral	Solar PV	✓	✕	✕	✕	-	Maximize the social welfare of the community of agents	Dual variable (product differentiation)

Table 2.4. Classification of different articles based on their considerations, approach, and pricing model

Chapter 3. Proposed Model for Local P2P Markets

This chapter describes the proposed mathematical model for a local P2P market. The first section presents the hypothesis considered for the model. The second and third sections present its objective function and constraints respectively. Finally, the last sections summarize the resulting linearized model and the resolution method.

3.1 Hypothesis

The proposed model represents a P2P local market where its participants can trade energy among each other and with the grid, to maintain the energy balance within the community. It is based on the SDR but, in addition, it computes the optimal PV and battery capacity to be installed by each participant, as well as their contracted power, to minimize their individual energy cost.

The hypotheses considered in this model are:

- The formulation is based on a **static approach** [33]. This means that all the investment in PV panels and batteries is made in the first year.
- All the energy generated by prosumers in the community comes from **RES** (PV).
- Participants in the P2P local market can install **storage equipment** (batteries). Standard discrete battery dimensions are not considered to avoid integer variables and increase computational efficiency.
- The **energy prices from the grid** are the same for all the participants in the P2P local market, in the same way as the articles analyzed in Table 2.4.
- The **internal energy price** in the P2P local market is calculated through the SDR pricing mechanism without compensation, to avoid the randomness of estimating the $\beta_{n,m}$ coefficients in the game theory approach.
- **Technical grid constraints** are not considered as the aim of this thesis is to analyze the economic behavior of the P2P market.

- The **demand** is **inelastic** for all participants, although they all can have flexibility coming from their battery

3.2 Objective Function

The objective function consists in the minimization of the energy cost for every participant.

$$\begin{aligned} C(n) = TP \cdot qc_n + \sum_t IC_{t,n} \cdot iq_{t,n} + \sum_h ps_h \cdot \left(dql_{n,h} - eql_{n,h}\right) \\ + \sum_h PB_h \cdot dqg_{n,h} - \sum_h PS_h \cdot eqg_{n,h} \quad \forall\, n \end{aligned} \tag{3.1}$$

The energy cost of a participant *n* consists of 3 terms:

- $TP \cdot qc_n$ is the term due to the contracted power tariff.
- $IC_{t,n} \cdot iq_{t,n}$ is the investment cost due to the installed capacity in PV and batteries.
- $ps_h \cdot \left(dql_{n,h} - eql_{n,h}\right)$ is the variable term due to the energy consumed and sold in the P2P market. The internal energy price is calculated according to the SDR pricing mechanism described in 2.3.1. It is the same for all the participants in the energy community for a same delivery time and depends on the energy availability (local generation and demand).
- $PB_h \cdot dqg_{n,h}$ is the variable term due to the energy consumed from the grid, where the grid buying energy price includes the access tariff and the price of the electricity.
- $PS_h \cdot eqg_{n,h}$ is the variable term due to the energy sold to the grid.

The objective function presented in equation (3.1) should be solved for each participant. However, in this project, to simplify, a minimization of the total community's energy cost approach has been selected.

$$\begin{aligned} C = \sum_n TP \cdot qc_n + \sum_{t,n} IC_{t,n} \cdot iq_{t,n} + \sum_h ps_h \cdot (dql_h - eql_h) \\ + \sum_h PB_h \cdot dqg_h - \sum_h PS_h \cdot eqg_h \end{aligned} \tag{3.2}$$

As demonstrated in (2.4), the total energy bought and sold in the local P2P market in the community is the same ($dql_h = eql_h$). Therefore, the third term of the objective function cancels out eliminating the nonlinearity.

3.3 Constraints

The model comprises four groups of restrictions: 1) supply-demand balance equation, 2) installed capacity limitations, 3) storage capabilities, and 4) trade restrictions and P2P market price computation.

3.3.1 Load Balance

The energy demand ($D_{n,h}$) and the energy stored in the battery ($c_{n,h}$) is supplied by the energy bought from the P2P market ($dql_{n,h}$), from the grid ($dqg_{n,h}$) and by the production of the installed technologies (both the PV panel and the battery, $e_{t,n,h}$). Besides, in case there is an excess of energy, it can be sold to the P2P market ($eql_{n,h}$) and to the grid ($eqg_{n,h}$).

$$D_{n,h} + eql_{n,h} + eqg_{n,h} + c_{n,h} = \sum_t e_{t,n,h} + dql_{n,h} + dqg_{n,h} \tag{3.3}$$

The energy exchanged in the P2P market ($dql_{n,h}$ and $eql_{n,h}$) is the sum of the energy exchanged with all the participants as presented in (2.3a) and (2.3b).

The energy bought or sold to the grid is limited by the contracted power (qc_n).

$$dqg_{n,h} \leq qc_n \tag{3.4}$$

$$eqg_{n,h} \leq qc_n \tag{3.5}$$

The energy produced by the PV panels depends on the solar radiation profile ($SR_{n,h}$).

$$e_{"PV",n,h} = SR_{n,h} \cdot q_{"PV",n} \tag{3.6}$$

3.3.2 Installed capacity

The installed capacity of each technology ($q_{t,n}$) is bounded by a maximum threshold ($Q_{t,n}^{max}$) and includes the investment decided before the year of study ($Q_{t,n}$).

$$q_{t,n} = Q_{t,n} + iq_{t,n} \leq Q_{t,n}^{max} \tag{3.7}$$

3.3.3 Batteries

The state of charge of the battery ($soc_{n,h}$) is defined through the classical balance equation that considers the SOC in the previous hour and the charging ($c_{n,h}$) and discharging ($e_{"B",n,h}$) of the battery in the hour.

$$soc_{n,h} = \left(soc_{n,h-1} \cdot I_{h>1} + SOC_{n,0} \cdot I_{h=1}\right) - \frac{e_{"B",n,h}}{\eta d_n} + c_{n,h} \cdot \eta c_n \tag{3.8}$$

The SOC of the battery is limited by a maximum threshold ($soc_{n,h}^{max}$) which depends on the charging hours of the battery (CH).

$$soc_{n,h}^{max} = CH \cdot q_{"B",n} \tag{3.9}$$

$$soc_{n,h} \leq soc_{n,h}^{max} \tag{3.10}$$

The energy charging ($c_{n,h}$) and discharging ($e_{"B",n,h}$) of the battery in the hour is limited by the installed capacity.

$$c_{n,h} \leq q_{"B",n} \tag{3.11}$$

$$e_{"B",n,h} \leq q_{"B",n} \tag{3.12}$$

3.3.4 P2P Local Market

The internal energy price in the P2P market is defined using the SDR pricing mechanism as in [22]. Therefore, the energy selling price (ps_h) in the community is defined according to equation (2.11a). This price is calculated hourly, and it is always between the energy buying (PB_h) and selling prices (PS_h) to the grid, to ensure that all the participants benefit from participating in the P2P market.

According to the mathematical reformulation described in
Annex II. Model Reformulation, the price in the local market is defined as follows:

$$(PB_h - PS_h) \cdot ps_h \cdot sdr'_h + PS_h \cdot ps_h = PB_h \cdot PS_h \tag{3.13}$$

$$sdr'_h \leq sdr_h \tag{3.14}$$

$$sdr'_h \leq 1 \tag{3.15}$$

$$sdr_h = \frac{\sum_{t,n} e_{t,n,h}}{\sum_n \left(D_{n,h} + c_{n,h}\right)} \tag{3.16}$$

The nonlinear terms in equations (3.13) and (3.16) are approximated to a linear function using the first-order Taylor series expansion described in

Annex III. Model Linearization.

3.4 Proposed Linearized Model

The resulting lineal model for a P2P local energy market is:

$$\min \sum_n TP \cdot qc_n + \sum_{t,n} IC_{t,n} \cdot iq_{t,n} + \sum_h PB_h \cdot dqg_h - \sum_h PS_h \cdot eqg_h \tag{3.17}$$

s.t.

$$D_{n,h} + eql_{n,h} + eqg_{n,h} + c_{n,h} = \sum_t e_{t,n,h} + dql_{n,h} + dqg_{n,h} \tag{3.18}$$

$$dql_{n,h} = \sum_{m \neq n} e_{m,n,h} \tag{3.19}$$

$$eql_{n,h} = \sum_{m \neq n} e_{n,m,h} \tag{3.20}$$

$$dqg_{n,h} \leq qc_n \tag{3.21}$$

$$eqg_{n,h} \leq qc_n \tag{3.22}$$

$$e_{"PV",n,h} = SR_{n,h} \cdot q_{"PV",n} \tag{3.23}$$

$$q_{t,n} = Q_{t,n} + iq_{t,n} \leq Q_{t,n}^{max} \tag{3.24}$$

$$soc_{n,h} = \left(soc_{n,h-1} \cdot I_{h>1} + SOC_{n,0} \cdot I_{h=1}\right) - \frac{e_{"B",n,h}}{\eta d_n} - c_{n,h} \cdot \eta c_n \tag{3.25}$$

$$soc_{n,h}^{max} = CH \cdot q_{"B",n} \tag{3.26}$$

$$soc_{n,h} \leq soc_{n,h}^{max} \tag{3.27}$$

$$c_{n,h} \leq q_{"B",n} \tag{3.28}$$

$$e_{"B",n,h} \leq q_{"B",n} \tag{3.29}$$

$$(PB_h - PS_h) \cdot com\_price_h + PS_h \cdot ps_h = PB_h \cdot PS_h \tag{3.30}$$

$$sdr'_h \leq sdr_h \tag{3.31}$$

$$sdr'_h \leq 1 \tag{3.32}$$

$$sdr_h = sdr\_tay_h \tag{3.33}$$

The linearized functions with the first-order Taylor series expansion are:

$$com\_price_h = ps_h \cdot sdr'_h \tag{3.34}$$

$$com\_price_h \approx PS\_AP_h^k \cdot SDR'\_AP_h^k + SDR'\_AP_h^k \cdot (ps_h - PS\_AP_h^k) + PS\_AP_h^k \cdot (sdr'_h - SDR'\_AP_h^k)$$

$$sdr\_tay_h = \frac{e_h}{D_h + c_h}$$

$$sdr\_tay_h \approx \frac{E\_AP_h^k}{D_h + C\_AP_h^k} + \frac{1}{D_h + C\_AP_h^k} \cdot (e_h - E\_AP_h^k) - \frac{E\_AP_h^k}{(D_h + C\_AP_h^k)^2} \cdot (c_h - C\_AP_h^k) \tag{3.35}$$

3.5 Resolution Method

The proposed linearized model will be solved using mixed-integer programming in GAMS. Since the nonlinear functions of the model are approximated to a linear function using the first-order Taylor series expansion, the problem needs to be iterated several times until the initial values adopted in the Taylor approximation converge. Table 3.1 describes the iterative algorithm to solve the proposed model.

Algorithm
Step 1 Initialize $PS\_AP_h^k, SDR'\_AP_h^k, E\_AP_h^k$ and $C\_AP_h^k$. The initial values adopted consider that there is no energy generation in the community and therefore, all the energy demand is bought from the grid. ***Step 2*** Solve the optimization problem. ***Step 3*** Determine the values of $PS\_AP_h^{k+1}, SDR'\_AP_h^{k+1}, E\_AP_h^{k+1}$ and $C\_AP_h^{k+1}$. These values are the result of the variables ps_h, sdr'_h, e_h and c_h from the optimization problem. ***Step 4*** Calculate the difference between the resulting variables and the values from the previous iteration. For a generic variable: $$VAR\_DIF_h^k = VAR\_AP_h^{k+1} - VAR\_AP_h^k$$ ***Step 5*** Select the maximum difference among all the hours considered in the period studied. For a generic variable:

$$MAX\_VAR\_DIF^k = \max\{VAR\_DIF^k_{h=1}, VAR\_DIF^k_{h=2} \dots\}$$

Step 6

Convergence criterion:

- If the maximum difference < UCONV or k > K → The optimization problem converges, and iteration stops.
- If the maximum difference > UCONV and k < K → The optimization problem has to be solved again (all steps repeat from step 2).

Table 3.1. Iterative algorithm description

Lastly, it is important to note that since the objective function is solved for the community rather than for each participant individually, the local energy exchanges between participants ($dql_{n,h}$ and $eql_{n,h}$) are undetermined. GAMS provides an arbitrary solution for these variables, but to compare results from different case studies, it would be necessary to include a rule for the internal energy sharing between participants. In the case study described in Chapter 4, this problem is explained in more detail.

Chapter 4. Case Study

This chapter presents the results of the application of the proposed model to a fictitious energy community in different situations. The base case presents the results for the community without P2P exchanges. The first case analyzes the results for the community with P2P exchanges, solar PV investments but no storage capabilities, and the second case adds the possibility of installing storage.

4.1 Initial Assumptions

The model is solved for a time horizon of one year, in particular 2019. It optimizes the installed capacity of each technology considered and the contracted power for an energy community with the possibility of exchanging energy in a P2P local market, to minimize its annual energy cost.

Several initial assumptions were considered when solving the model with the aim of obtaining more plausible outcomes.

- The power term of the access tariffs was set as a constant throughout the time horizon.
- The energy term of the access tariffs was set as constant at every hour of the time horizon.
- Negligible distribution losses.
- Consumers are considered price-takers.

The computer used to solve the model is a Lenovo ideapad 710-13ISK with Intel (R) Core (TM) i5-6260U CPU and 8 GB RAM. The computer's operating system is 64-bit, x64-based processor. The models have been coded with GAMS version 34.3.0 released on February 25th, 2021.

4.2 Input Data

The energy community is hypothetically located in the southern of Madrid and consists of 4 participants. The load profile of each participant ($D_{n,h}$) has been determined arbitrarily based on the average Spanish consumption similarly to [34] and [35]. Each participant presents a different consumption profile:

- Participant 1 has a consumption profile equal to the average behavior.
- Participant 2 has a profile delayed one hour with respect to the first one.
- Participant 3 has a profile one hour ahead of the first one.
- Participant 4 has a low consumption profile, half of the first one.

The grid electricity prices have been downloaded from the Spanish system operator, REE [36]. The energy selling price (PS_h) corresponds to the pool market price, and the energy buying price (PB_h) corresponds to this price plus the grid access tariff which has been set to 44.03 €/MWh (from Spanish tariff in 2019 named as tariff 2.0.A). Besides, the fixed tariff for the contracted power (TP) has been set to 38.04 €/kW per year (from Spanish tariff in 2019 named as tariff 2.0.A).

Figure 4.1 presents the average monthly demand and grid electricity prices profiles for the year considered (demand arbitrarily determined based on [34] and prices from [36]).

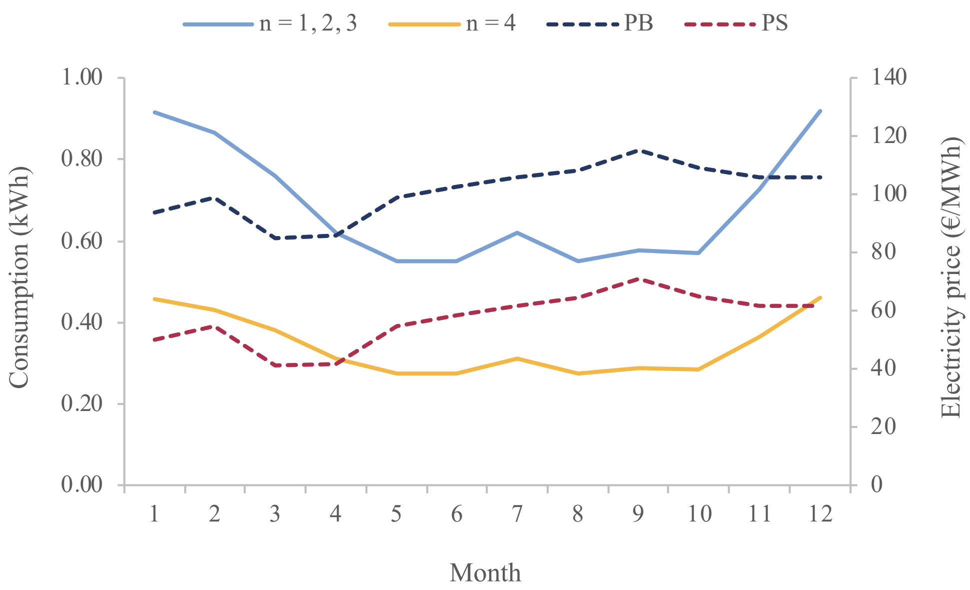


Figure 4.1. Average monthly demand and grid electricity prices profiles

Figure 4.2 and Figure 4.3 presents the weekly demand and grid electricity prices profiles (demand arbitrarily determined based on [35] and the previous hypothesis, and prices from [36]).

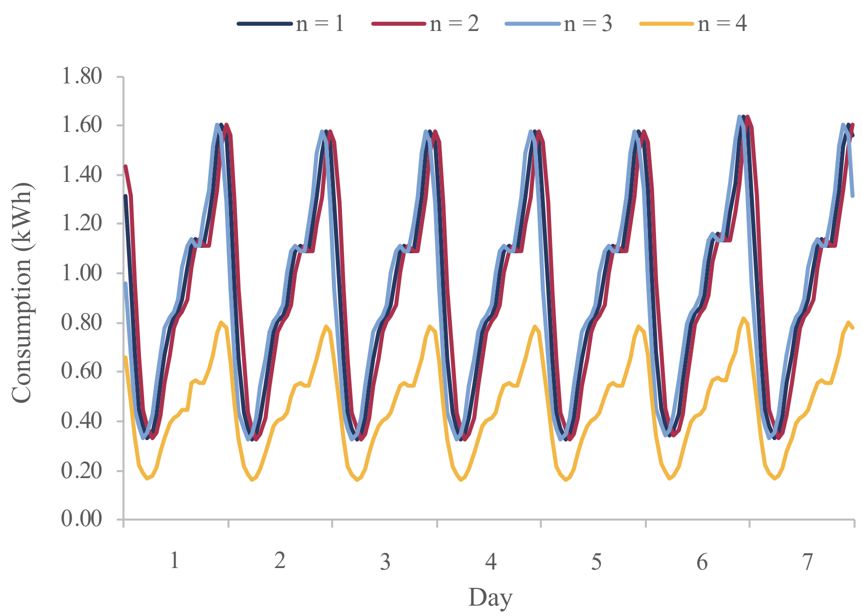


Figure 4.2. Weekly demand profiles

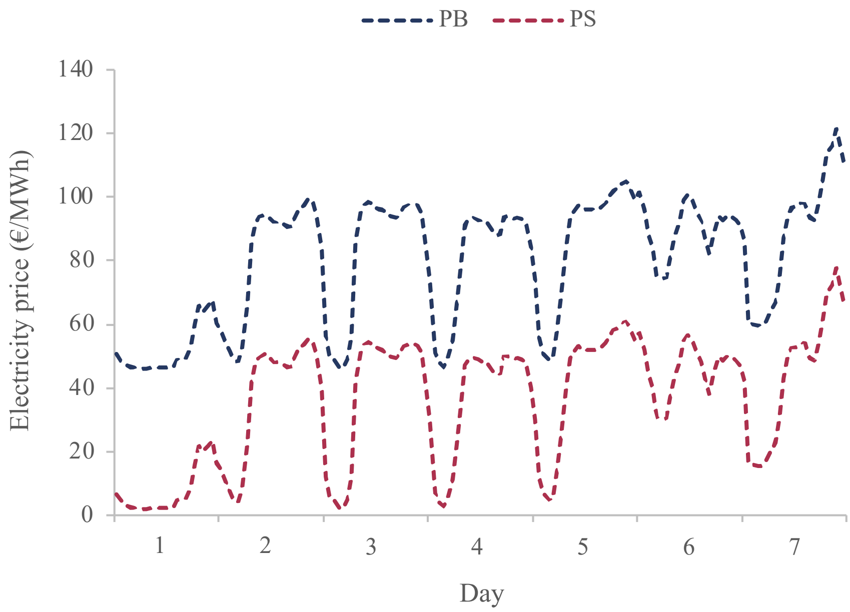


Figure 4.3. Weekly grid electricity prices profiles

No participant has PV panels or batteries installed initially ($Q_{t,n} = 0$). The maximum installed capacity per participant ($Q_{t,n}^{max}$) has been set to 2 kW for PV panels (according to peak demand) and to 1.1 kW for batteries [35]. Participants 1 ,2 and 3 are prosumers who are interested in investing in PV panels and batteries, while participant 4 is a consumer, who does not invest in PV panels nor batteries.

The solar radiation (SR) in Madrid and the technical characteristics of the batteries come from [35], being $\eta c_n = 86\%$, $\eta d_n = 86\%$ and $CH = 4$ hours.

The investment costs of the assets ($IC_{t,n}$) come from [35] and [37], being 2785 €/kW for PV panels and 450 €/kWh for batteries. A lifespan of 20 years has been assumed for PV panels and of 10 years for batteries.

4.3 Results and Analysis

The proposed model is applied for the described energy community in different cases. The aim is to analyze the impact and the results when P2P energy exchanges or storage capabilities are considered. The results analyzed in each case are:

- The installed capacity of each technology and the contracted power by each participant.
- The energy balance, energy prices and SDR for the community and each participant individually, during a day in winter and a day in summer.
- The annual energy cost for the community and each participant.
- The final buying energy price for the community and each participant.

After the description of the results obtained in all cases, Section 4.3.4 then compares all of them and Section 4.3.5 presents a brief analysis of the convergence of the model.

4.3.1 Base Case. Energy Community without P2P

The base case analyzes the results for the energy community without the possibility of investing in PV panels or batteries ($q_{t,n} = 0$) to represent the initial situation, where all participants must satisfy their energy demand with the grid.

Table 4.1 presents the installed capacity and the contracted power by each participant.

	n = 1	n = 2	n = 3	n = 4
PV Installed Capacity (kW)	0.00	0.00	0.00	0.00
BAT Installed Capacity (kW)	0.00	0.00	0.00	0.00
Contracted Power (kW)	1.64	1.64	1.64	0.82

Table 4.1. Installed capacity and contracted power (base case)

Table 4.2 presents the annual energy cost for each participant and for the community. This cost includes the fixed term due to the contracted power, the annualized investment cost, the grid and P2P purchases as well as the benefit from the grid and P2P sell-downs. These costs are obtained from the objective function described in Section 3.2.

	ANNUAL ENERGY COST (€)						
	Fixed Term due to Contracted Power	Investment Cost	Grid Purchase	Grid Sell-down	P2P Purchase	P2P Sell-down	Total
n = 1	62.27	0.00	609.70	0.00	0.00	0.00	671.96
n = 2	62.27	0.00	606.89	0.00	0.00	0.00	669.16
n = 3	62.27	0.00	611.81	0.00	0.00	0.00	674.08
n = 4	31.13	0.00	304.85	0.00	0.00	0.00	335.98
Community	**217.93**	**0.00**	**2133.25**	**0.00**	**0.00**	**0.00**	**2351.18**

Table 4.2. Annual energy cost for the community and each participant (base case)

4.3.2 Case 1. Energy Community with P2P

In this first case, the results are analyzed for an energy community with the possibility of investing in PV panels and exchanging energy in a P2P market.

The model is solved for two cases with different PV investment cost. Case 1.1. Initial PV Investment Cost presents the results with the initial investment cost defined in section 4.2 and Case 1.2. Higher PV Investment Cost by 10% presents the results for the PV investment cost a 10% higher.

According to the proposed model, the objective function minimizes the energy cost for the community and therefore, as explained in Section 3.5 the P2P exchanges among participants are undetermined. To solve this problem, in this case, instead of presenting the arbitrary solution obtained with GAMS, it is assumed that the local exchanges are made proportionally according to the energy surplus or deficit of each participant. The result of the objective function was verified to be the same in both cases. To better illustrate this issue, both results are shown in the individual energy balance during a day in summer (Figure 4.8 vs Figure 4.9).

Case 1.1. Initial PV Investment Cost

The installed capacity and contracted power by each participant are presented in Table 4.3. Each prosumer install the maximum PV capacity allowed since today's PV investment cost is highly competitive

	n = 1	**n = 2**	**n = 3**	**n = 4**
PV Installed Capacity (kW)	2.00	2.00	2.00	0.00
BAT Installed Capacity (kW)	0.00	0.00	0.00	0.00
Contracted Power (kW)	1.64	1.64	1.64	0.82

Table 4.3. Installed capacity and contracted power (case 1.1)

The following figures presents the results of the model for the community and each participant individually during a **day in winter** (January 2nd).

Figure 4.4 represents the energy balance for the community which is almost energy self-sufficient during the day.

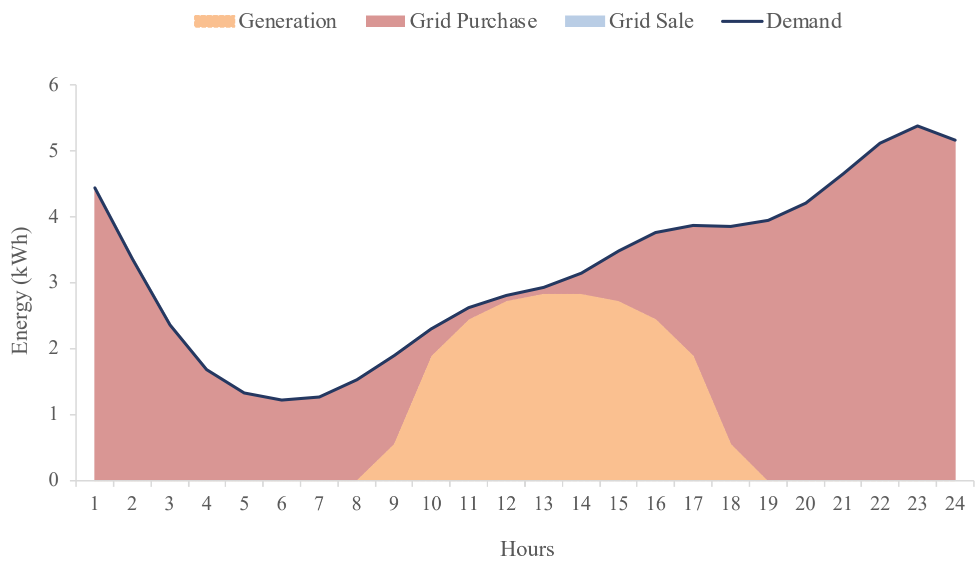


Figure 4.4. Energy balance of the community during a day in winter (case 1.1)

With a same type of graphic, Figure 4.5 represents the energy balance for each participant individually. Participants 1, 2 and 3 (the prosumers) have some surplus energy from their PV panels at midday which they sell to participant 4 in the P2P market instead of to the grid. Participant 4 satisfies its demand with energy from the P2P market and buys the remainder deficit from the grid.

As previously mentioned, it is assumed that the local exchanges are made proportionally according to the energy surplus or deficit of each participant.

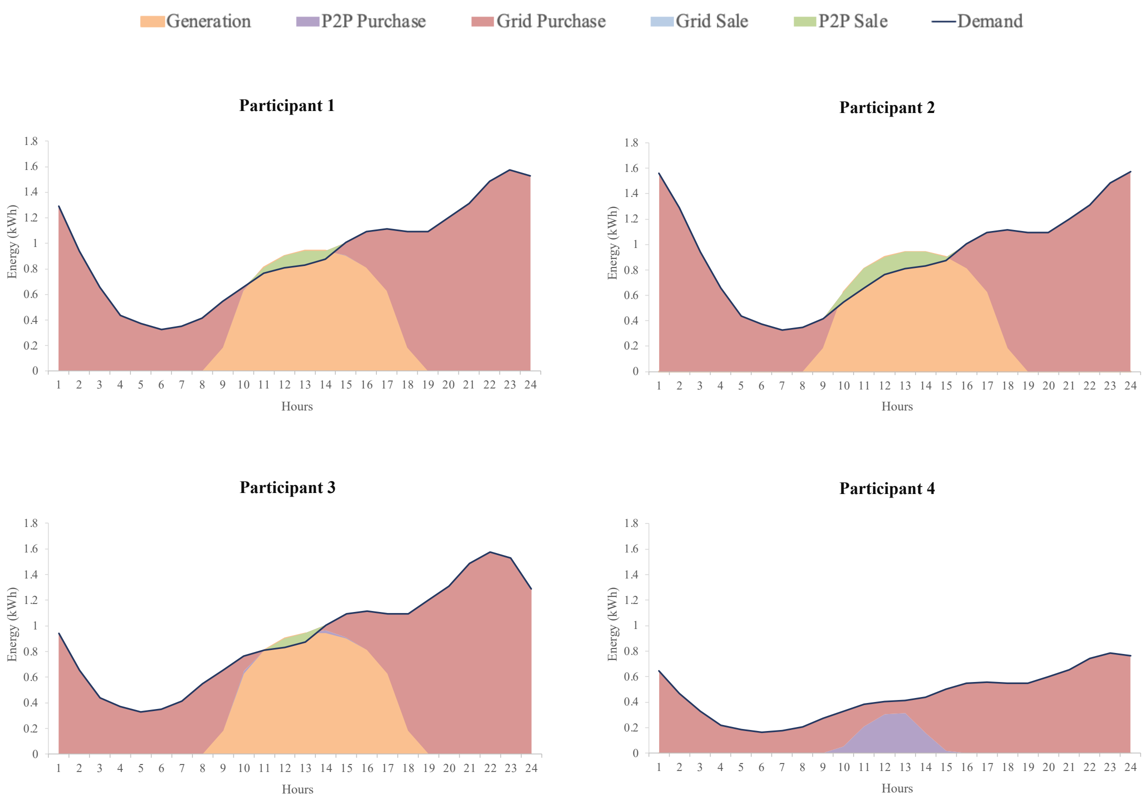


Figure 4.5. Energy balance of each participant during a day in winter (case 1.1)

Figure 4.6 represents the energy prices in the community and the SDR. It shows that at night, when there is no generation in the community, the SDR is equal to 0 and the price in the local market is the same as the energy buying price from the grid. As the energy generation in the community increases, the SDR approaches 1 and the price in the local market decreases approaching its minimum value, the energy selling price to the grid. This happens at noon when solar radiation is maximum. Since the community does not have surplus energy at any time during this day, the SDR always has a value below 1.

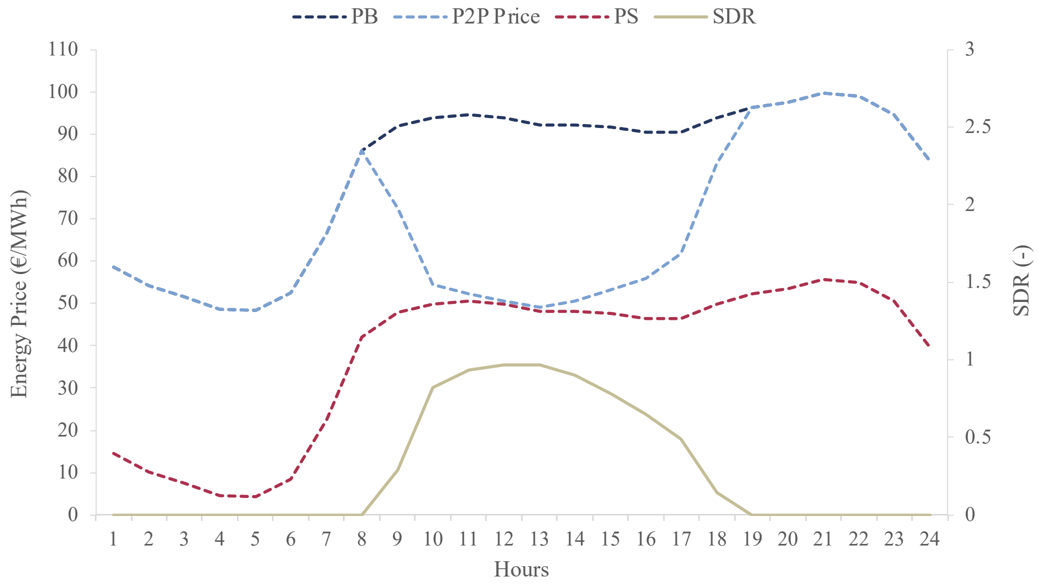


Figure 4.6. Energy prices and SDR during a day in winter (case 1.1)

Below, the same analysis is conducted but during a **day in summer** (July 17th).

Figure 4.7 represents the energy balance for the community. During the summer, the solar radiation profile in Madrid is very high, and therefore there is a lot of surplus energy in the community which is sold to the grid.

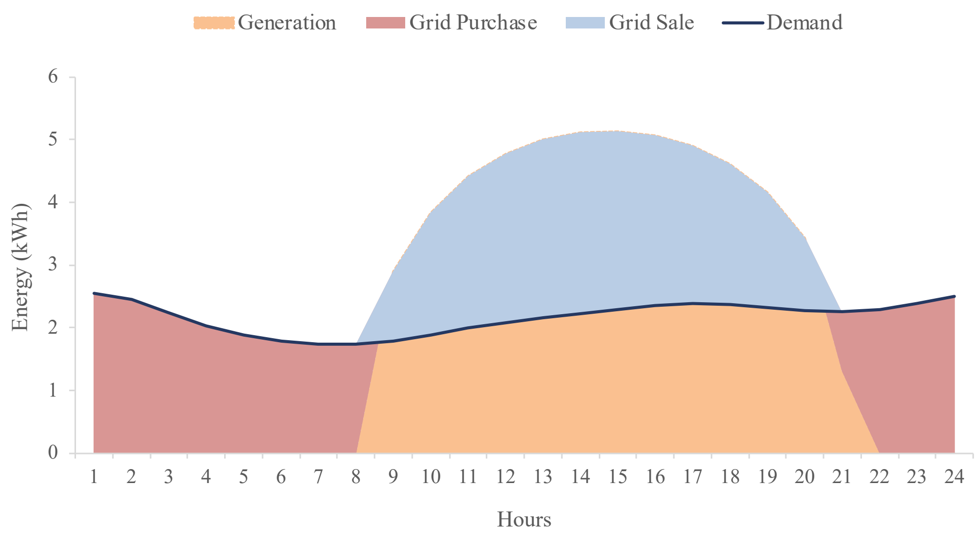


Figure 4.7. Energy balance of the community during a day in summer (case 1.1)

Figure 4.8 represents the energy balance for each participant individually. Prosumers satisfy completely their energy demand during the day with their PV energy generation and have energy surplus. This surplus is sold in the P2P market to participant 4, who does not have PV panels installed, maximizing renewable energy consumption in the community. The rest of surplus energy is sold to the grid.

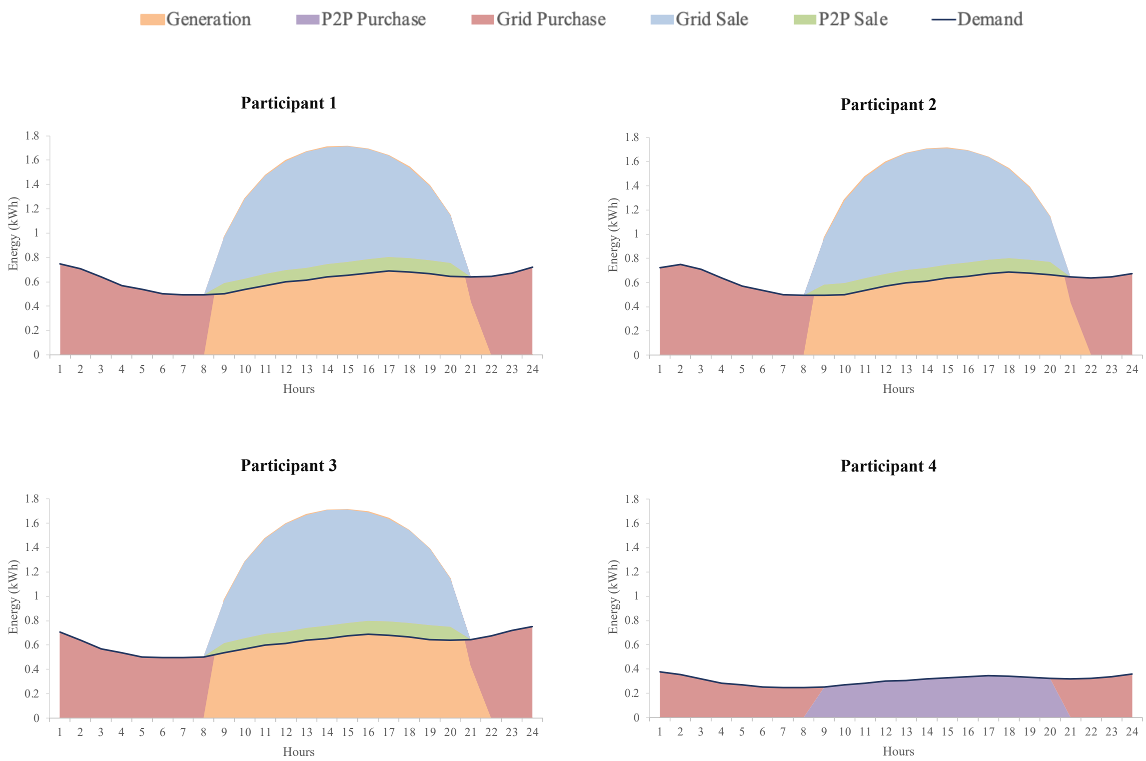


Figure 4.8. Energy balance of each participant during a day in summer (case 1.1)

As previously explained, Figure 4.8 presented the results for internal P2P exchanges proportionally shared among participants. Below, Figure 4.9 presents the results obtained from GAMS.

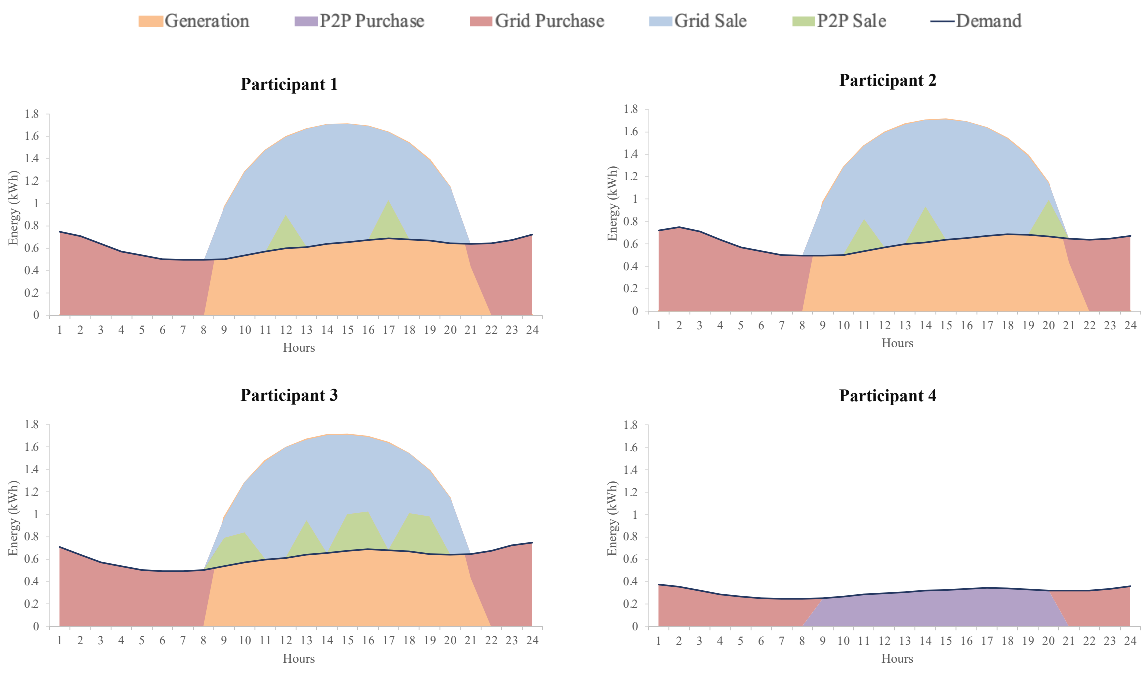


Figure 4.9. Energy balance of each participant during a day in summer (case 1.1, arbitrary solution)

Figure 4.10 represents the energy prices in the community and the SDR. In summer, as there is a lot of energy surplus in the community during the day, the SDR rapidly reaches a value greater than 1 and the local price drops to its minimum value. This incentives participant 4 to buy its energy demand in the local P2P market instead of from the grid.

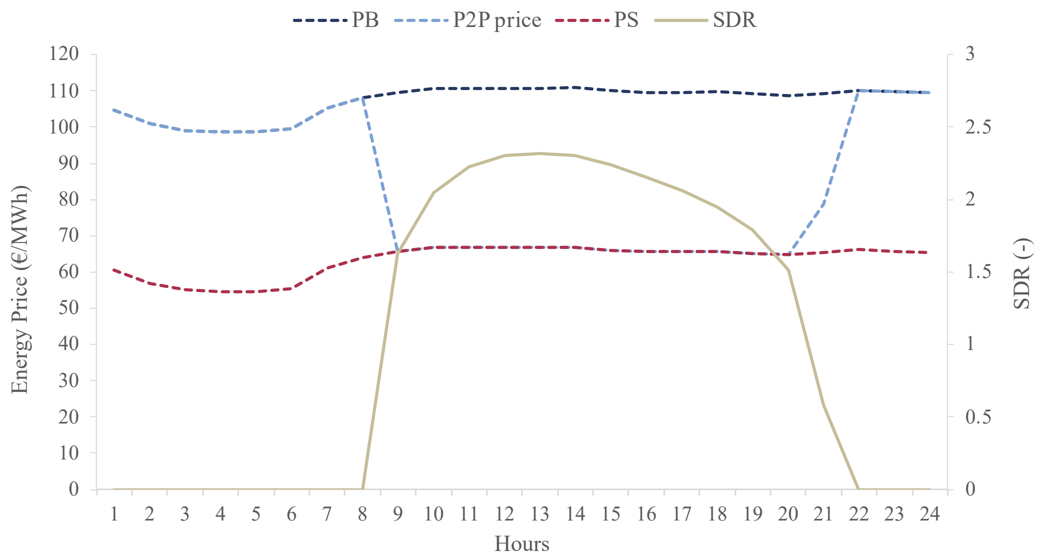


Figure 4.10. Energy prices and SDR during a day in summer (case 1.1)

Finally, Table 4.4 summarizes the annual energy cost for the community and each participant individually. The annual energy cost for the community is reduced by 13% compared to the base case, in which the community does not have PV panels. This reduction is principally due to the avoided energy purchases from the grid and the revenues from the sale of surplus energy from prosumers. At the individual level, all participants have a lower annual energy cost, between 12% and 14% less than in the base case.

	ANNUAL ENERGY COST (€)						
	Fixed Term due to Contracted Power	Investment Cost	Grid Purchase	Grid Sell-down	P2P Purchase	P2P Sell-down	Total
n = 1	62.27	278.42	350.22	-89.36	0.03	-18.77	582.80
n = 2	62.27	278.42	359.06	-93.11	0.00	-21.62	585.01
n = 3	62.27	278.42	342.87	-86.11	0.19	-16.81	580.82
n = 4	31.13	0.00	205.48	0.00	56.98	0.00	293.59
Community	**217.93**	**835.25**	**1257.62**	**-268.58**	**57.20**	**-57.20**	**2042.23**

Table 4.4. Annual energy cost for the community and each participant (case 1.1)

Case 1.2. Higher PV Investment Cost by 10%

The installed PV capacity and contracted power by each participant is presented in Table 4.5. As the PV investment cost has increased, the installed capacity of PV panels is lower.

	n = 1	n = 2	n = 3	n = 4
PV Installed Capacity (kW)	1.65	1.51	1.77	0.00
BAT Installed Capacity (kW)	0.00	0.00	0.00	0.00
Contracted Power (kW)	1.64	1.64	1.64	0.82

Table 4.5. Installed capacity and contracted power (case 1.2)

The following figures presents the results of the model for the community and each participant individually during a **day in winter** (January 2nd).

Figure 4.11 and Figure 4.12 represent the energy balance for the community and each participant individually respectively. As PV installed capacity is lower, the generation in the community is also lower. No prosumer has surplus energy during the day, and they must satisfy part of their energy demand with the grid. Participant 4 must buy all its energy demand from the grid.

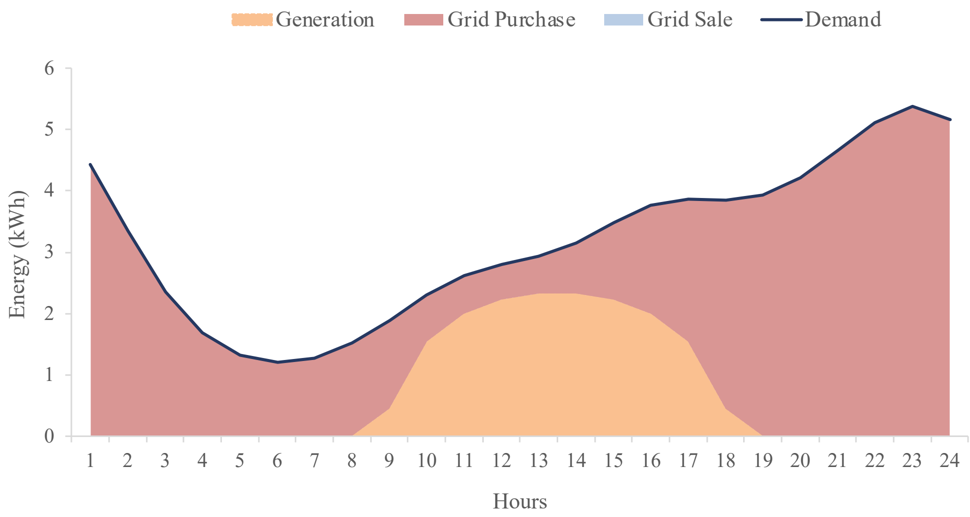


Figure 4.11. Energy balance of the community during a day in winter (case 1.2)

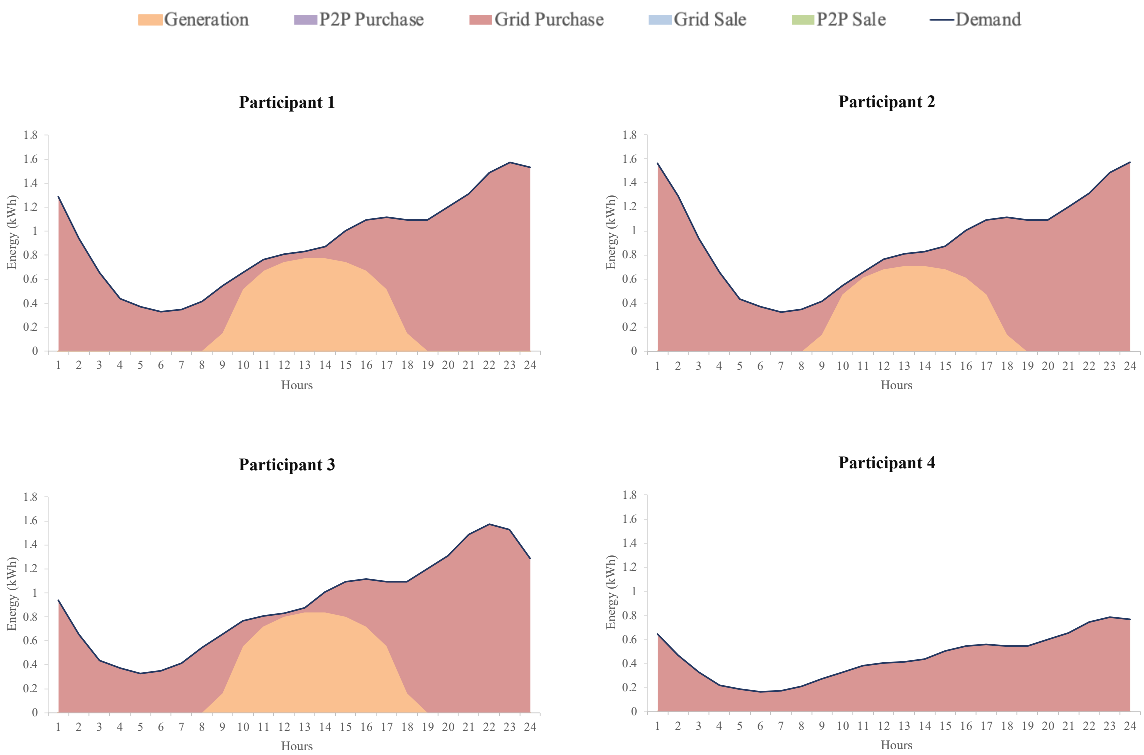


Figure 4.12. Energy balance of each participant during a day in winter (case 1.2)

Figure 4.13 represents the energy prices in the community and the SDR. As there is no energy surplus available in the community, the SDR is always below 1.

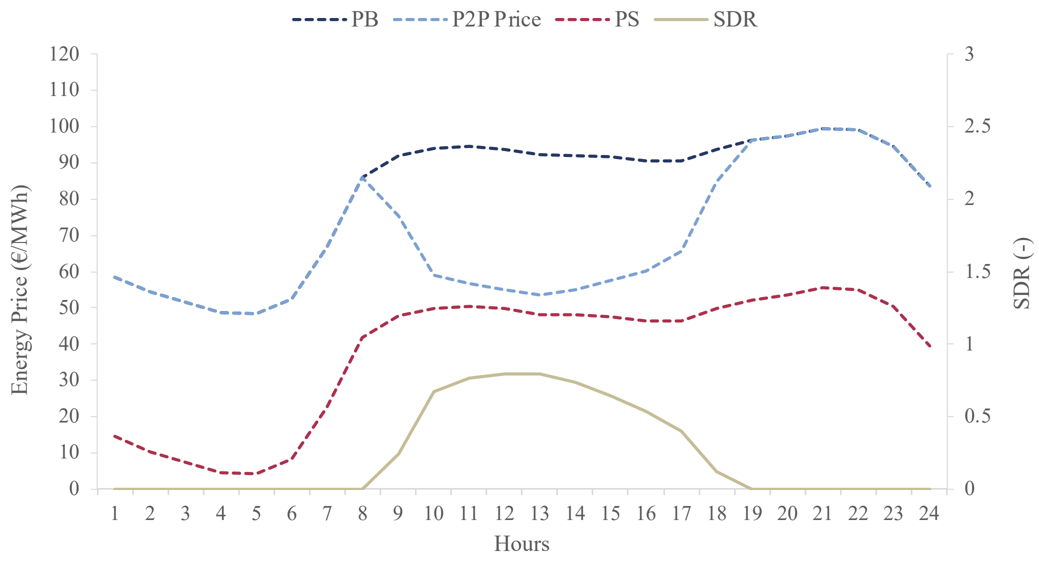


Figure 4.13. Energy prices and SDR during a day in winter (case 1.2)

Below, the same analysis is conducted but during a **day in summer** (July 17th).

Figure 4.14 and Figure 4.15 represent the energy balance for the community and each participant individually respectively. This situation is similar to the one in case 1.1 on a summer day. As the solar radiation in Madrid in summer is very high, the PV generation in the community during the day is very high and there is a lot of surplus energy. Prosumers sell energy to participant 4 and the rest of their surplus is sold to the grid. As there is less installed capacity, the energy surplus and sales to the grid are lower than in case 1.1.

As previously mentioned, the P2P energy exchanges are distributed proportionally among all participants.

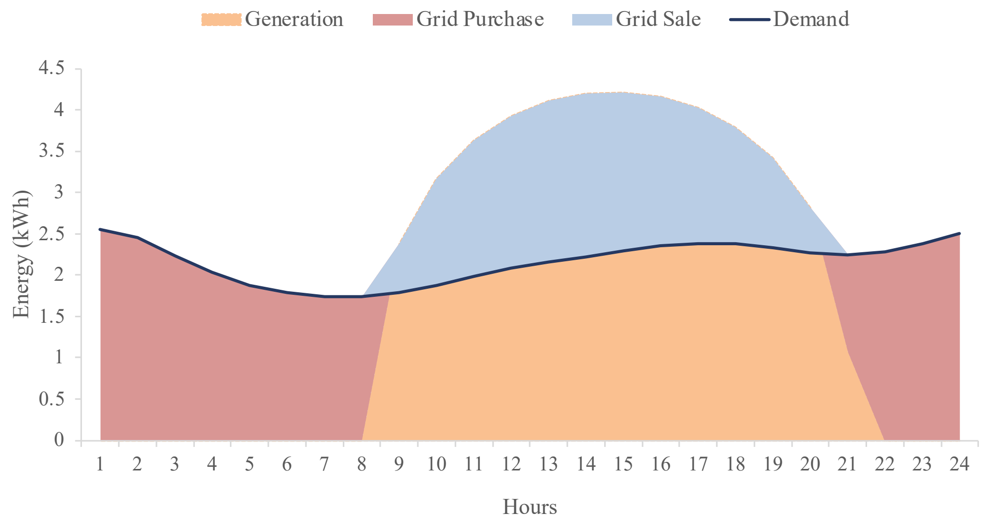


Figure 4.14. Energy balance of the community during a day in summer (case 1.2)

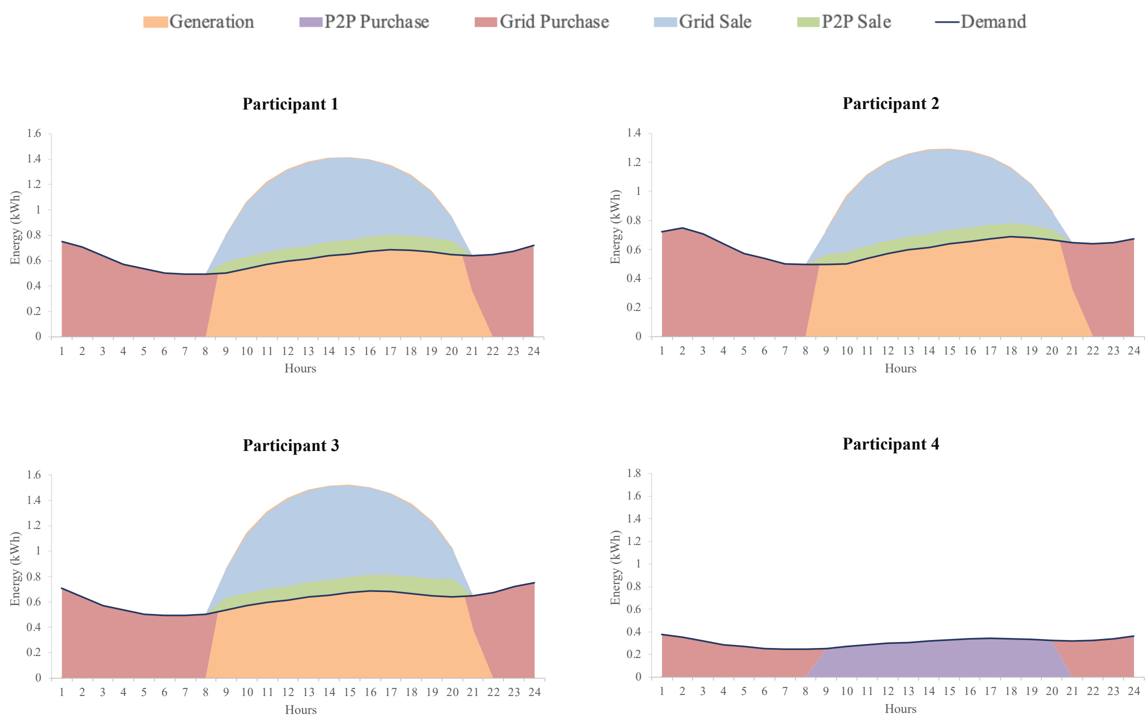


Figure 4.15. Energy balance of each participant during a day in summer (case 1.2)

Figure 4.16 represents the energy prices in the community and the SDR. As there is a lot of energy surplus in the community, the SDR is greater than 1 and the local price takes its minimum value during the day, similarly to case 1.1.

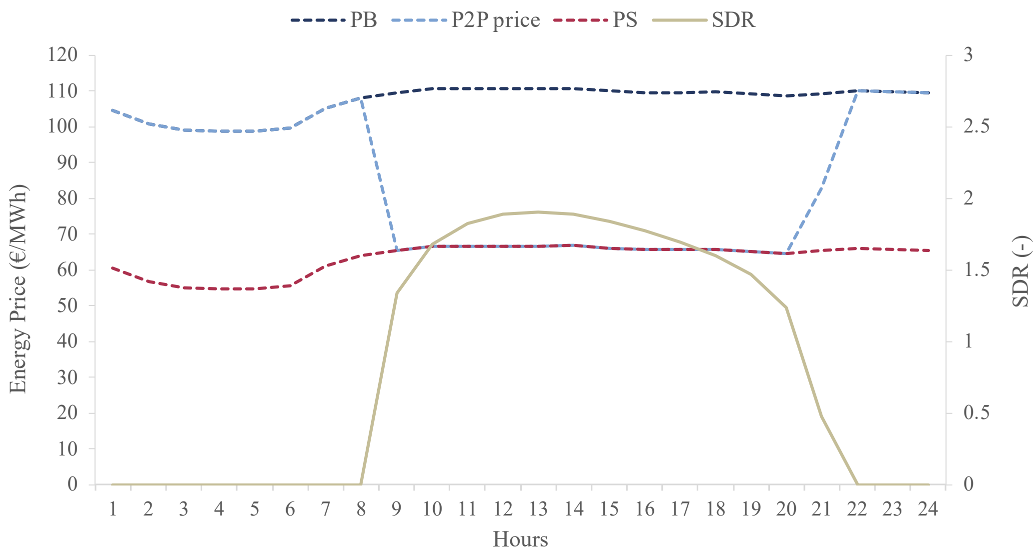


Figure 4.16. Energy prices and SDR during a day in summer (case 1.2)

Finally, Table 4.6 summarizes the annual energy cost for the community and each participant individually. As PV installed capacity is lower than in case 1.1, the annual energy cost for the community is increased by 4% compared to case 1.1. This rise is mainly due to the reduction in revenues from sales to the grid, as there is less generation in the community. At the individual level, the annual energy cost for each participant is also increased by 4% compared to case 1.1, except for participant 4 whose energy cost only increases by 2%, as he still benefits from P2P exchanges. Yet, the annual energy cost is still lower than in the base case, without PV capacity installed.

	ANNUAL ENERGY COST (€)						
	Fixed Term due to Contracted Power	Investment Cost	Grid Purchase	Grid Sell-down	P2P Purchase	P2P Sell-down	Total
n = 1	62.27	252.54	361.84	-53.44	0.00	-16.29	606.91
n = 2	62.27	230.69	374.11	-46.03	0.02	-13.95	607.11
n = 3	62.27	271.58	351.03	-59.98	0.02	-18.42	606.50
n = 4	31.13	0.00	220.41	0.00	48.62	0.00	300.16
Community	**217.93**	**754.81**	**1307.39**	**-159.46**	**48.66**	**-48.66**	**2120.68**

Table 4.6. Annual energy cost for the community and each participant (case 1.2)

4.3.3 Case 2. Energy Community with P2P and Batteries

In this second case, the results are analyzed for an energy community with the possibility of investing in PV panels and batteries and exchanging energy in a P2P market.

The model is solved for two cases with different battery investment cost. Case 2.1. Initial Battery Investment Cost presents the results with the initial investment cost defined in section 4.2 and Case 2.2. Lower Battery Investment Cost by 10% presents the results for the battery investment cost a 10% lower.

In this case, the results only present the arbitrary solution obtained with GAMS due to the increased complexity. It was verified that there is more than one possible solution with the same objective function. Because of this randomness, the individual charging and discharging results of the batteries are also arbitrary.

Case 2.1. Initial Battery Investment Cost

The installed capacity of each technology and the contracted power by each participant is presented in Table 4.7

Each prosumer install the maximum PV capacity allowed since today's PV investment cost is highly competitive, similarly to Case 1.1. Initial PV Investment Cost. The installed capacity of batteries is very small which indicates that the selected batteries investment cost (based on its current value estimation) is starting to be competitive, although it is not yet.

Besides, the contracted power is lower than in the cases studied without batteries. Since batteries reduce the intermittency of solar generation, participants can be more independent from the grid.

	n = 1	n = 2	n = 3	n = 4
PV Installed Capacity (kW)	2.00	2.00	2.00	0.00
BAT Installed Capacity (kW)	0.02	0.00	0.01	0.00
Contracted Power (kW)	1.61	1.61	1.61	0.82

Table 4.7. Installed capacity and contracted power (case 2.1)

The following figures presents the results of the model for the community and each participant individually during a **day in winter** (January 2nd).

Figure 4.17 represents the energy balance for the community, which is almost energy self-sufficient during the day. The charging and discharging of the batteries cannot be appreciated.

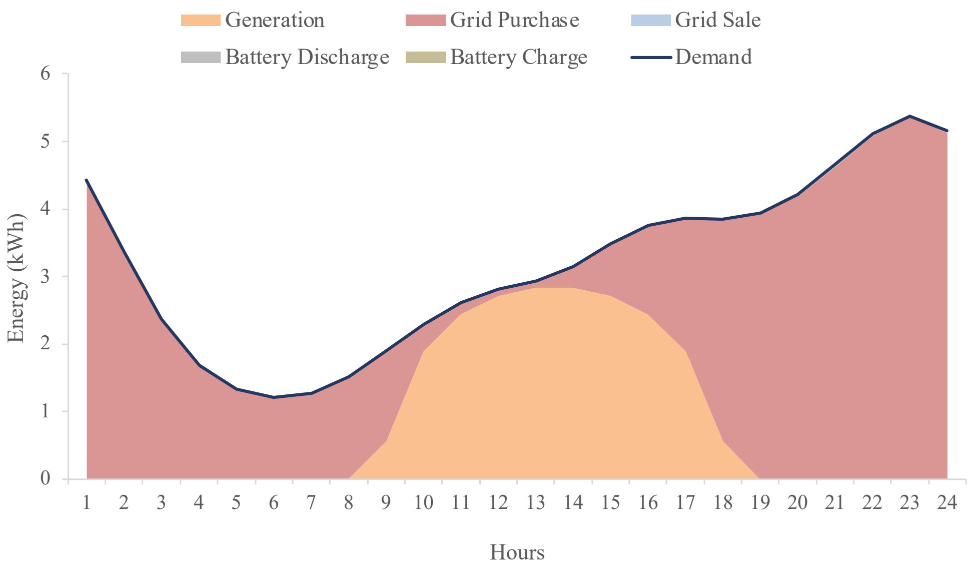
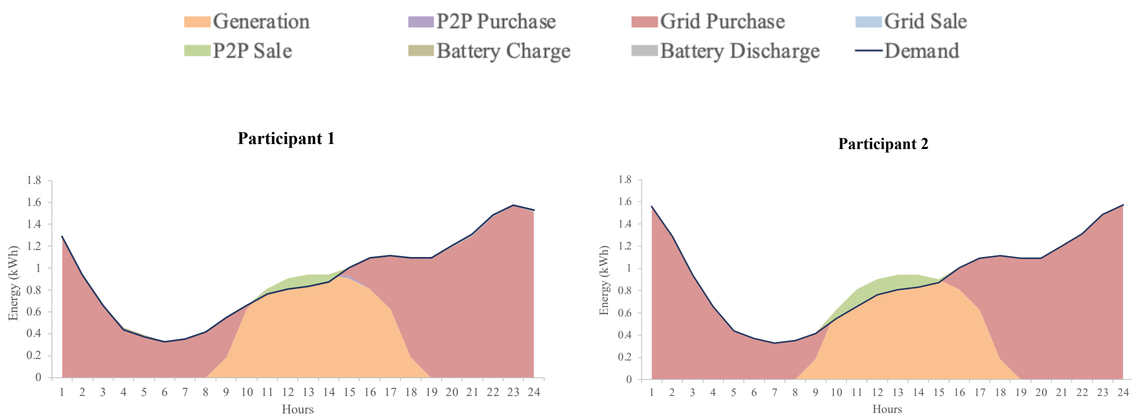


Figure 4.17. Energy balance of the community during a day in winter (case 2.1)

Figure 4.18 represents the energy balance for each participant individually. Prosumers 1 and 3 charge their battery at times of low demand and low grid prices (around 4:00) and discharge them in the evening (around 20:00), when demand and prices are higher. Their surplus energy during the day is sold P2P to the participant 4.



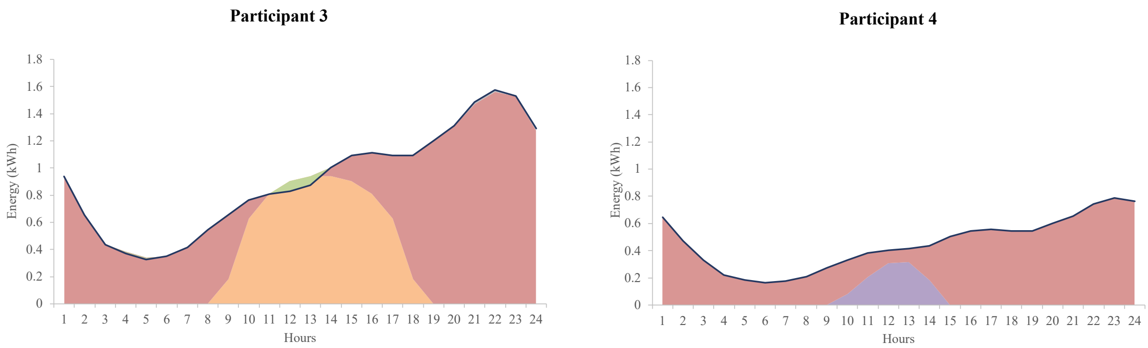


Figure 4.18. Energy balance of each participant during a day in winter (case 2.1)

Figure 4.19 represents the state of charge of the battery of each participant. As previously mentioned, each prosumer charges progressively its battery to the maximum in the early morning and discharges it during the night.

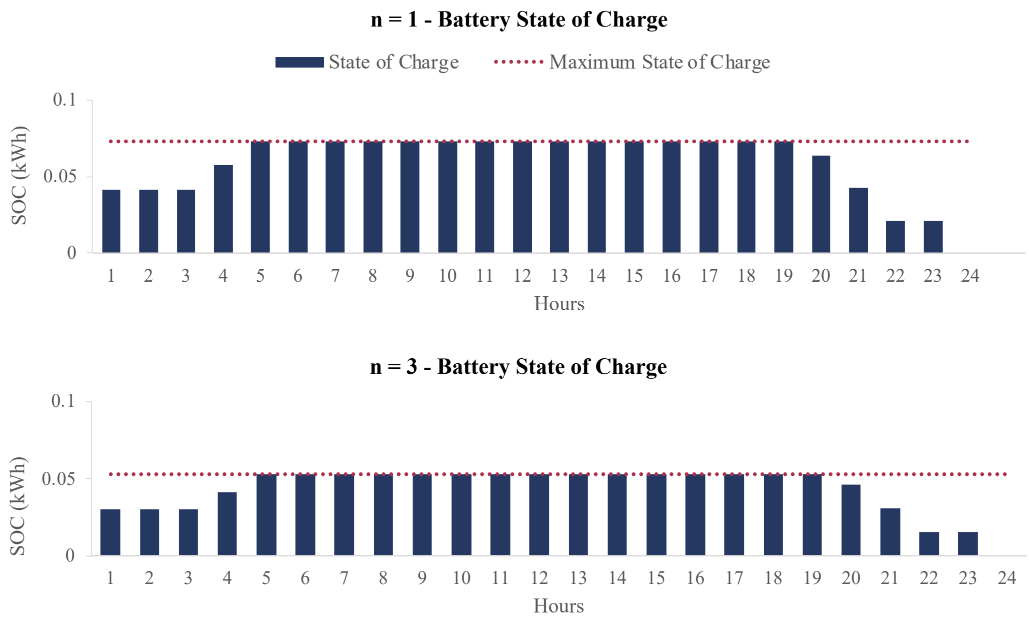


Figure 4.19. State of charge of the batteries during a day in winter (case 2.1)

Figure 4.20 represents the energy prices and the SDR for the community. As the energy community is almost self-sufficient at midday, the SDR reaches 1 at this moment and there are no energy exchanges with the grid. Besides, the hours with lowest grid energy prices coincide with the charging of the batteries and the hours with highest grid energy prices, with the discharging of the batteries, as previously mentioned.

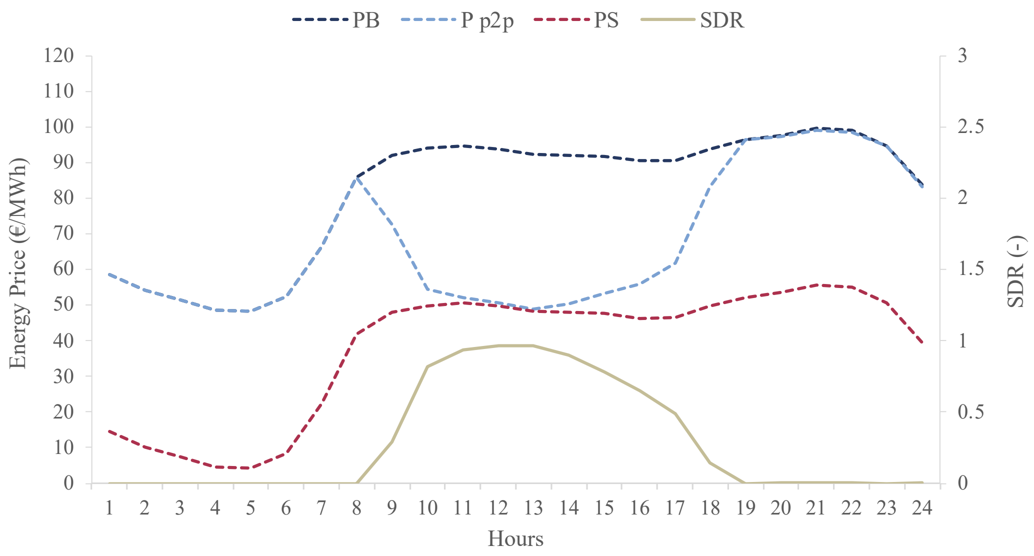


Figure 4.20. Energy prices and SDR during a day in winter (case 2.1)

Below, the same analysis is conducted but during a **day in summer** (July 17th).

Figure 4.21 represents the energy balance for the community. As in the previous cases, in summer, the solar radiation profile in Madrid is very high and therefore there is a lot of surplus energy in the community which is used for charging the batteries and the rest is sold to the grid. Again, the charging and discharging of the batteries cannot be appreciated.

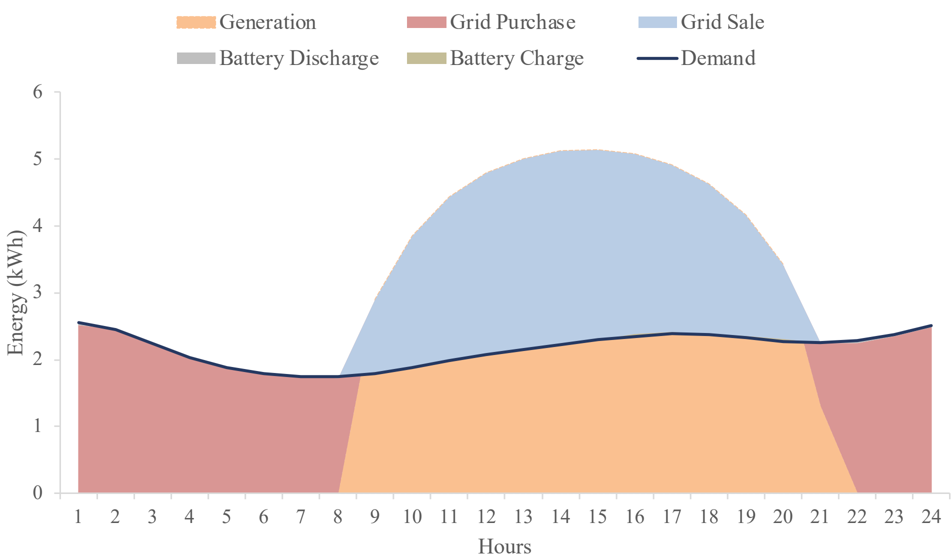


Figure 4.21. Energy balance of the community during a day in summer (case 2.1)

Figure 4.22 represents the energy balance for each participant individually. Prosumers sell their energy surplus in the P2P market to participant 4, who satisfies completely its energy demand during the day with energy from the local market. Besides, part of this surplus energy is used for charging the batteries which is latter discharged at night. At the first hour, the battery is discharged from the energy stored the previous day. The state of charge of the batteries can be observed in Figure 4.23.

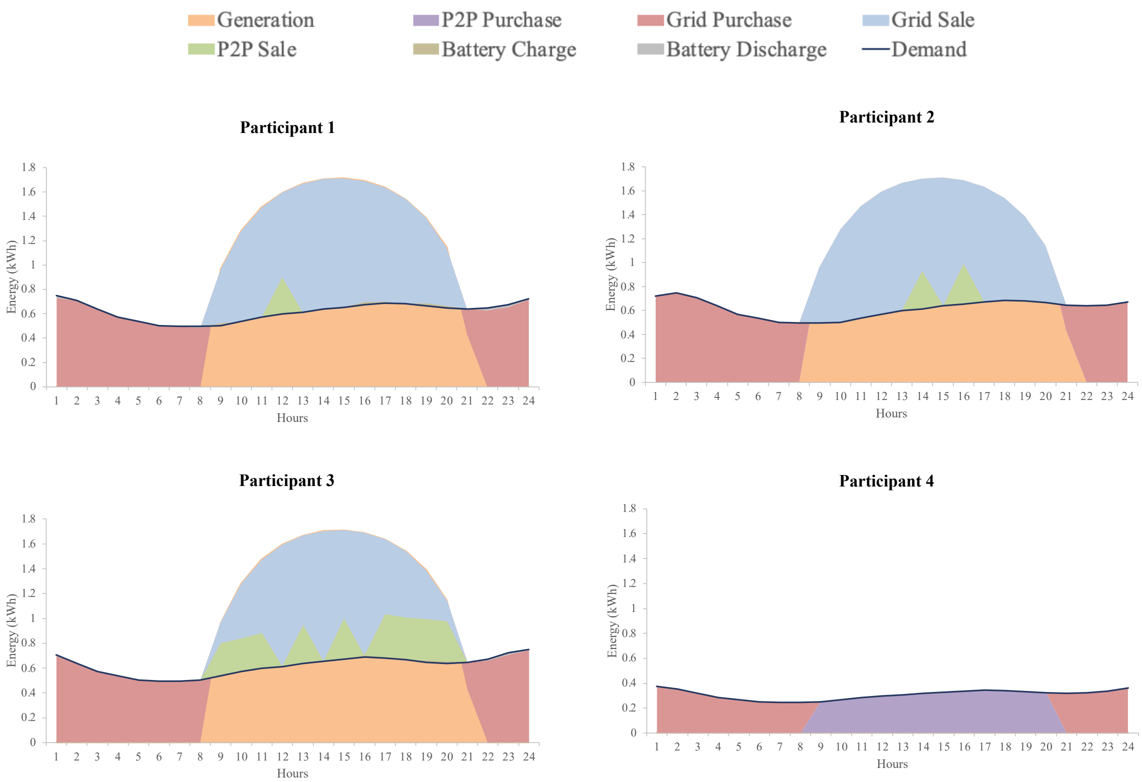
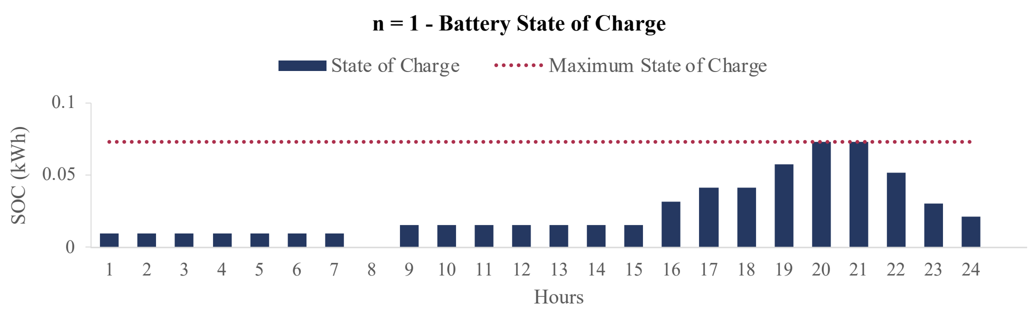


Figure 4.22. Energy balance of each participant during a day in summer (case 2.1)



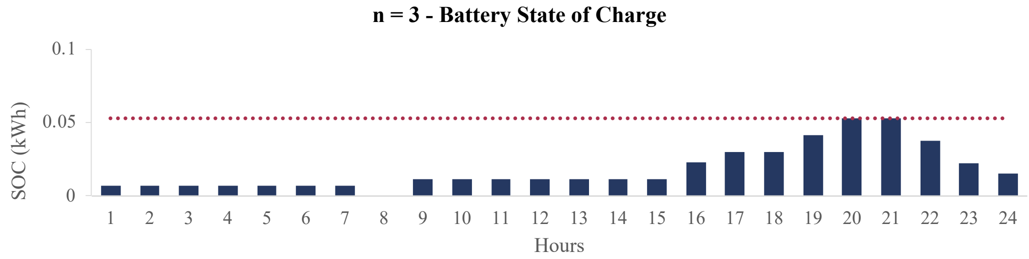


Figure 4.23. State of charge of the batteries during a day in summer (case 2.1)

Figure 4.24 represents the energy prices and the SDR for the community. As there is a lot of energy available in the community, the SDR is greater than 1 during the day and the local energy price reaches its minimum value. Due to the small installed capacity of the batteries, this result is very similar to the one obtained in Case 1.1. Initial PV Investment Cost.

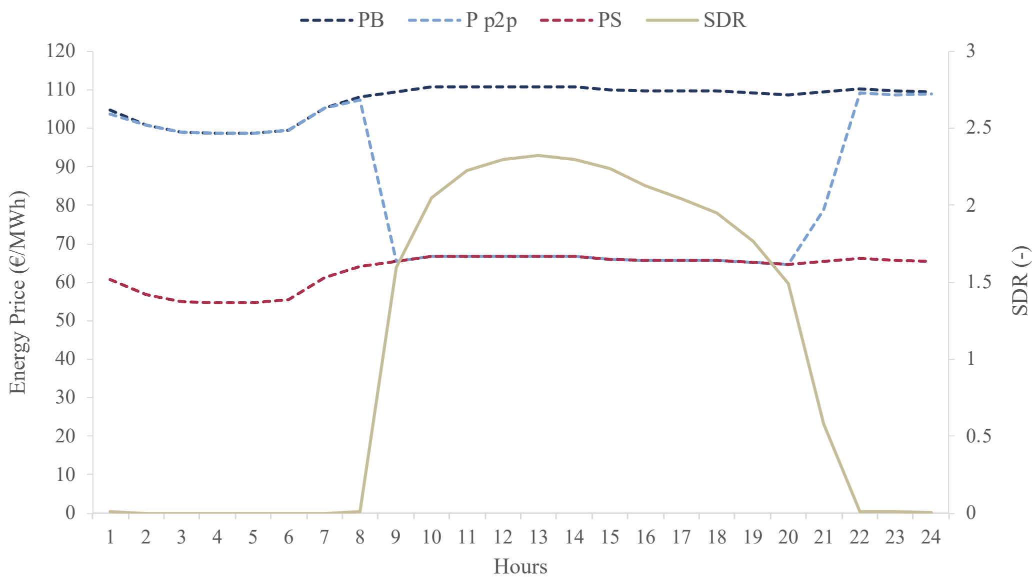


Figure 4.24. Energy prices and SDR during a day in summer (case 2.1)

Finally, Table 4.8 summarizes the annual energy cost for the community and each participant individually. The annual energy cost for the community is similar to Case 1.1. Initial PV Investment Cost, in which the community does not have storage capabilities, since the batteries installed capacity in this case is very small. Nevertheless, there are some slight differences. As the contracted power is lower than in the cases without batteries, the fixed term due to contracted power is reduced. Besides, thanks to the discharging of the batteries, the cost due to grid purchases is also reduced, compensating the higher investment cost. The energy sell-downs to the grid and P2P exchanges remain similar.

	ANNUAL ENERGY COST (€)						
	Fixed Term due to Contracted Power	Investment Cost	Grid Purchase	Grid Sell-down	P2P Purchase	P2P Sell-down	Total
n = 1	61.07	281.70	348.19	-90.24	0.07	-16.45	584.34
n = 2	61.07	278.42	359.03	-95.20	0.03	-19.53	583.81
n = 3	61.07	280.80	341.27	-80.58	0.30	-21.29	581.57
n = 4	31.13	0.00	205.66	0.00	56.87	0.00	293.67
Community	**214.34**	**840.92**	**1254.15**	**-266.03**	**57.27**	**-57.27**	**2043.38**

Table 4.8. Annual energy cost for the community and each participant (case 2.1)

Case 2.2. Lower Battery Investment Cost by 10%

The installed capacity of each technology and the contracted power by each participant is presented in Table 4.9. Each prosumer install the maximum PV capacity allowed since today's PV investment cost is highly competitive, similarly to Case 1.1. Initial PV Investment Cost. As the battery investment cost has decreased, the installed capacity of batteries is higher.

Besides, the contracted power is lower than in all the previous cases studied. Therefore, the more batteries' installed capacity, the more independent are participants from the grid.

	n = 1	n = 2	n = 3	n = 4
PV Installed Capacity (kW)	2.00	2.00	2.00	0.00
BAT Installed Capacity (kW)	0.28	0.19	0.23	0.00
Contracted Power (kW)	1.33	1.41	1.49	0.67

Table 4.9. Installed capacity and contracted power (case 2.2)

The following figures presents the results of the model for the community and each participant individually during a **day in winter** (January 2nd).

Figure 4.25 represents the energy balance for the community. Similarly to Case 2.1. Initial Battery Investment Cost, the community is almost energy self-sufficient during the day and takes advantage of hours with low demand and low grid energy prices to charge its batteries, which are discharged at night, when demand and grid energy prices are higher.

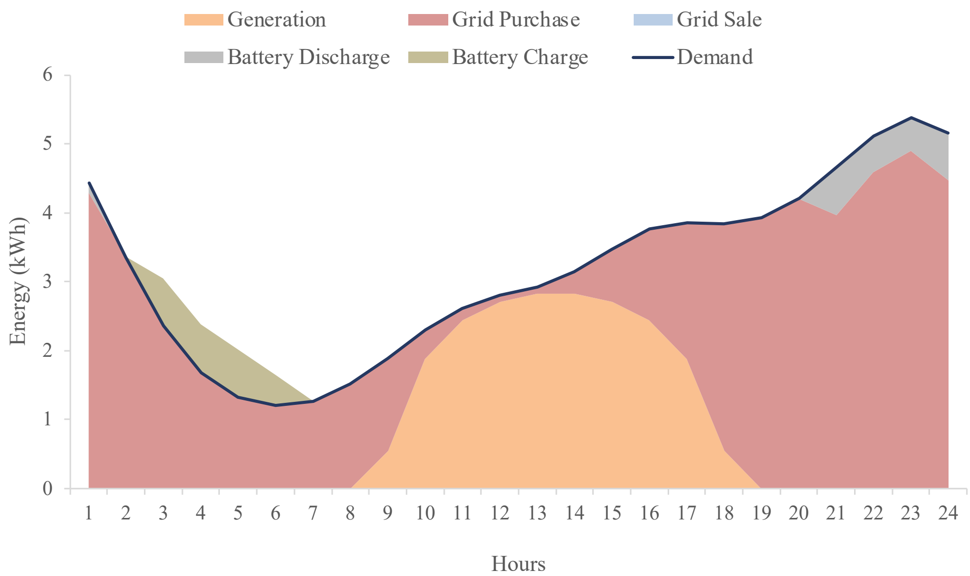
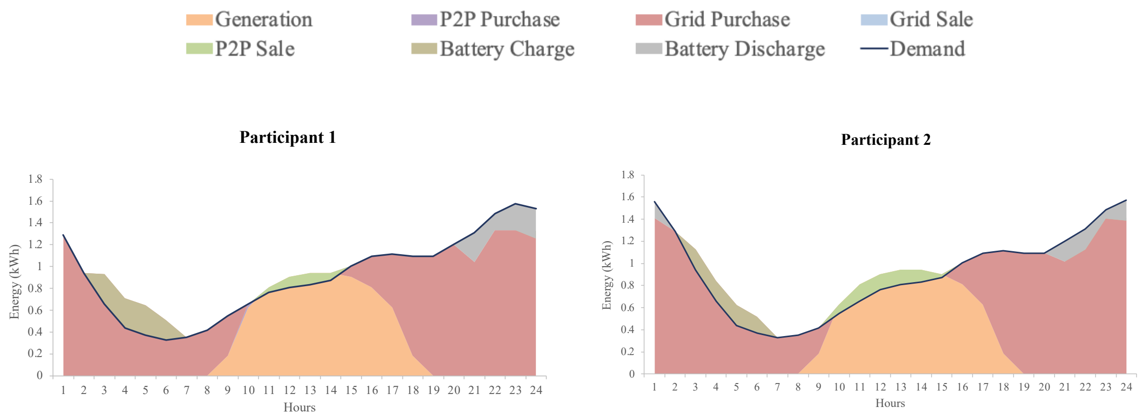


Figure 4.25. Energy balance of the community during a day in winter (case 2.2)

Figure 4.26 represent the energy balance for each participant individually. Prosumers sell their surplus energy during the day in the P2P market to participant 4 instead of to the grid. Besides, they take advantage of hours with low demand and low grid energy prices to charge its batteries, which then they discharge during the night, at hours of higher demand and grid energy prices.



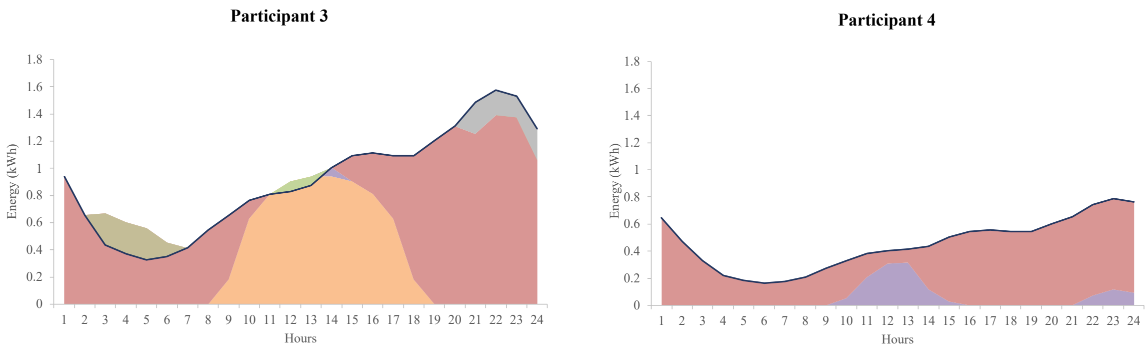


Figure 4.26. Energy balance of each participant during a day in winter (case 2.2)

Figure 4.27 represents the state of charge of the battery of each participant. As previously mentioned, each prosumer charges progressively its battery to the maximum in the early morning and discharges it during the night.

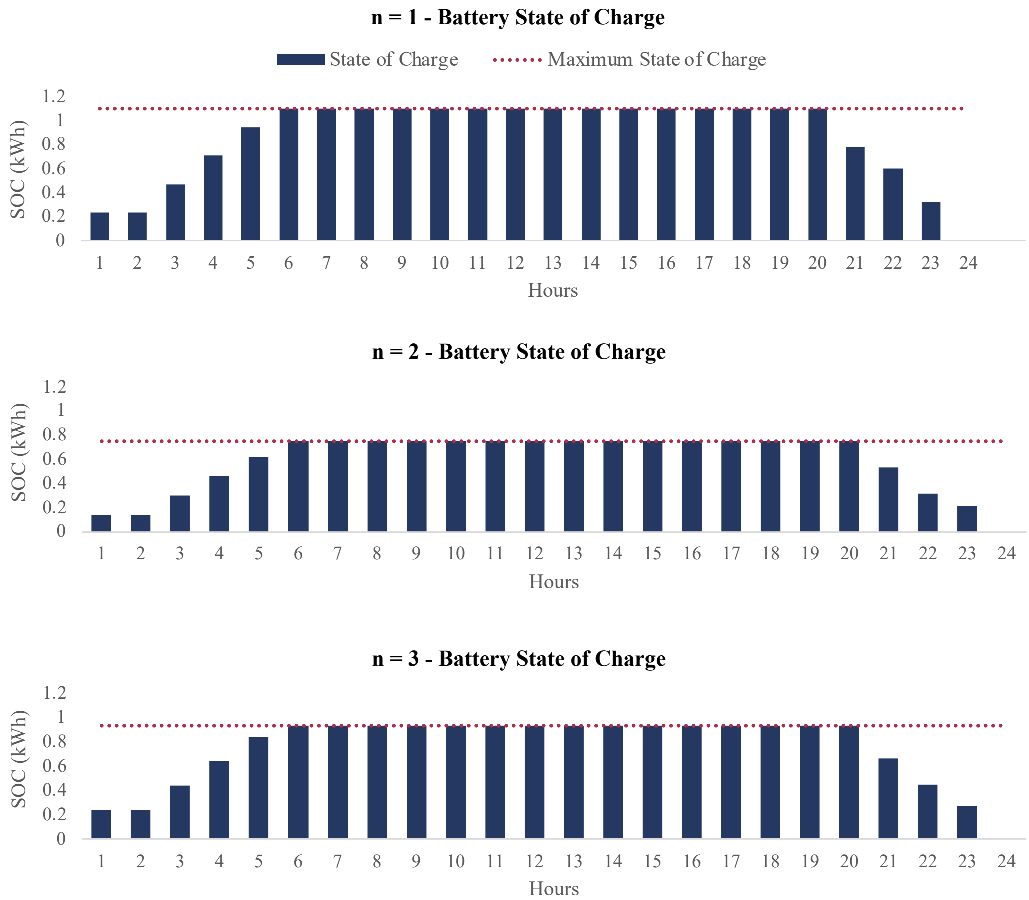


Figure 4.27. State of charge of the batteries during a day in winter (case 2.2)

Figure 4.28 represents the energy prices and the SDR for the community. As the energy community is almost self-sufficient at midday, the SDR reaches 1 at this moment and there are no energy exchanges with the grid. At night, there is more energy available in the community due to the batteries discharge and therefore, the SDR increases. Besides, the hours with lowest grid energy prices coincide with the charging of the batteries and the hours with highest grid energy prices, with the discharging of the batteries, as previously mentioned.

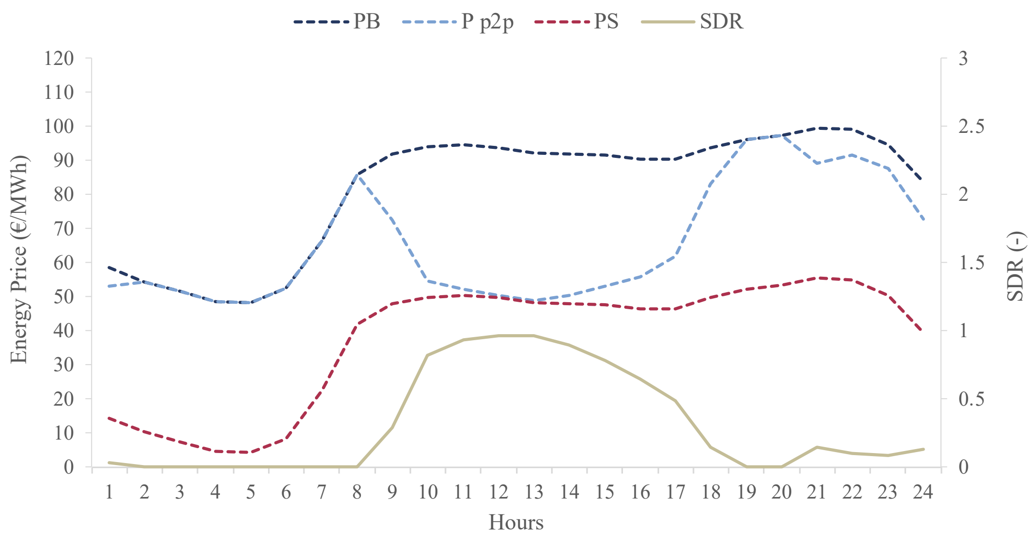


Figure 4.28. Energy prices and SDR during a day in winter (case 2.2)

Below, the same analysis is conducted but during a **day in summer** (July 17th).

Figure 4.29 and Figure 4.30 represent the energy balance for the community and each participant individually respectively. Similarly to Case 2.1. Initial Battery Investment Cost, in summer, the solar radiation profile in Madrid is very high and therefore there is a lot of surplus energy in the community. Prosumers sell this surplus in the P2P market to participant 4 and charge their batteries, the rest is sold to the grid. Prosumers discharge their batteries during the night to satisfy their energy demand, maximizing renewable energy consumption in the community. At the first hour, the battery is discharged from the energy stored the previous day. The state of charge of the batteries can be observed at Figure 4.31.

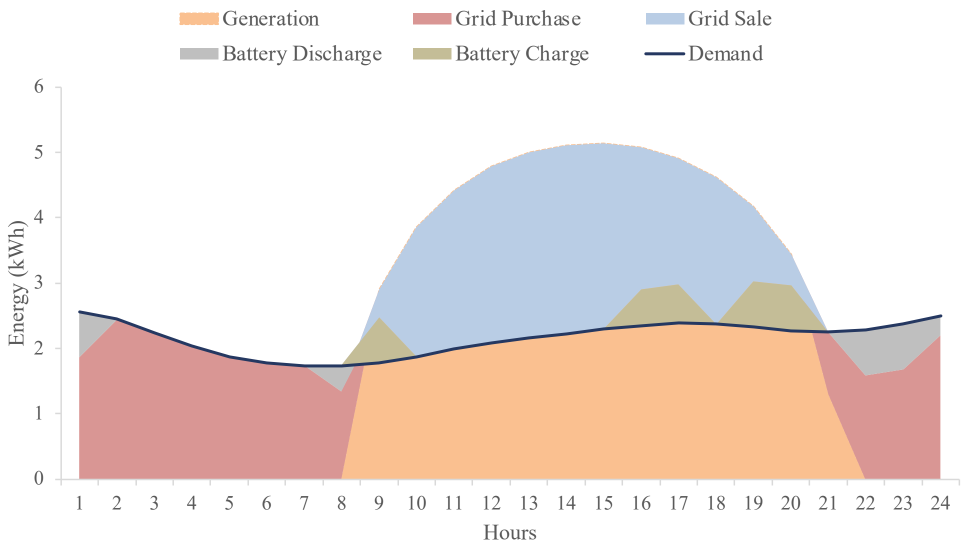


Figure 4.29. Energy balance of the community during a day in summer (case 2.2)

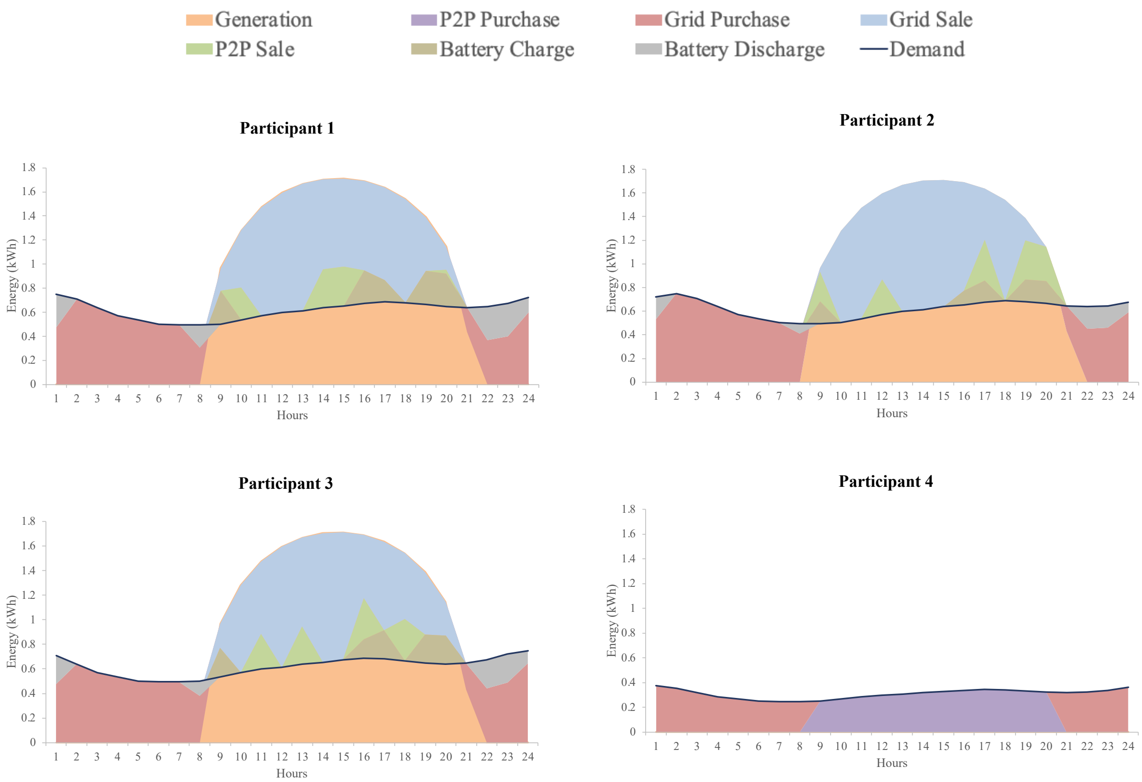


Figure 4.30. Energy balance of each participant during a day in summer (case 2.2)

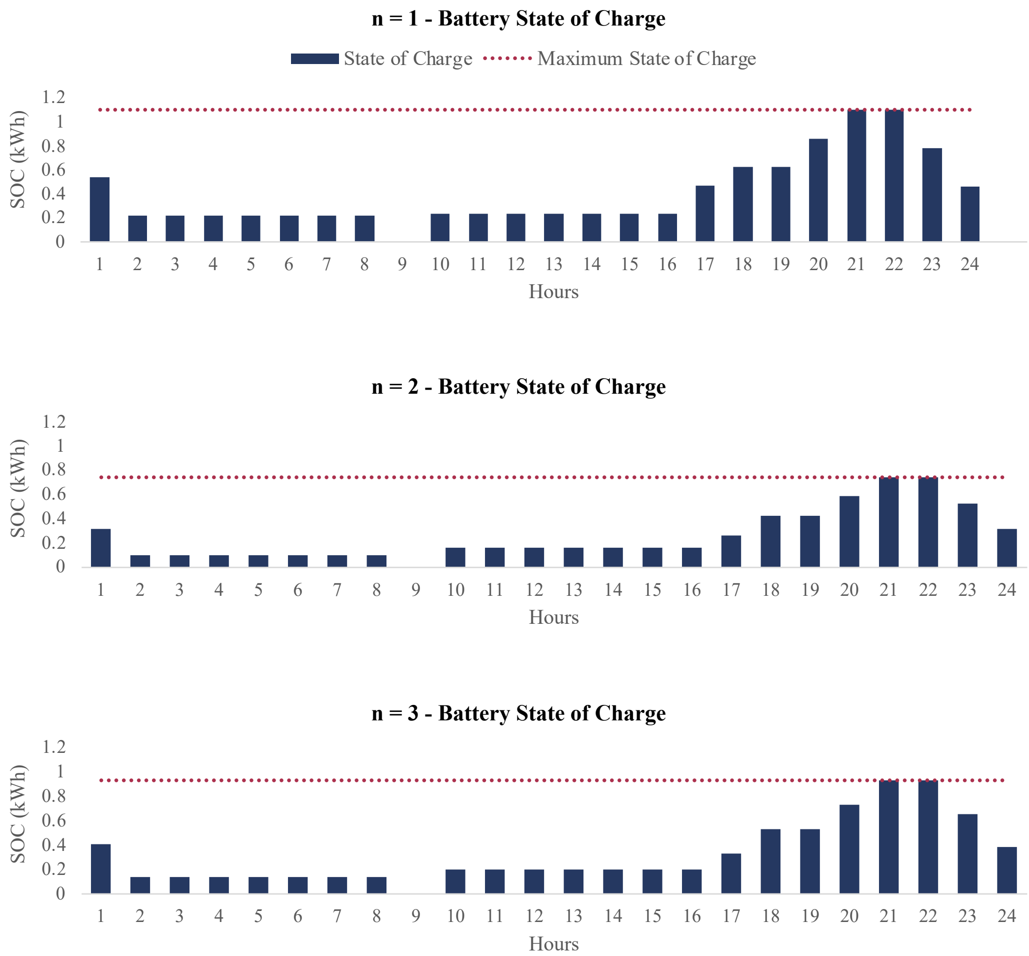


Figure 4.31. State of charge of the batteries during a day in summer (case 2.2)

Figure 4.32 represents the energy prices and SDR in the community. As there is a lot of surplus energy in the community, during the day, the SDR is greater than 1 and the local energy price takes its minimum value. In the afternoon, as there is less energy available in the community due to the batteries' charging, the SDR goes down. At night, the SDR is greater than zero, as there is more energy available due to the discharge of the batteries.

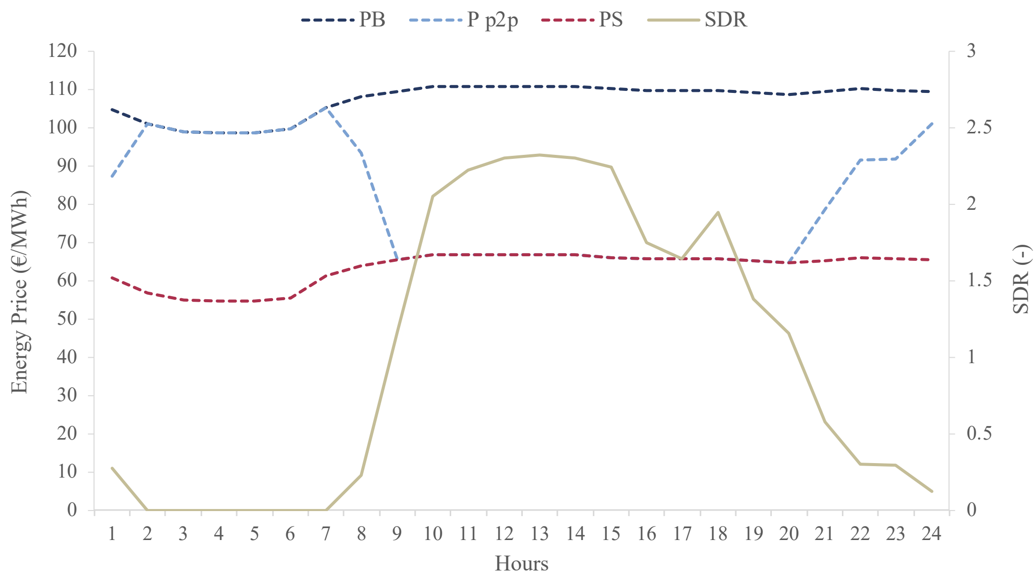


Figure 4.32. Energy prices and SDR during a day in summer (case 2.2)

Finally, Table 4.10 summarizes the annual energy cost for the community and each participant individually. The annual energy cost for the community is increased by 3% compared to Case 1.1. Initial PV Investment CostCase 2.1. Initial Battery Investment Cost due to a higher investment cost, as the battery installed capacity is higher. Despite this, results show that the community is more independent from the grid. First, the fixed term due to contracted power is reduced, as the contracted power is lower. Second, the energy exchanges with the grid are reduced, with lower grid purchases and sell-downs. And third, the energy exchanges in the local market remain similar as prosumers use the energy stored in their batteries to satisfy their own energy demand. This demonstrates that the community is more independent from the grid and maximizes renewable energy consumption.

	ANNUAL ENERGY COST (€)						
	Fixed Term due to Contracted Power	**Investment Cost**	**Grid Purchase**	**Grid Sell-down**	**P2P Purchase**	**P2P Sell-down**	**Total**
n = 1	50.60	322.45	321.59	-68.44	0.08	-18.26	608.02
n = 2	53.68	308.23	340.18	-77.18	0.09	-23.51	601.48
n = 3	56.55	315.67	320.01	-67.93	0.30	-18.31	606.28
n = 4	25.51	0.00	202.51	0.00	59.61	0.00	287.63
Community	**186.33**	**946.34**	**1184.30**	**-213.56**	**60.08**	**-60.08**	**2103.41**

Table 4.10. Annual energy cost for the community and each participant (case 2.2)

4.3.4 Cases Comparison

To conclude this chapter, this section compares the results obtained in the four cases studied. Since there is no common rule defined for the distribution of local energy among the participants, conclusions can only be derived at the community level.

The four cases studied are summarized in Table 4.11:

	P2P market	PV	PV Investment Cost	Batteries	Batteries Investment Cost
Base Case	×	×	-	×	-
Case 1.1	✓	✓	Initial	×	-
Case 1.2	✓	✓	10% Higher	×	-
Case 2.1	✓	✓	Initial	✓	Initial
Case 2.2	✓	✓	Initial	✓	10% Lower

Table 4.11. Cases description

Figure 4.33 compares the annual energy cost of the community. Analyzing the total cost, it can be concluded that the investment in PV panels and batteries reduces the annual energy cost. Regarding each of the terms included in the annual cost, the following conclusions can be derived:

- The addition of batteries reduces the fixed term due to contracted power as the community becomes more independent from the grid.
- The more installed capacity of the technologies, the higher the investment cost. But it is compensated by the lower dependence of the grid, reflected in the rest of the terms.
- The installation of PV panels reduces the cost of purchasing energy from the grid. The higher the installed capacity of batteries, the lower is this cost, as they provide more flexibility to the consumption of the energy generated by the PV panels.
- The installation of batteries reduces the benefit obtained for the sell-downs to the grid. As seen in Case 2.2. Lower Battery Investment Cost by 10%, the surplus energy during the day is partly used to charge the batteries instead of selling it to the grid.

- The exchanges in the P2P market increase as more energy is available in the community. The more PV capacity installed, the more surplus energy and the more P2P exchanges. The more battery capacity installed, the more flexibility, allowing also more P2P exchanges.

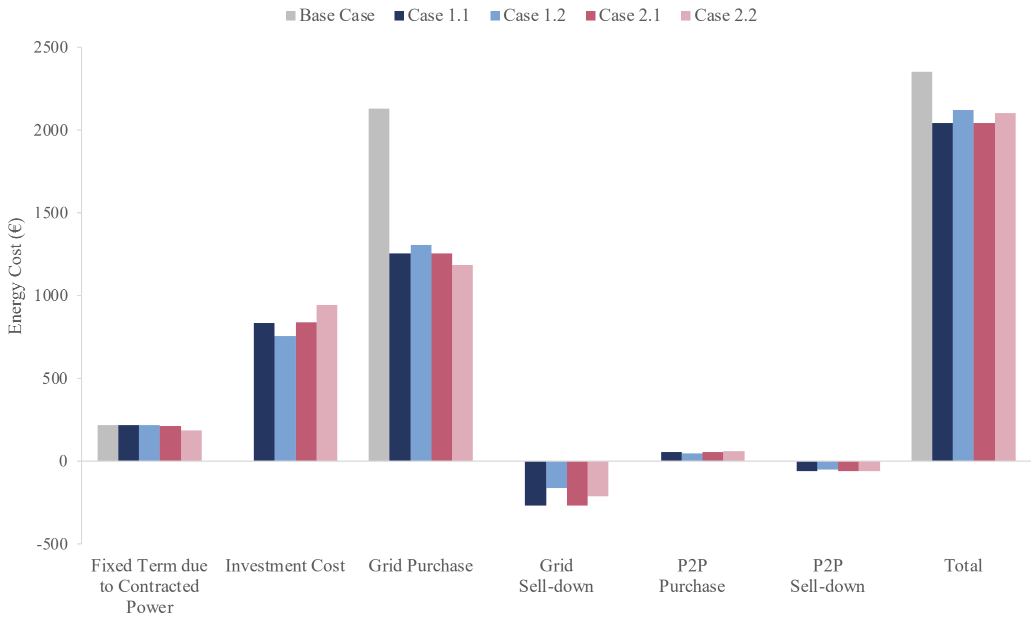


Figure 4.33. Community annual energy cost comparison

Lastly, to analyze the impact of participating in a P2P market, the average buying and selling prices for each participant and the community are presented in Figure 4.34 and Figure 4.35 respectively.

Although no common rule has been followed for the distribution of local exchanges, given that throughout the year under study the community has a lot of excess energy and due to the SDR price computation, the internal price is the same as the selling price to the grid. Therefore, for the participants who sell energy, their results are the same whether they sell their energy surplus to the local market or to the grid. And since there is only one participant who buys energy in the local market in this situation, the results obtained at the individual level are not far from reality. Even though a more in-depth analysis is required, it is possible to derive conclusions from these individual results.

Figure 4.34 represents the average energy buying price for each participant and for the community. It can be noted how the installation of PV panels and batteries reduces the final buying energy price. Besides, the existence of the P2P local market also has a significant impact. Participant 4, the most benefited by buying energy in the P2P local market, reduces its average energy buying price by up to 14%, compared to traditional energy consumption from the grid.

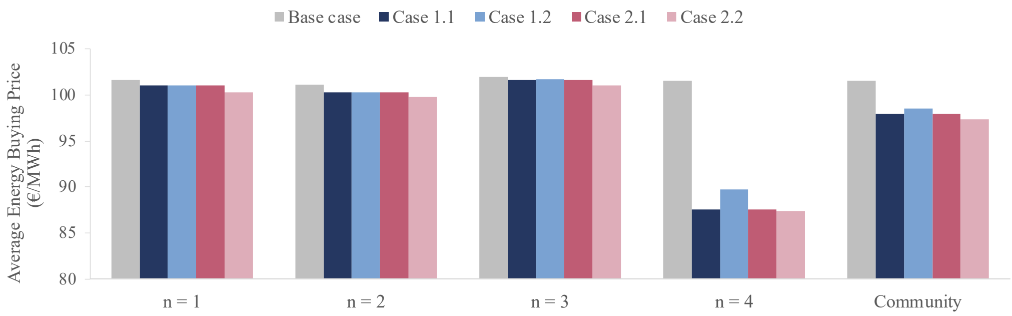


Figure 4.34. Average energy buying price comparison

Figure 4.35 represents the average energy selling price for each participant and for the community. It can be noted that the resulting average price is not very different from the situation where all the surplus energy is sold to the grid (grey bars). As mentioned before, as there is a lot of energy surplus in the community and due to the SDR price computation, the internal price is the same as the selling price to the grid. However, it can be noted that in the cases where there is less surplus energy, in case 1.2 with less PV installed capacity and case 2.2 with higher batteries installed capacity, the average selling price increases, showing how sellers can also benefit from participating in the P2P market.

Figure 4.35. Average energy selling price comparison

4.3.5 Model Convergence Analysis

To test the convergence of the model, we analyzed the difference of the approximated variables between two consecutive iterations.

Figure 4.36 presents the convergence analysis for the four cases studied. As the approximated variables depend on hours, we have represented the maximum difference between two consecutive iterations among all the hours. The analysis shows that convergence is achieved very quickly in the two first cases, and in a few more iterations in the two last ones.

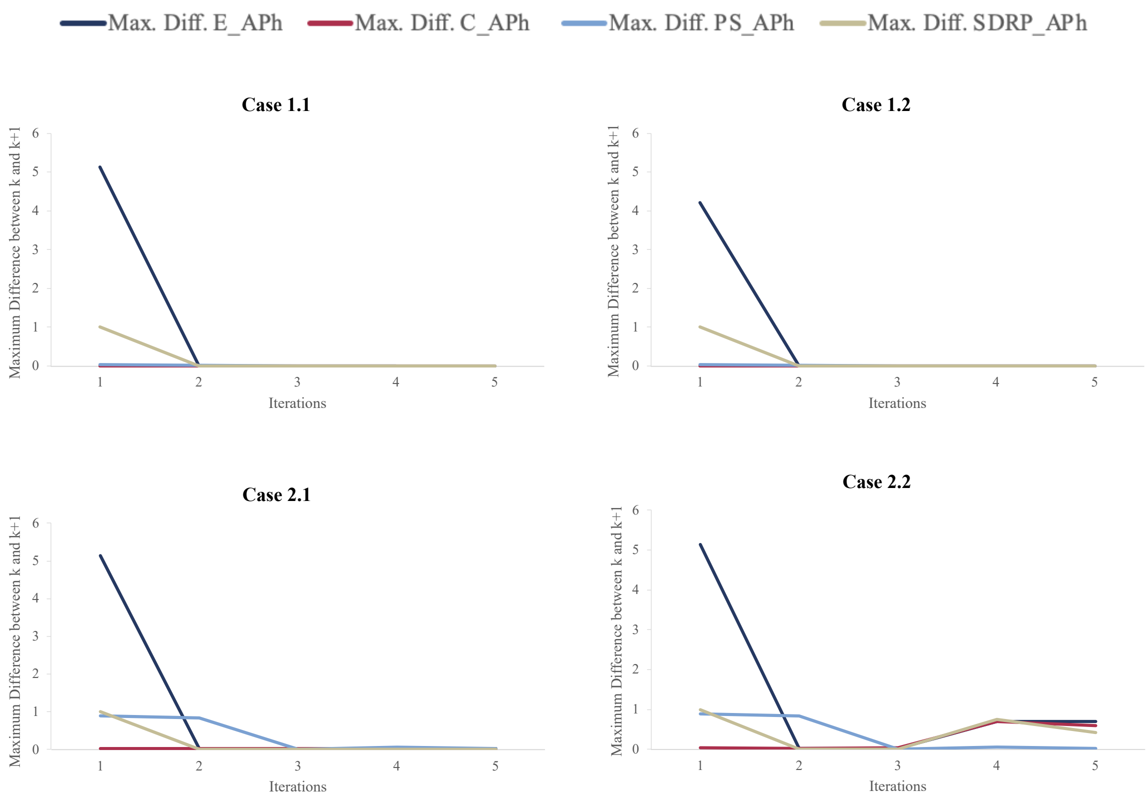


Figure 4.36. Convergence analysis

Chapter 5. Conclusions

The EU Energy Strategy and the National Energy and Climate Plans of European countries include different decarbonization strategies to combat climate change, with ambitious targets for the energy sector. In the coming years, the presence of renewable energies in the EU energy mix is expected to increase considerably. To this end, one of the strategies proposed is the decentralization of energy.

These initiatives, together with the increasingly competitive cost of renewable technologies and the growing environmental awareness of society, have led to the emergence of renewable energy communities. Consequently, there is a need for a new market structure to regulate their behavior. This thesis presents a study of renewable energy communities and local P2P energy markets to organize their internal prices and energy exchanges.

Three approaches to model a local P2P energy market have been identified. The three of them establish an internal price in the local market, which is between the buying of and selling prices to the grid, that incentivizes the consumption of renewable energy in the community. From a specific case study for each of them, the following conclusions can be derived.

Two of them, pricing mechanisms based on price computation and agent-based models, simulate a P2P energy market with a pool-type market clearing. In this market there are only energy bids, and the internal price is calculated from the energy available in the community and the grid prices, and it is the same for all the participants in the community.

The third approach is based on game theory and simulates a P2P energy market with also a pool-type market clearing, but with bilateral results. These bilateral prices are obtained by assigning a cost to each transaction between participants. Therefore, its results strongly depend on the random values assigned to each transaction.

To analyze the behavior of an energy community, a mathematical model has been formulated. This model represents a P2P energy market where its participants have PV and storage capabilities. The internal price in the local market is determined using the SDR mechanism without compensation. This model has been applied to the case of a residential Spanish neighborhood, from which the following conclusions can be derived.

The investment in PV panels and batteries reduces the annual energy cost for the community up to 13% compared to the traditional energy supply from the grid. The addition of batteries reduces the dependence of the community from the grid since batteries provide more flexibility to the consumption of PV generation. Therefore, both the contracted power and the energy exchanges with the grid are reduced.

Regarding the internal price in the P2P market, it can be concluded that the SDR method effectively incentivizes the consumption of renewable energy in the community. In the case study, the participant who does not install PV panels always buys its energy demand in the local market, as long as it is available. Consequently, he reduces its average energy buying price by up to 14% compared to buying all the energy to the grid. However, an important contribution to the model would be computing the internal price using the SDR with compensation (Figure 2.3). In the proposed model, when there is energy surplus in the community, prosumers obtain the same benefit either by selling their surplus to the grid or in the local P2P market. Adding the compensation, the benefit of those that are consuming when there is excess PV generation would be partially shared with those that are generating.

The proposed model minimizes the energy cost of the community. Therefore, the internal energy exchanges between participants are undetermined. Future researchers are oriented to solve the model using game theory, minimizing the energy cost for each participant individually, or to include rules to distribute the benefit of the community among participants. Also, it can be interesting to include the possibility of demand-response in the community, to maximize the energy consumption from renewable technologies.

All in all, from this thesis it can be concluded that local P2P energy markets may be a feasible structure to organize energy communities. With the proper regulation, they can contribute to the expansion of renewable distributed generation, incentivizing the members of an energy community to collaborate among each other, maximizing their renewable consumption. However, if decentralization of energy continues expanding and the contracted power of these energy communities decreases, it may imply that there is a need to revise the electricity tariffs to keep financing the maintenance of the electricity system.

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Annex I. Sustainable Development Goals

The Sustainable Development Goals (SDGs) are a group of 17 objectives designed by the United Nations aimed to achieve a better and more sustainable future for the world. They are considered an urgent call for action by all the countries and provides them with a guideline to work aligned to end poverty, reduce inequalities, and tackle climate change. They are classified into three main groups according to the problems they are intended to solve: economy, environment, and society [38].

This thesis is mainly aligned with **SDG 7 "Ensure access to affordable, reliable, sustainable and modern energy".** The goal of this SDG is that energy becomes more sustainable and widely available. Still today, 13% of global population lacks access to electricity and the energy sector accounts for around 60% of total global greenhouse gas emissions. Thus, there is still a lot to improve in relation to this objective. More precisely, this thesis focuses on 2 targets [39]:

- Target 7.2: "By 2030, increase substantially the share of renewable energy in the global energy mix".
- Target 7.B: "By 2030, expand infrastructure and upgrade technology for supplying modern and sustainable energy services for all in developing countries, in particular least developed countries, small island developing States, and land-locked developing countries, in accordance with their respective programs of support".

This thesis aims to integrate distributed generation into the existing electricity system, thus increasing the percentage of renewable energy in the global energy mix. This integration is achieved through a new electricity market structure where renewable energies become the main energy source. This allows to reduce electricity cost and increase balancing efficiency thanks to a local market mechanism. Moreover, this new market structure can also be considered for the electrification of small islands or isolated rural areas based on renewable energies.

Besides, this thesis is also aligned to a minor extent with **SDG 11 "Make cities inclusive, safe, resilient and sustainable"** and **SDG 13 "Take urgent action to combat climate change and its impact"**.

On the one hand, this thesis studies the internal negotiations inside energy communities, shaping a future where cities may be much more organized around local communities, reducing their dependence on the grid, increasing efficiency, and basing their consumption in their own local RES generation. Besides, in these new local markets, the electricity price is reduced, facilitating access to electricity in the cities.

On the other hand, as energy is the dominant contributor to climate change, accounting for 60% of total global greenhouse emissions, this thesis promotes the use of renewable energies to substantially reduce these emissions.

These objectives are illustrated in the case study described in Chapter 4. It consists in evaluating the impact of installing PV panels and batteries in an energy community, as an alternative to traditional consumption from the grid. In addition, in this community there is a local P2P energy market that allows for local energy exchanges, to maximize the consumption of renewable energy inside the community.

To quantify the contribution of this thesis to the previously mentioned SDGs, based on the results of the case study, two indicators are analyzed: the **tons of CO_2 per year avoided** and the **economic savings**.

Assuming that in 2019 the Spanish electricity system emitted 0.19 ton CO2 eq/MWh [40], Figure I.1 presents the tons of CO_2 eq avoided by the community in each of the cases studied. The number in parenthesis shows the percentage of emissions reduction compared to the base case, in which all the energy is consumed from the grid.

The higher the energy consumption from PV panels in the community, the higher the CO_2 emissions avoided. Therefore, the more installed capacity of PV panels in the community, the higher the emissions avoided (1.62 tons of CO_2 eq avoided in Case 1.1 vs 1.53 in Case 1.2). And, the more installed capacity of batteries, the more flexibility to consume energy from PV panels and therefore, the more renewable consumption and the more emissions avoided (1.75 tons of CO_2 eq avoided in Case 2.2 vs 1.63 in Case 1.1).

To conclude, CO_2 emissions in the community are reduced between 38% and 44% compared to satisfying all the energy demand with the grid.

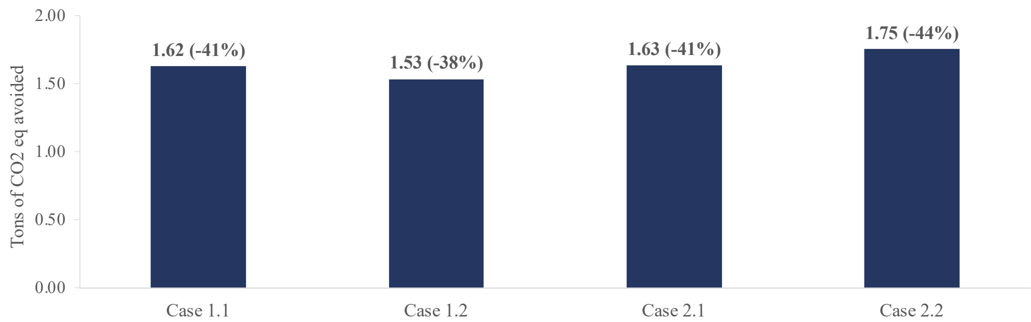

Figure I.1. Tons of CO_2 eq avoided in the community

Moreover, comparing the annual energy cost from each case with the base case, we can obtain the economic savings of the community and each participant individually.

Figure I.2 presents the economic savings of the community. The number in parenthesis shows the percentage of cost reduction compared to the base case, in which all the energy is consumed from the grid. It can be observed that the greatest economic savings are obtained by installing PV panels and selling surplus energy to the grid (Case 1.1). Due to the high investment cost of batteries, their installation results in lower economic savings.

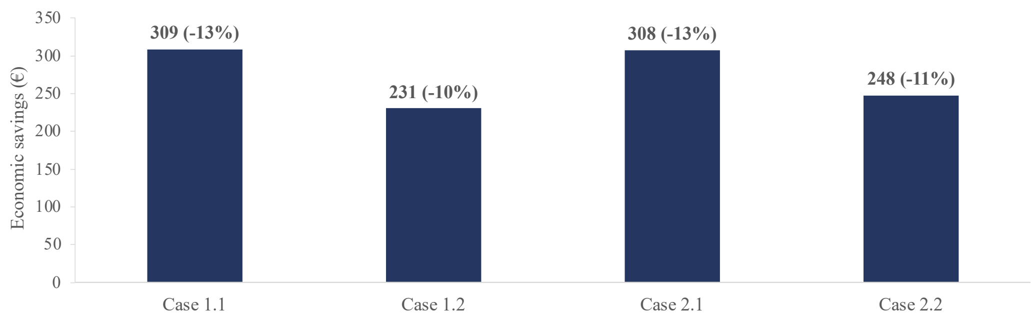

Figure I.2. Economic savings of the community

Figure I.3 presents the economic savings of each participant individually. It can be observed that all the participants obtain economic benefit from participating in the local P2P market.

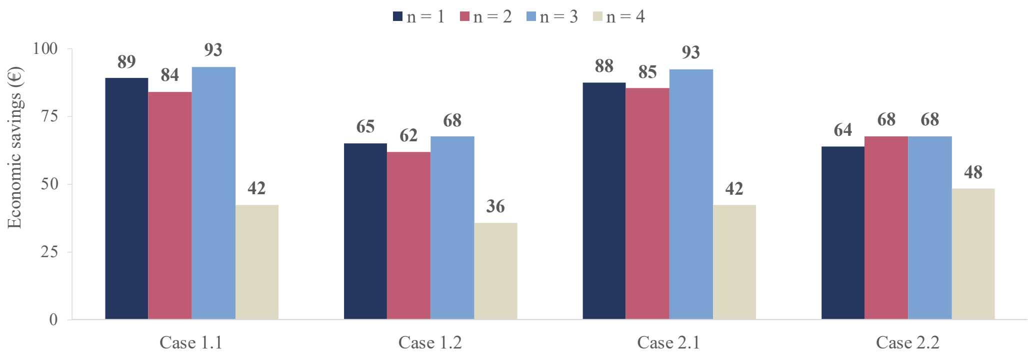

Figure I.3. Economic savings of each participant

To conclude, based on the results from the case study, it is demonstrated that this thesis effectively contributes to the SDGs. It successfully promotes the expansion of distributed renewable generation, with positive impact for both the environment and society. This impact is measured by the reduction of CO_2 emissions from energy consumption and the reduction of the energy cost.

Annex II. Model Reformulation

In the proposed model, the energy buying (pb_h) and selling prices (ps_h) in the P2P market vary depending on the value of the SDR. When there is energy deficit in the community ($0 < sdr_h < 1$), the internal prices have a value between the buying and selling prices of the grid, while if there is excess energy in the community ($sdr_h > 1$), the internal prices are the same as the selling price to the grid.

$$ps_h = \begin{cases} \dfrac{PB_h \cdot PS_h}{(PB_h - PS_h) \cdot sdr_h + PS_h}, & 0 < sdr_h < 1 \\ PS_h, & sdr_h \geq 1 \end{cases}$$

$$pb_h = \begin{cases} ps_h \cdot sdr_h + PB_h \cdot (1 - sdr_h), & 0 < sdr_h < 1 \\ PS_h, & sdr_h \geq 1 \end{cases}$$

The value of the internal prices when there is excess energy in the community ($sdr_h > 1$) is the same as the result from equations when there is energy deficit ($0 < sdr_h < 1$) when sdr_h equals to 1. Therefore, we can eliminate the dependance on the energy availability in the community by replacing the variable sdr_h in previous equations with a new variable sdr'_h, which is the minimum between $\{sdr_h, 1\}$. Substituting the variable sdr_h by sdr'_h and clearing the equations, the prices in the P2P local market are calculated as:

$$(PB_h - PS_h) \cdot ps_h \cdot sdr'_h + PS_h \cdot ps_h = PB_h \cdot PS_h$$

$$pb_h = ps_h \cdot sdr'_h + PB_h \cdot (1 - sdr'_h)$$

The formulation of the minimum between $\{sdr_h, 1\}$ is:

$$sdr'_h \leq sdr_h$$

$$sdr'_h \leq 1$$

Annex III. Model Linearization

The Taylor series expansion allows to approximate a k-times differentiable function by a polynomial of order k around a given point. In particular, the first-order Taylor series is the linear approximation of the function. The general expression of the first-order Taylor series for m variables at point $\vec{a}$ is:

$$f(\vec{x}) = f(\vec{a}) + \nabla f(\vec{a}) \cdot (\vec{x} - \vec{a})$$

$$f(\vec{x}) = f(\vec{a}) + \sum_{i=1}^{m} \frac{\partial f}{\partial x_i}(\vec{a}) \cdot (x_i - a_i)$$

To linearize the model proposed in Chapter 3the non-linear functions presented in equations (3.2), (3.12), (3.13) and (3.16) are approximated to its first-order Taylor series. The linear Taylor approximation for the non-linear functions is shown below with a generic formulation. Given the two variables $\vec{x} = (x, y)$ and the point $\vec{a} = (x_0, y_0)$ then,

- Linear Taylor approximation of $f(\vec{x}) = x \cdot y$

$$\nabla f(\vec{x}) = \left(\frac{\partial f}{\partial x}(\vec{x}), \frac{\partial f}{\partial y}(\vec{x})\right) = (y, x)$$

$$f(\vec{x}) = x \cdot y \approx x_0 \cdot y_0 + y_0 \cdot (x - x_0) + x_0 \cdot (y - y_0)$$

- Linear Taylor approximation of $g(\vec{x}) = \frac{x}{y}$

$$\nabla g(\vec{x}) = \left(\frac{\partial g}{\partial x}(\vec{x}), \frac{\partial g}{\partial y}(\vec{x})\right) = \left(\frac{1}{y}, \frac{-x}{y^2}\right)$$

$$g(\vec{x}) = \frac{x}{y} \approx \frac{x_0}{y_0} + \frac{1}{y_0} \cdot (x - x_0) - \frac{x_0}{y_0^2} \cdot (y - y_0)$$