UNIVERSIDAD PONTIFICIA COMILLAS

ESCUELA TÉCNICA SUPERIOR DE INGENIERÍA (ICAI)

OFFICIAL MASTER'S DEGREE IN THE
ELECTRIC POWER INDUSTRY

Master's Thesis

ANALYSIS OF THE PROFITABILITY OF BUSINESS MODELS FOR ENERGY COMMUNITIES TAKING INTO ACCOUNT THE CHARACTERISTICS OF THE ELECTRICITY SYSTEM

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Madrid, July 2024

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SUMMARY

In the context of skyrocketing electricity prices, aggravated by global events such as the Ukraine crisis, the energy, oil and wage sectors are facing unprecedented challenges. This has led to a significant economic impact, particularly on gas and electricity prices, due to Europe's heavy dependence on Russian gas. To address these challenges and reduce energy dependence, the implementation of measures such as energy communities has become crucial. These communities encourage the adoption of renewable energy, citizen participation and environmental sustainability. By promoting local energy production and consumption, energy communities mitigate grid losses, improve efficiency and contribute to climate change mitigation.

This study evaluates three distinct energy sharing models tailored for energy communities. Model 1, termed the Grid Interaction Minimization Model, facilitates direct transactions between generators and consumers, aiming to eliminate intermediaries and foster active participation in energy markets; Model 2, known as the Cost Minimization Model, focuses on minimizing total energy costs within geographically close communities and Model 3, the Independent Cost Minimization Model, aims to minimize total energy costs without allowing energy exchange between households within communities. The thesis methodology involves performing a two-stage optimization process: initial centralized optimization determines energy dispatch with hourly market decisions, followed by a power flow analysis assessing grid impacts.

The results obtained show how Model 1 demonstrated economic viability by achieving a balanced approach between revenues and costs. Although not the most profitable, its emphasis on energy self-sufficiency and reduced CO2 emissions makes it a sustainable choice in the long term. Model 2 emerged as the most cost-effective option among the three models. It effectively minimized costs and maximized revenues through efficient allocation of locally generated energy. However, its strategy of prioritizing cost-effective power generation led to significant grid loads and voltage fluctuations, needing careful management and potentially grid reinforcements to handle operational demands. On the other hand, Model 3, showed the lowest cost-effectiveness due to limitations in optimizing energy efficiency and revenue. Despite these constraints, Model 3 remains a viable option and could be enhanced through adjustments in energy exchange policies or revenue strategies.

With electricity prices escalating, aggravated by global events, the study highlights the critical role of energy communities in mitigating the economic impact and reducing dependence on external energy sources.

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1. Introduction

In a context marked by record highs in electricity prices, exacerbated by the situation in Ukraine, we are facing a triple bill impacting the energy, oil and wage sectors. This conjuncture has generated an unprecedented increase in prices, leaving a significant footprint on the economy. In particular, gas and electricity prices have been affected, given that approximately 40% of the continent's gas supply comes from Russia. As a result, energy costs have risen sharply, contributing to the complexity of the situation [1].

1.1 - Motivation for the study

Therefore, it is essential to implement measures to reduce energy dependence. One of these measures could be energy communities as an option to promote renewable energies, citizen participation, sustainability and the environment [2]. Energy communities are groups of energy consumers or producers that organize and join together collectively to consume, produce or distribute their own renewable energy [3]. These relationships or unions are able to establish better agreements with electricity companies and thus achieve great participation and involvement of citizens and end consumers, generating great economic and social advantages. Some advantages to be highlighted from the implementation of energy communities are the following [4]:

- **Energy transition:** due to the overheating that is occurring on earth in recent years, the sea level is rising, and some glaciers are melting and disappearing, in addition to the appearance of more catastrophic phenomena such as floods, hurricanes or fires. The most significant cause of all these events are the emissions of greenhouse gases found in the atmosphere, which began to be generated with the beginning of the Industrial Revolution as mentioned above [5].

  The main gas found in the atmosphere is carbon dioxide, the main source of which is from energy sector activities. This is why it is essential that an energy transition takes place. One of the main activities that can contribute to decarbonization is the electrification of household consumption, replacing electricity produced from fossil sources with that generated by renewable sources. This is where energy communities come in, promoting the production of clean and renewable energy and thus achieving energy efficiency in homes and reducing emissions of gases harmful to the atmosphere, thus helping to reduce and even mitigate climate change. Some of the alternative energy sources that can be used for this purpose in homes are solar, wind and hydroelectric [6].

- **Energy Decentralization:** with the advances that have been taking place in recent years, such as the distributed energy resources, the power grid landscape has changed. In this new situation we find ourselves in, energy storage devices able to store and redistribute energy when required making the grid not the only way to obtain energy. To this end, energy communities play a key role in contributing to decentralization, promoting local renewable energy generation in each of the communities and facilitating exchange between users of the same energy community.

Their community-centered approach and their ability to adapt to new technologies are transforming the way energy is produced, distributed and consumed today [7].

- **Efficiency and Sustainability:** energy communities can develop sustainable energy infrastructures that promote distributed generation, energy storage and the integration of renewable energy systems into the grid [8].

- **Reduction of Energy Dependence:** energy dependence is defined as the amount of primary energy that needs to be imported into a country to supply the entire demand. This entails a series of negative energy consequences, including the instability of supply, given that it depends on the exporting country or countries, and if there were to be crisis and conflict situations, as in the COVID-19 period or the war between Ukraine and Russia, there would be a lack of supply and there could be, as at present, a large increase in the price of energy in a short period of time as alternative sources of energy would have to be sought in other countries. At present, in Spain, 70% of the total energy demand is supplied by imports from other countries. This makes Spain one of the most energy-dependent countries in the European Union, with an EU average of 53%, and shows that in Spain we need to implement changes to reduce this worrying value [9].
  Through the use and installation of energy communities, this problem could be mitigated to a large extent by promoting the generation of energy through renewable energies locally in an efficient manner, thus reducing this dependence.

1.2- Objectives and methodology for the techno-economic evaluation of the various energy distribution models

The objective of this thesis is to determining which local electricity sharing models for energy communities are available; leveraging the untapped potential of Distributed Energy Resources (DERs) and to make a techno-economic evaluation of the various energy distribution models. To do so, the methodology used will be the followed.

Firstly, various energy sharing models with different conditions and challenges are selected. Different scenarios are defined to reflect different operating conditions for the energy sharing models. In these scenarios, the main difference is the main goal of each energy community. This is described in Section 3.

The second step is to perform an optimization of the different cases using a two-stage approach. Initially, a centralized CET optimization is performed to determine the energy dispatch for homes over a one-month period, with hourly market decisions. Then, a power flow analysis will be performed to evaluate the impacts on the physical grid based on the optimized market results. For each of the different scenarios chosen, the objective function of the model changes to optimize the goal of each of the different energy sharing models, whether it is to minimize the energy exchanged by the grid, reduce supply costs or minimize emissions. This is described in Section 0.

The third step is to examine how the electricity sharing models can be integrated into the electrical system. An analysis will be carried out on how the integration of energy sharing models affects the generation and distribution of energy in the power grid. This includes assessing how small-scale distributed generation can complement or replace centralized generation, as well as how local power distribution can reduce grid losses and improve overall system efficiency. In addition, evaluation criteria to measure efficiency are defined (sustainability, economic efficiency, etc.). This is described in Section 5.

Finally, Section 6 provides the recommendations formalized based on the result obtained in the previous steps. Those recommendations concern the identification of the most suitable energy sharing model to be adopted considering the objectives to be achieved by the community of electricity customers.

2. Energy sharing models for energy communities

In this section, a detailed overview of the primary energy sharing models for energy communities is provided. These models outline various mechanisms through which community members can share and optimize energy usage, promoting efficiency and sustainability within the community. The discussion encompasses different approaches and frameworks that facilitate energy exchange and cooperation among households, ultimately contributing to a more resilient and self-sufficient energy system.

2.1. Peer to peer

The peer-to-peer energy sharing model consists of an interconnected platform that allows local distributed energy generators to sell their electricity at the desired price to consumers willing to pay it, without the need for intermediaries [1]. The main objective is to provide energy users with an incentive to actively participate in energy markets [2]. But not only does it offer benefits for users, it helps the power grid to decrease grid losses, to achieve peak demand reduction and to decrease reserve requirements [3]. A representation of the typical structure of a peer-to-peer network can be seen in Figure 1.

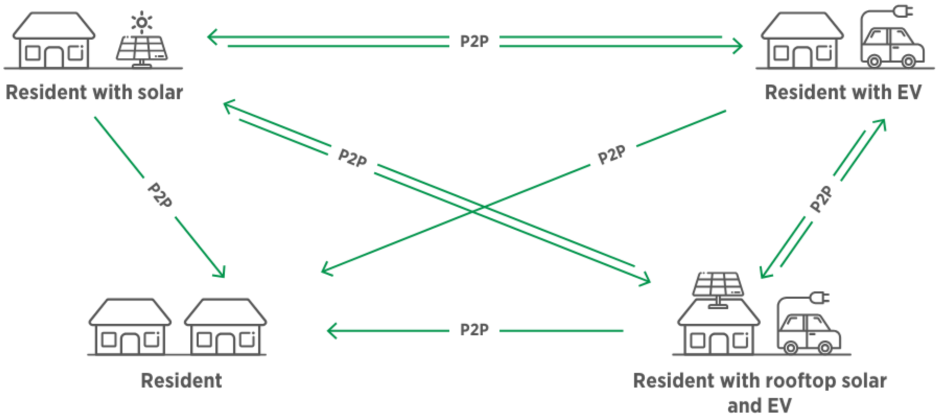


Figure 1: Structure of P2P electricity trading model [9]

Within the peer-to-peer model, different types can be found depending on their architecture and structure. These are [5]:

- Structured and unstructured peer to peer systems: In unstructured P2P systems, no information is available about the links between the different individual sources and the destination. The data is distributed more randomly among the nodes of the network, which means that each node can store a portion of the data and there is no specific rule indicating which portion of the information is contained in each of them. Therefore, if you want to search for a specific file, it is necessary to send a search request to all the nodes in the network asking if it contains the part of the file you need. This process is known as "flooding". The main disadvantage of this process is the network traffic that can be generated causing inefficiency in large networks and even congestion. Most of the popular networks, such as Gnutella and KaZaA, are unstructured networks [6].

On the other hand, structured peer-to-peer systems store information and data about links in a distributed hash table (DHT), which is a decentralized data store that looks up data based on key-value pairs. Each node in a distributed hash table is responsible for a set of keys and their associated values. In this way, when a specific file needs to be accessed, it can be determined quickly which node contains that information by consulting the distributed hash table [7]. This makes this kind of systems more efficient than the unstructured ones since the data is stored in a more organized way and its search is more direct and simpler. That is why these kinds of systems are more suitable for large and scalable networks, such as Pastry P2P Network and Tapestry P2P Network [6].

- Centralized and decentralized peer to peer networks: Centralized P2P networks have a unified architecture in which there is a single server from which all transactions are carried out and which in addition serves as a link between two nodes, stores and distributes the nodes in which the contents are stored. If there are new users who want to belong to a particular peer to peer network, they would have to enter their information in this central server, which makes it very limited in terms of user privacy. Examples of such networks are Napster and Audiogalaxy [6].
  On the other hand, decentralized networks have no central server, so the information is stored on all computers. This brings with it a number of risks, so it has been necessary to establish a number of special solutions. In friend-to-friend or Web of Trust networks, the workload is distributed evenly among all participants, but only users who know each other are allowed to enter the P2P network. In this way the principle of “trusted Friends” is established, creating trust between users and preventing misuse of the decentralized peer to peer system [10]. Some examples of this type of networks are Kademlia, Ares Galaxy [6].

- Hybrid peer to peer networks: this type of network has a central server that functions as a hub and has the task of managing broadband resources, routing and communication between nodes but without knowing the identity of each node and without storing any information, so the server does not share files of any kind to any node. It has the peculiarity of working in both ways, meaning that it can incorporate more than one server that manages the shared resources, but also, in case the server or servers that manage everything go down, the group of nodes can remain in contact through a direct connection between themselves, so it is possible to continue sharing and downloading more information in the absence of the servers [3].

2.2. Community self-consumption

Collective self-consumption is a scheme that enables the sharing of locally produced electricity among producers and consumers who are connected to the public distribution grid, located in the same geographical area. Residential customers, businesses or local authorities, producers and consumers can take part in a collective self-consumption process [11]. The primary goal is to set up a distribution of coefficients for each individual consumer. The sum of these coefficients has to be equal to 100%, meaning that all the energy generated by the collective self-consumption installation is being distributed. To set these coefficients, it can be done by different methods [12]:

- Fixed allocation keys: Distribution is allocated in accordance with a fixed criterion such for example as the surface area of each consumer's home, his investment in the project or his co-ownership share. Such an organization is easy to establish but is not ideal for the operation (for instance, if a consumer is temporarily away, the production that he has not consumed cannot be distributed to the others involved in the operation).
- Variable (or dynamic) dispatch keys: In each 30-minute time slot, dispatch is performed based on the consumption of each participant in the operation, retrieved from the communicating meters. This is the default key that is used by network operators. It benefits all players but may have a tendency to increase consumption.
- Variable distribution keys according to a rule: A rule specific to the collective self-consumption operation can be edited to optimize the distribution. For example, the two previous keys can be combined, allocating the production based on a fixed key, then modified based on the consumption at each time slot. However, this type of key involves more significant calculations and data gathering.

A measuring device is installed in the photovoltaic system to record the energy generated. The total amount produced is allocated to the participants at the end of the month in accordance with their respective coefficients. Such distribution is evaluated on an hourly basis, i.e., the distribution is analyzed every single hour of every single day of the month [13]. Figure 2 shows an example of the collective self-consumption scheme where the aforementioned coefficients can be seen.

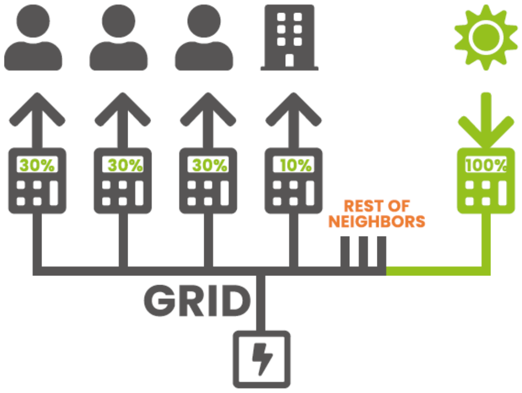


Figure 2: Example of collective self-consumption [13]

The functioning of the system is that producers and consumers, located within a restricted distance of one another, are required to join together to create a legal entity (LE). The LE is in responsible for the management of the operation, and also for establishing a collective self-consumption agreement with the operator of the public distribution network. Such agreement guarantees that the information on the distribution of electricity consumption resulted by the collective self-consumption operation among the consumers is transferred to the operator of the public distribution grid. The participants in the collective self-consumption operation jointly determine the terms and conditions for sharing the electricity produced by them. In this way, every consumer benefits of the share of local production allocated to him or her. Only the additional energy supply to fulfill their demand will be billed by their electricity supplier. This type of operation does not need any particular equipment for the consumers, which stays directly connected to the public distribution network [11].

Collective energy consumption initiatives have many significant advantages for the participants and the electricity system in general. Firstly, they allow energy to be purchased and resold at mutually profitable prices, optimizing costs and economic benefits for consumers and producers. In addition, these initiatives maximize the use of renewable energies, which have variable prices depending on their availability, promoting more efficient and sustainable consumption. At the infrastructure level, they help to balance the electricity grid, a complex process that involves managing energy injections and consumption in a balanced and efficient manner. This not only optimizes the use of the existing grid, avoiding the need to install new lines and power plants, but also encourages the deployment of decentralized green energy generation systems, boosting their use to the maximum and contributing to a more sustainable and efficient energy transition [14].

Some of the already existing projects of collective self-consumptions is Heidelberg Energiegenossenschaft eG in Germany, an energy cooperative that enables apartment residents to obtain cheaper electricity by installing and sharing solar energy.; and ValSophia in Francia, in which a set of four office buildings generate more energy than they consume annually thanks to a 238 kWp photovoltaic system and a private microgrid that allows the connected companies to consume the solar energy produced, storing the excess or selling it to the grid [15].

2.3. Transactive energy

Transactive energy (TE) could be described as "*a system of economic and control mechanisms that enables the dynamic balancing of supply and demand throughout the electricity infrastructure using value as a key operational parameter" [16]*.

Transactive power is distinguished by several key features that make it unique and effective in modern energy management. First, it enables real-time control of distributed intelligent systems, with the ability to operate in times ranging from fractions of a second to hours, as opposed to traditional demand response measured in hours or days. These mechanisms operate under economic incentives instead of centralized orders, and their participation in the balance of supply and demand is completely voluntary. In addition, they perform information exchanges and transactions in a decentralized manner, which guarantees scalability within the control system. The management of these devices is automatic, supervised by humans, but does not require direct human intervention, allowing real-time transactions and controls. This approach also respects customer autonomy and privacy, as the devices are controlled by their owners and not by the utilities. Transactive energy combines control and market functions, coordinating both supply and demand-side resources. As an evolution of demand response, it leverages the adaptability of distributed generation and load resources to efficiently balance supply and demand. In addition, it differentiates itself from the smart grid by enabling faster transmission of supply and demand information, adapting to new generation assets with a decentralized supply model, managing bi-directional energy flows, and operating at the retail level. It also provides for end-users to have energy management systems, facilitating broader and more dynamic integration into the energy grid [17]. Figure 3 shows the conceptual model of a transactive energy market.

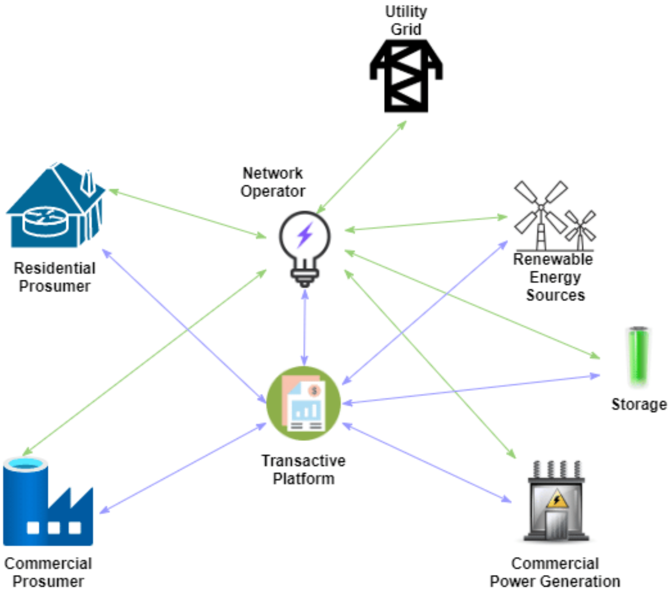


Figure 3: Conceptual model of a transactive energy market [18]

The transactional energy approach brings several core benefits to consumers. First, it enables better use of grid infrastructure assets, from transformers and switchgear to vehicle charging stations and smart meters, which can reduce costs, particularly during peak demand. In addition, it improves grid resilience and reliability in extreme situations, such as major storms, reducing the duration and frequency of outages. Consumers also benefit from a greater variety of options and information, giving them more precise control about their personal energy use. Finally, the integration of more renewable energy resources allows consumers to contribute significantly to broader environmental social goals, giving them additional satisfaction in knowing that they are helping to protect the environment.

At the same time, the transactive energy approach also provides a number of other key benefits to society. First, it enables better consumer response in the event of grid overload, thereby decreasing the necessity to install new power plants. By giving consumers the right tools to manage and adjust the timing of their energy consumption, large daily fluctuations in energy use, a process known as "demand response," can be smoothed out. If utilities can reduce peak demand, for example, on the hottest day of the year, they might not be required to construct extra power plants. In addition, greater use of cost-effective renewable energy generation, particularly from varying energy sources such as wind and solar, may need additional tools to operate the grid, and transactive energy could facilitate these tools. Utilities also will be enabled to "ask" consumers, via price signals delivered to smart devices, homes, or buildings, to increase or decrease their consumption, providing an improved supply/demand balancing in real-time. Finally, reliability and resilience can be enhanced with a much more decentralized system empowered by transactive energy. Since the increase in the occurrence of extreme weather conditions, this will be particularly relevant. Furthermore, the deployment of market forces may encourage grid-responsive technologies and grid-friendly consumer practices, as well as drive improvements in the efficiency and reliability of the energy system [19].

3. Comparative analysis of the energy sharing models for energy communities

An analysis of the main similarities and differences of the three models described in section 2.1, 2.2 and 2.3 is provided in this section. Their theoretical differences are further examined and quantitatively assessed considering the numerical results obtained through a model evaluation.

3.1. Objectives and scope

The three models examined represent different but complementary approaches to energy management and distribution. Model 1, which will be referred to as the **Grid Interaction Minimization Model**, focuses on facilitating direct transactions between generators and individual consumers, eliminating intermediaries and encouraging active participation in energy markets. This model promotes energy autonomy and cost optimization by allowing users to set prices and negotiate directly according to their needs and preferences.

On the other hand, Model 2, referred to as the **Cost Minimization Model** aims to minimize the total energy costs within a geographically close community. By optimizing the allocation of locally generated energy, this model seeks to reduce the need for costly imports from the conventional power grid. It focuses on maximizing the use of available renewable resources and minimizing energy losses, often associated with long-distance transportation. By doing so, it promotes sustainable practices and ensures that the community can achieve the lowest possible energy costs.

Lastly, the main objective of Model 3, referred to as the **Independent Cost Minimization Model**, is to minimize the total energy costs without allowing energy exchange between households within the community. This approach ensures that each household operates independently, optimizing its own energy consumption and production. By restricting energy sharing, the model focuses on real-time balancing of supply and demand through decentralized economic and control mechanisms. This method not only enhances the resilience of the power grid to fluctuations and extreme events but also facilitates the integration of variable renewable energy sources, such as solar and wind. By enabling consumers to actively manage their energy usage and respond to price signals, the model aims to optimize the use of existing electricity infrastructure and promote more efficient and sustainable consumption practices.

3.2. Technology and infrastructure

The three models under study represent different approaches to optimizing electricity consumption and distribution, each with unique characteristics in terms of the technology and infrastructure required.

Model 1 focuses on establishing digital platforms that enable direct transactions between network customers, encouraging active participation in energy markets. This involves the implementation of advanced technological systems that guarantee trust and transparency in transactions, as seen in decentralized structures and distributed data storage systems.

In contrast, Model 2 focuses on minimizing costs by sharing locally generated energy within a geographically close community, promoting efficiency and optimal use of renewable resources. Although it may require significant organizational infrastructure, including the

creation of a legal entity like an energy cooperative to ensure organization and equity in the distribution of generated energy, it typically requires less sophisticated digital technology compared to Model 1. This is because Model 2 primarily relies on local energy exchanges within a small community, reducing the need for complex, real-time transaction systems and extensive data storage and security measures that are essential for broader, decentralized market participation as seen in Model 1.
Model 3 aims to minimize costs without allowing energy exchange between houses. It is characterized by its ability to balance energy supply and demand in real-time through economic incentives, improving the resilience and efficiency of the global power grid. This model requires advanced technological infrastructure to facilitate decentralized and automatic transactions between distributed generation and load resources, enabling smooth integration of renewable energy sources and dynamic energy demand management.

3.3. Impact on the electric grid

In terms of their impact on the electric grid, Models 1, 2, and 3 contribute differently based on their objectives and operational strategies.
Model 1 aims to minimize imported and exported energy with the grid by establishing digital platforms for direct transactions between generators and consumers. This approach reduces the need for long-distance energy transport, thereby minimizing energy losses associated with transmission. By more efficiently integrating distributed energy resources such as solar and wind, Model 1 helps relieve pressure on centralized grids, promoting stability and resilience to fluctuations and unexpected events.

Model 2 focuses on minimizing costs by locally balancing supply and demand within communities. By maximizing the use of locally generated renewable energy like solar PV or wind, this model reduces reliance on energy imported from conventional power grids. This localized approach not only mitigates losses from long-distance transmission but also optimizes existing infrastructure without the need for costly expansions.

Model 3 aims to minimize costs without allowing energy exchange between houses, utilizing real-time responsiveness to dynamically manage energy supply and demand. This adaptive capability not only enhances operational efficiency but also facilitates the integration of renewable energy sources such as solar and wind. By reducing dependence on conventional energy sources, Model 3 contributes to grid consistency and resilience, particularly during periods of peak demand or emergencies.

Table 1 summarizes all aspects of the comparison.

	Model 1	**Model 2**	**Model 3**
Objectives and scope	Minimize grid interactions	Minimize total costs	Minimize total costs without allowing energy exchanges between houses
Technology and infrastructure	Advanced technological systems for transparent transactions	Creation of a legal entity for effective management of power distribution operations and agreements	Advanced technological infrastructure to facilitate transactions between distributed generation and load resources
Impact on the electric grid	Helps relieve pressure on centralized grids, promoting stability and resilience to fluctuations	Mitigates losses from long-distance transmission and optimizes existing infrastructure	Enhances operational efficiency but also facilitates the integration of renewable energy sources

Table 1: Comparison between P2P, CSC and TE

4. Mathematical formulation of the energy sharing models

This study involves performing a centralized CET optimization, where the output is the energy dispatch of market participants over the considered time horizon T and considering h homes. The market choices are analyzed and optimized every time interval of one hour (t). To develop the market model, MATLAB is used.

The variables, parameters, scalars and sets to be used in the model are defined in Table 2 and Table 3:

Variables	
$G^{t,h}$	Energy consumption from the grid of home *h* at instant *t*
$I^{t,h}$	Imports from peers in the community to home *h* at instant *t*
$E^{t,h}$	Energy stores at ESS of home *h* at instant *t*
$D^{t,h}$	ESS discharge power at home *h* at instant *t*
$D_{EV}{}^{t,h}$	EV discharge power at home *h* at instant *t*
$X^{t,h}$	Exports to peers in the community from home *h* at instant *t*
$E_{EV}{}^{t,h}$	Energy stored at EV of home *h* at instant *t*
$F^{t,h}$	Energy supply to the main grid from home *h* at instant *t*
$C^{t,h}$	ESS charge power at home *h* at instant *t*
$C_{EV}{}^{t,h}$	EV charge power at home *h* at instant *t*
$I_P{}^{(t,h<-p)}$	Energy imported to home *h* from its peer *p* at instant *t*
$X_P{}^{(t,h->p)}$	Energy imported from home *h* to its peer *p* at instant *t*

Table 2: Definition of variables for the model

Parameters, scalars and sets	
$dem^{t,h}$	Demand of home *h* at instant *t*
$pv^{t,h}$	PV generation of home *h* at instant *t*
$p_G{}^t$	Import price at instant *t*
$p_F{}^t$	Export price at instant *t*
η^c	ESS charging efficiency
η^d	ESS discharging efficiency
$P_d{}^{t,h}$	Net power demand of home *h* at instant *t*
η_{EV}^c	EV charging efficiency
η_{EV}^d	EV discharging efficiency
$\overline{C}$ and $\overline{D}$	Upper limits of charging and discharging power of ESS
$\overline{C}_{EV}$ and $\overline{D}_{EV}$	Upper limits of charging and discharging power of EV
$\overline{E}$ and $\underline{E}$	Upper and lower limits of ESS storage level
$\overline{E}_{EV}$ and $\underline{E}_{EV}$	Upper and lower limits of EV storage level
b^t	Binary parameter to define if the EV is connected to the LVDN
Δt	Trading period duration
ψ^{P2P}	P2P trade loss factor
$t \in T$	Time instant *t* in time horizon *T*
$h,p \in H$	Home *h* and peers *p* in a community of *H* homes
λ	Penalty for imbalance of home *h* at instant *t*

Table 3: Definition of parameters, scalars and sets for the model

After examining the typical energy sharing models for energy communities, four distinct scenarios have identified and selected that illustrate potential objectives and goals these models could achieve. These scenarios encompass a range of strategies aimed at optimizing energy distribution, enhancing community engagement, and promoting sustainability. Each scenario reflects a unique approach to leveraging the benefits of energy sharing within a community framework.

The objective of the first case proposed, Model 1, is to facilitate the direct transaction between producers and consumers without the need for intermediaries, so for the formulation of the objective function it could be translated into the minimization of the energy that is imported from the grid and exported to the grid, since in both cases intermediaries are necessary, unlike in the case of energy exchanges from one house to another. The objective function would be as follows:

$$\min \sum_{t \in T} \sum_{h \in H} (G^{t,h} + F^{t,h}) * \Delta t$$

Equation 1: Objective function for Model 1

For Model 2, the main objective is to optimize the equilibrium between energy demand and supply in real time by using price signals. Therefore, the objective function is going to minimize the cost of importing energy for the community from the retailer and maximize the profit from exporting the community's energy surplus back to the retailer. The objective function would be as follows:

$$\min \sum_{t \in T} \sum_{h \in H} (G^{t,h} * p_G^t - F^{t,h} * p_F^t) * \Delta t$$

Equation 2: Objective function for Model 2

For Model 3, a model closely resembling Model 3 will be utilized, where the objective function aims to minimize the cost of importing energy for the community from the retailer and maximize profits from exporting surplus energy back to the retailer. However, in this case, energy exchange between households within the same energy community is strictly prohibited. This restriction means that each household operates independently, without sharing or trading energy with other houses in the community. This scenario has been chosen to determine which case offers more advantages, minimizing costs with or without allowing energy exchange between households. The objective function for this scenario will be defined, and specific boundary conditions tailored accordingly will be detailed later in the definition phase:

$$\min \sum_{t \in T} \sum_{h \in H} (G^{t,h} * p_G^t - F^{t,h} * p_F^t) * \Delta t$$

Equation 3: Objective function for Model 3

In each domestic node, which represents an individual household or residential unit within the energy community, there must be an equilibrium demand-supply balance at each time instant t. This implies that the sum of the power consumption coming from the network $G^{t,h}$, the imports of community peers $I^{t,h}$, PV generation $pv^{t,h}$, ESS discharge $D^{t,h}$, and EV discharge $D_{EV}{}^{t,h}$, has to be greater or equal than to the sum of the exports to peers of the community

$X^{t,h}$, supply to the main grid $F^{t,h}$, demand $dem^{t,h}$, ESS charge $C^{t,h}$, and EV charge $C_{EV}{}^{t,h}$. This expression is as shown below:

$$G^{t,h} + I^{t,h} + pv^{t,h} + D^{t,h} + D_{EV}^{t,h} \geq X^{t,h} + \; F^{t,h} + dem^{t,h} + C^{t,h} + C_{EV}^{t,h} \qquad \forall t \in T, \quad \forall h \in H$$

Equation 4: Constraint 1

The ESS installed must operate within its nominal values. The charging $C^{t,h}$ and discharging $D^{t,h}$ are constrained by the power rating of the electronic converter that links the ESS to the LVDN. The minimum charging and discharging power limits are set to zero, while the maximum limits are $\bar{C}$ and $\bar{D}$, respectively, as described in equations (5) and (6). Additionally, the ESS has defined lower and upper limits for the stored energy $E^{t,h}$ in kWh, as specified in equation (7). The state of charge (SoC) for the ESS is assumed to stay within a range of 20% to 100%. the equations mentioned above are as follows:

$$0 \leq \; C^{t,h} \leq \underline{C} \qquad \forall t \in T, \qquad \forall h \in H$$

Equation 5: Constraint 2

$$0 \leq \; D^{t,h} \leq \underline{D} \qquad \forall t \in T, \qquad \forall h \in H$$

Equation 6: Constraint 3

$$\underline{E} \leq \; E^{t,h} \leq \bar{E} \qquad \forall t \in T, \qquad \forall h \in H$$

Equation 7: Constraint 4

The energy stored in each ESS $E^{t,h}$ at a given time *t* for a home *h* is determined by equation (8). Here, $\eta^{c}$and η^{d} represent the charging and discharging efficiencies, respectively. $E^{(t-1,h)}$ is the energy stored at the previous time instant t−1. On the first day, the initial SoC of each ESS is a random value that is at least 20% (i.e., 2.7 kWh). For subsequent days, the ESS storage level at the beginning of the day is set to the final storage level from the previous day. This approach is used consistently throughout the simulation period.

$$E^{t,h} = E^{t-1,h} + \eta^{c} * \; C^{t,h} * \Delta t - \left(\frac{1}{\eta^{d}}\right) * \; D^{t,h} * \Delta t \qquad \forall t \in T, \qquad \forall h \in H$$

Equation 8: Constraint 5

In a similar manner, the installed EVs must function within their designated ratings. The charging $C_{EV}{}^{t,h}$ and discharging $D_{EV}{}^{t,h}$ are restricted by the power rating of the charger connecting the EV to the LVDN. The minimum charging and discharging power limits are zero, while the maximum limits are $\bar{C}_{EV}$ and $\bar{D}_{EV}$, respectively, as specified in equations (9) and (10). Additionally, the EV has defined lower and upper limits for the stored energy $E_{EV}{}^{t,h}$ in kWh, as described in equation (11).

$$0 \leq C_{EV}^{t,h} \leq \overline{C_{EV}} * b^{t} \qquad \forall t \in T, \qquad \forall h \in H$$

Equation 9: Constraint 6

$$0 \leq D_{EV}^{t,h} \leq \overline{D_{EV}} * b^{t} \qquad \forall t \in T, \qquad \forall h \in H$$

Equation 10: Constraint 7

$$\underline{E_{EV}} \leq E_{EV}^{t,h} \leq \overline{E_{EV}} * b^t \quad \forall t \in T, \quad \forall h \in H$$

Equation 11: Constraint 8

b^t is a binary parameter indicating whether the EV is connected to the LVDN for charging at time instant t, as specified in equation (12). The value of b^t is 1 when the EV is connected to the LVDN and 0 when it is not as the following expression shows:

$$b^t = \begin{cases} 1, if \text{ EV is connected to the LVDN at time instant t} \\ 0, otherwise \end{cases}$$

Equation 12: Constraint 9

The energy stored in each EV $E_{EV}^{t,h}$ connected to the grid at a given time t is determined by equation (13). Here, η_{EV}^{c} and η_{EV}^{d} represent the EV charging and discharging efficiencies, respectively. $E_{EV}^{t-1,h}$ is the energy stored at the previous time instant t−1. On the first day, the initial stored energy in each EV is a random value of at least 4.8 kWh (i.e., 20% SoC). For subsequent days, the EV storage level at the beginning of the day is set to the final storage level from the previous day. This pattern continues throughout the simulation period. EVs are assumed to be connected to the grid from 5 pm to 8 am daily and used for transportation during the remaining hours. The EV battery's SoC decreases during use for transportation, and the initial SoC at the start of charging depends on the SoC when disconnected from the grid and the driving distance. The EV battery's SoC is assumed to remain between 20% and 100%. The SoC at departure time (8 am) should be at least 75% to ensure the EV owner's mobility needs and comfort are met.

$$E_{EV}^{t,h} = E_{EV}^{t-1,h} + \eta_{EV}^{c} * C_{EV}^{t,h} * \Delta t - \left(\frac{1}{\eta_{EV}^{d}}\right) * D_{EV}^{t,h} * \Delta t \quad \forall t \in T, \quad \forall h \in H$$

Equation 13: Constraint 10

In the local community, the import of prosumer h from peer p equals the export from p to h at each time instant t, accounting for P2P trade losses in the LVDN, as specified in equation (14). ψ^{P2P} accounts for the losses in the LVDN due to P2P trade. A 5% loss is adopted for P2P trade within the community (i.e., ψ^{P2P}=0.95).

$$I_p^{t,h\leftarrow p} = \psi^{P2P} * X_p^{t,h\rightarrow p} \quad \forall \neq h$$

Equation 14: Constraint 11

Each home with installed DERs can sell energy to any peer within the community. The total energy sold (i.e., exported) $X^{t,h}$ from any home in the community h ∈ H at time instant t is the sum of the energy exported $X_p^{t,h\rightarrow p}$ from this home h to another peer p ∈ H, as described in equation (15).

$$X^{t,h} = \sum_{p\neq h} X_p^{t,h\rightarrow p} \quad \forall t \in T, \quad \forall h \in H$$

Equation 15: Constraint 12

In the same way, the total amount of purchased energy (i.e., imported) $I^{t,h}$ for any home h ∈ H at time instant *t* is the sum of the energy imported $I_p^{t,h\leftarrow p}$ for this home *h* from another peer p ∈ H, as described in the following equation (16).

$$I^{t,h} = \sum_{p \neq h} I_p^{t,h\leftarrow p} \quad \forall t \in T, \quad \forall h \in H$$

Equation 16: Constraint 13

Since P2P trading occurs within the community, the total sales from homes must equal the total purchases by homes, taking into account the P2P trade losses in the LVDN, as stated in equation (17).

$$\sum_{h} \psi^{P2P} * X^{t,h} = \sum_{h} I^{t,h}$$

Equation 17: Constraint 14

In the case of Model 4, it will be necessary in addition to constraints 5 to 18, to add the following ones:

$$X_p^{t,h\rightarrow p} = 0$$

Equation 18: Constraint 15

$$I_p^{t,h\rightarrow p} = 0$$

Equation 19: Constraint 16

The second step of this analyses is to study the impact that each of the scenarios has in the distribution network. This will be done using the following model. For each of the scenarios mentioned above, the net power demand $P_d^{t,h}$ of each home *h* at each time instant *t* is calculated by is computed using the following expression:

$$P_d^{t,h} = G^{t,h} + I^{t,h} - X^{t,h} - F^{t,h}$$

Equation 20: Net power demand

The value obtained for $P_d^{t,h}$ is then entered as input into the Pandapower software to run the power flow.

In practical operating conditions, it's ideal for the load across the three phases to be balanced. This balance ensures that no current flows through the neutral line, minimizing power losses. However, in reality, there is often imbalance among the loads connected to each phase at distribution networks (DNs). Managing this imbalance within specific limits is crucial to ensure normal DN operation and to meet the requirements of 3-phase loads that depend on a balanced supply.

Traditionally, maintaining balanced phase loads was straightforward due to similar consumption patterns among consumers in a given area. However, the rise of various single-phase Distributed Energy Resources (DERs) such as photovoltaic (PV) systems, Energy Storage Systems (ESS), and Electric Vehicles (EVs) is changing this scenario. These DERs can significantly alter consumption and production patterns based on retailer and local trading prices, potentially increasing phase unbalance in DNs.

Voltage Unbalance Factor (VUF%) is a critical metric in assessing this imbalance, typically defined as the ratio of negative sequence component to positive sequence component. The maximum allowable VUF% is generally set at 2%. Studying the impacts of Community Energy Trading (CET) on phase unbalance becomes crucial as it could further influence consumption behaviors and thereby affect VUF%. It is computed as follows:

$$VUF\% = \left(\frac{V2}{V1}\right) * 100$$

Equation 21: Voltage unbalance factor

5. Case study results

5.1. Definition of the scenarios to be analyzed

The model outlined in Section 0 will be applied to a scenario involving an energy community composed of 55 households. This community counts with a radial topology, typical in Low Voltage Distribution Networks (LVDN) in Europe. The test grid connects to the main grid through an MV/LV transformer rated at 800 kVA, stepping down the voltage from 11 kV to 416 V with delta/grounded star grounded winding connections. The transformer windings have a resistance of 0.4% and reactance of 4%. Within this setup, 55 single-phase residential consumers are linked to the LVDN, each having distinct connection points. Consumer connections to phases are designated by colors: phase A in blue, phase B in green, and phase C in orange, as shown in Figure 4. Specifically, 21 consumers are connected to phase A, 19 to phase B, and 15 to phase C. These configurations are based on anonymized real consumption data from Madrid, Spain, provided by i-DE, a Spanish DSO under the Iberdrola Group. Each consumer has a unique consumption profile randomly assigned from recorded measurements of Madrid consumers. Notably, the market model exclusively trades active power and disregards reactive power considerations, assuming a constant power factor of 0.95 pu for the loads in the power flow analysis [20].

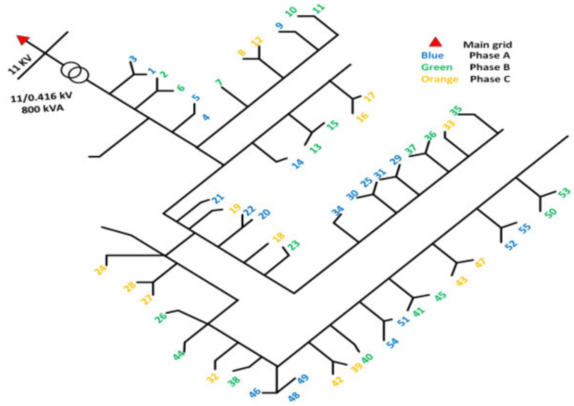


Figure 4: Low Voltage Distribution Network of study

Different Distributed Energy Resources (DERs), including photovoltaic systems (PV), energy storage systems (ESS), and electric vehicles (EV), are connected to the Low Voltage Distribution Network (LVDN) under study. Each consumer might have one or more of these DERs, or none at all. Table 4 provides details on the DER installations at each household. Cells marked in green indicate the presence of the DER, while cells marked in red indicate its absence. The PV systems have a power rating of 5 kWp, with 33 PV units installed across the community, representing 60% of the consumers. The ESS units are rated at 13.5 kWh/5 kW, with both charging and discharging efficiencies at 95%. A total of 22 ESS units are installed, covering 40% of the community. The EVs feature 24 kWh batteries and 3.6 kW chargers, reflecting the specifications of a Nissan Leaf, with charging and discharging efficiencies of 96%. These bidirectional EV chargers support both grid-to-vehicle (G2V) and vehicle-to-grid (V2G) energy transfers. In total, 18 EVs are installed, accounting for 33% of the consumers.

Home	PV	ESS	EV	Home	PV	ESS	EV	Home	PV	ESS	EV
1	🟩	🟩	🟥	20	🟩	🟩	🟩	39	🟩	🟥	🟩
2	🟩	🟩	🟩	21	🟥	🟥	🟥	40	🟩	🟩	🟥
3	🟩	🟩	🟥	22	🟥	🟥	🟥	41	🟩	🟥	🟩
4	🟥	🟥	🟥	23	🟩	🟩	🟥	42	🟥	🟥	🟥
5	🟩	🟩	🟥	24	🟩	🟥	🟥	43	🟩	🟥	🟥
6	🟥	🟥	🟥	25	🟩	🟥	🟩	44	🟥	🟥	🟥
7	🟩	🟥	🟩	26	🟥	🟥	🟥	45	🟩	🟩	🟥
8	🟩	🟥	🟥	27	🟩	🟩	🟥	46	🟥	🟥	🟩
9	🟩	🟩	🟩	28	🟥	🟥	🟩	47	🟥	🟥	🟥
10	🟥	🟥	🟥	29	🟥	🟥	🟥	48	🟩	🟩	🟥
11	🟥	🟥	🟥	30	🟩	🟩	🟥	49	🟩	🟥	🟩
12	🟩	🟩	🟩	31	🟥	🟥	🟩	50	🟩	🟩	🟩
13	🟥	🟥	🟥	32	🟩	🟥	🟥	51	🟥	🟥	🟥
14	🟥	🟥	🟥	33	🟩	🟩	🟥	52	🟩	🟩	🟥
15	🟩	🟩	🟥	34	🟩	🟥	🟥	53	🟩	🟩	🟩
16	🟩	🟥	🟩	35	🟥	🟥	🟩	54	🟩	🟩	🟩
17	🟥	🟥	🟥	36	🟥	🟥	🟥	55	🟩	🟩	🟩
18	🟩	🟩	🟥	37	🟩	🟩	🟥				
19	🟥	🟥	🟥	38	🟥	🟥	🟥				

Table 4: DERs installed in each household

For this analysis, Spanish energy prices for buying and selling from/to retailers are applied. Prosumers purchase energy according to the retailer's tariff and sell surplus energy based on the self-consumption surplus energy price under the regulated PVPC tariff in Spain, as shown in Figure 5. The energy prices for July 2021 were sourced from the Spanish Transmission System Operator, Red Eléctrica.

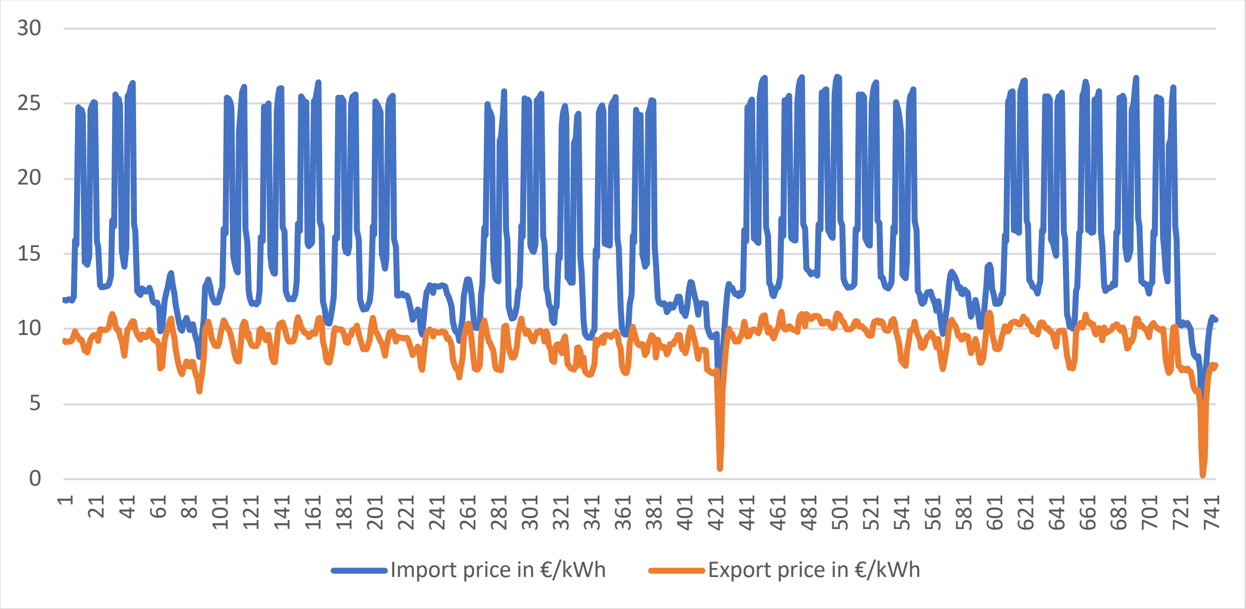


Figure 5: Prosumers purchase/sell prices from/to retailer

The baseline case against which all scenarios are compared is the one without distributed energy resources, and it has the following data for each month, as Table 6 shows. To estimate the consumption of the rest of the months the method explained below.

When taking into account the DERs, the only data available and collected as input for running the MATLAB model the first time were those corresponding to the month of July, so in order to carry out the economic analysis it will be necessary to extrapolate the results to the rest of the months of the year.

First, for the demand, two types of months will be assumed, in a first group will be the months of January, February, March, July, August and December. These months are characterized by very high or very low temperatures, and a constant demand will be assumed assuming that the heating consumption in the warmer months will be equivalent to the heating consumption in the colder months. The second group of months will be April, May, June, September, October and November, in which the demand is reduced by about 25% as can be seen in Figure 6, which represents the monthly consumption in an average household in Spain over a year [21].

Figure 6: Monthly electricity consumption of an average household in Spain

On the other hand, for the production of PV energy, it must be taken into account that the solar energy production of a fixed solar panel system varies during the different months of the year. That is why the months of the year will be grouped into three groups, taking into account the solar radiation in each month, as can be seen in Figure 7, and assuming that the hours of solar energy production remain constant during all months of the year. That is why the three differentiated groups will be composed, firstly, by the months of January, February, November and December, in which the solar production will be 65% less than the reference case, that is, the month of July; secondly by the months of March, April, May, June, September, October, in which the production of solar energy will be 30% less than the reference case; and finally the third group will be composed by July and August in which the production will be significantly higher than the rest, being the reference case.

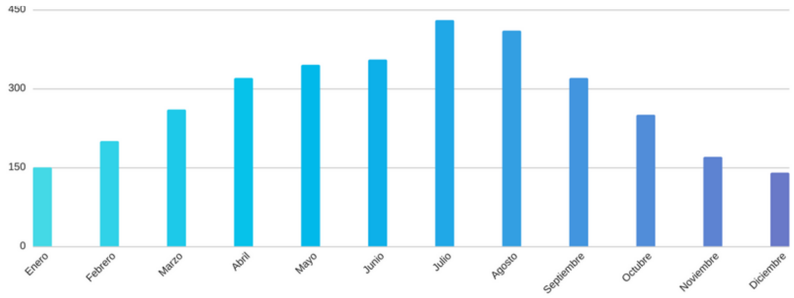


Figure 7: Solar radiation in each month in Spain

Taking as reference the base case, i.e., July, each of the months will have the following PV demand and production, with Dem_{JULY} and PV_{JULY} being the demand and production of electrical energy from the PV panels in July, respectively, as shown in Table 5:

Month	Demand	PV production
January	Dem_{JULY}	35% of PV_{JULY}
February	Dem_{JULY}	35% of PV_{JULY}
March	Dem_{JULY}	70% of PV_{JULY}
April	75% of Dem_{JULY}	70% of PV_{JULY}
May	75% of Dem_{JULY}	70% of PV_{JULY}
June	75% of Dem_{JULY}	70% of PV_{JULY}
July	Dem_{JULY}	PV_{JULY}
August	Dem_{JULY}	PV_{JULY}
September	75% of Dem_{JULY}	70% of PV_{JULY}
October	75% of Dem_{JULY}	70% of PV_{JULY}
November	75% of Dem_{JULY}	35% of PV_{JULY}
December	Dem_{JULY}	35% of PV_{JULY}

Table 5: Demand and PV production in each month

Once the values of demand and PV production for each month are obtained, the following indicators for each month are generated with the MATLAB model, as shown in Table 7 for the reference model, **¡Error! No se encuentra el origen de la referencia.** for Model 1, Table 8 for Model 2 and Table 9 for Model 3 with the information extrapolated for each month as explained above.

REFERENCE CASE													
Indicator	**Value**												
	January	**February**	**March**	**April**	**May**	**June**	**July**	**August**	**Semptember**	**October**	**November**	**December**	**TOTAL**
Total energy cost for the community	7622,45€	7622,45€	7622,45€	5716,83€	5716,83€	5716,83€	7622,45€	7622,45€	5716,83€	5716,83€	5716,83€	7622,45€	80035,68 €
Average total energy cost per household	138,59 €	138,59 €	138,59 €	103,94 €	103,94 €	103,94 €	138,59 €	138,59 €	103,94 €	103,94 €	103,94 €	138,59 €	1455,18 €
Total cost of energy imported from the grid	7622,45 €	7622,45 €	7622,45 €	5716,83€	5716,83€	5716,83€	7622,45 €	7622,45 €	5716,83€	5716,83€	5716,83€	7622,45 €	80035,68 €
Revenues generated by exporting energy to the grid	0 €	0 €	0 €	0 €	0 €	0 €	0 €	0 €	0 €	0 €	0 €	0 €	0 €
Total energy exchanged between households (imported and exported)	0 kWh	0 kWh	0 kWh	0 kWh	0 kWh	0 kWh	0 kWh	0 kWh	0 kWh	0 kWh	0 kWh	0 kWh	0 kWh
Total amount of energy imported from the grid	47228,78 kWh	47228,78 kWh	47228,78 kWh	35421,58 kWh	35421,58 kWh	35421,58 kWh	47228,78 kWh	47228,78 kWh	35421,58 kWh	35421,58 kWh	35421,58 kWh	47228,78 kWh	495902,16 kWh
Total amount of energy exported to the grid	0 kWh	0 kWh	0 kWh	0 kWh	0 kWh	0 kWh	0 kWh	0 kWh	0 kWh	0 kWh	0 kWh	0 kWh	0 kWh
Percentage of energy supplied from the grid	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	
Percentage of energy supplied by distributed energy resources (DERs including exchanges between households)	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	
Maximum power consumption from the grid at any given time	105,91 kW	105,91 kW	105,91 kW	105,91 kW	105,91 kW	105,91 kW	105,91 kW	105,91 kW	105,91 kW	105,91 kW	105,91 kW	105,91 kW	

Table 6: Results obtained in MATLAB for the reference case

MODEL 1													
Indicator	**Value**												
	January	**February**	**March**	**April**	**May**	**June**	**July**	**August**	**Semptember**	**October**	**November**	**December**	**TOTAL**
Total energy cost for the community	6349,50 €	6349,50 €	4720,10 €	2567,70 €	2567,70 €	2567,70 €	**3446,60 €**	3446,60 €	2567,70 €	2567,70 €	4457,50 €	6349,50 €	47957,8 €
Average total energy cost per household	115,4457 €	115,4457 €	85,8205 €	46,6856 €	46,6856 €	46,6856 €	**62,6651 €**	62,6651 €	46,6856 €	46,6856 €	81,0447 €	115,4457 €	871,961 €
Total cost of energy imported from the grid	6349,50 €	6349,50 €	4720,10 €	2567,70 €	2567,70 €	2567,70 €	**3446,60€**	3446,60€	2567,70 €	2567,70 €	4457,50 €	6349,50 €	47957,8 €
Revenues generated by exporting energy to the grid	0 €	0 €	0 €	0 €	0 €	0 €	**0 €**	0 €	0 €	0 €	0 €	0 €	0 €
Total energy exchanged between households (imported and exported)	3320,7 kWh	3320,7 kWh	9247,40 kWh	10196 kWh	10196 kWh	10196 kWh	**13790 kWh**	13790 kWh	10196 kWh	10196 kWh	4223,7 kWh	3320,7 kWh	101993,2 kWh
Total amount of energy imported from the grid	42184 kWh	42184 kWh	32814 kWh	19302 kWh	19302 kWh	19302 kWh	**25482 kWh**	25482 kWh	19302 kWh	19302 kWh	30422 kWh	42184 kWh	337262 kWh
Total amount of energy exported to the grid	0 kWh	0 kWh	0 kWh	0 kWh	0 kWh	0 kWh	**0 kWh**	0 kWh	0 kWh	0 kWh	0 kWh	0 kWh	0 kWh
Percentage of energy supplied from the grid	89,3185%	89,3185%	69,4788%	58,3835%	58,3835%	58,3835%	**53,9538%**	53,9538%	58,3835%	58,3835%	86,886%	89,3185%	-
Percentage of energy supplied by distributed energy resources (DERs including exchanges between households)	10,6815%	10,6815%	30,5212%	41,6165%	41,6165%	41,6165%	**46,0462%**	46,0462%	41,6165%	41,6165%	14,114%	10,6815%	-
Maximum power consumption from the grid at any given time	112,4707 kW	112,4707 kW	111,433 kW	96,4449 kW	96,4449 kW	96,4449 kW	**110,0069 kW**	110,0069 kW	96,4449 kW	96,4449 kW	100,221 kW	112,4707 kW	-

Table 7: Results obtained in MATLAB for Model 1

MODEL 2													
Indicator	**Value**												
	January	**February**	**March**	**April**	**May**	**June**	**July**	**August**	**Semptember**	**October**	**November**	**December**	**TOTAL**
Total energy cost for the community	5341,40 €	5341,40 €	4016,1 €	2508,30 €	2508,30 €	2508,30 €	**3007,30 €**	3007,30 €	2508,30 €	2508,30 €	3721,60 €	5341,40 €	42318 €
Average total energy cost per household	97,1163 €	97,1163 €	73,0207 €	46,605 €	46,605 €	46,605 €	**54,6780 €**	54,6780 €	46,605 €	46,605 €	67,6646 €	97,1163 €	774,425 €
Total cost of energy imported from the grid	5344,60 €	5344,60 €	4028,5 €	2576,30 €	2576,30 €	2576,30 €	**3095,7 €**	3095,7 €	2576,30 €	2576,30 €	3743,20 €	5344,60 €	42878,5 €
Revenues generated by exporting energy to the grid	3,2304 €	3,2304 €	12,3224 €	67,9878 €	67,9878 €	67,9878 €	**88,4209 €**	88,4209 €	67,9878 €	67,9878 €	21,6934 €	3,2304 €	560,4878 €
Total energy exchanged between households (imported and exported)	10138 kWh	10138 kWh	13988 kWh	12916 kWh	12916 kWh	12916 kWh	**16796 kWh**	16796 kWh	12916 kWh	12916 kWh	9452,20 kWh	10138 kWh	152026,2 kWh
Total amount of energy imported from the grid	43749 kWh	43749 kWh	34089 kWh	22579 kWh	22579 kWh	22579 kWh	**26621 kWh**	26621 kWh	22579 kWh	22579 kWh	31819 kWh	43749 kWh	363292 kWh
Total amount of energy exported to the grid	30,8389 kWh	30,8389 kWh	122,0241 kWh	693,4945 kWh	693,4945 kWh	693,4945 kWh	**927,1702 kWh**	927,1702 kWh	693,4945 kWh	693,4945 kWh	211,2148 kWh	30,8389 kWh	5747,57 Kwh
Percentage of energy supplied from the grid	92,6326%	92,6326%	72,1791%	64,7425%	64,7425%	64,7425%	**56,3653%**	56,3653%	64,7425%	64,7425%	89,8282%	92,6326%	-
Percentage of energy supplied by distributed energy resources (DERs including exchanges between households)	7,3674%	7,3674%	27,8209%	36,2575%	36,2575%	36,2575%	**43,6347%**	43,6347%	36,2575%	36,2575%	10,1718%	7,3674%	-
Maximum power consumption from the grid at any given time	228,062 kW	228,062 kW	228,962 kW	215,4215 kW	215,4215 kW	215,4215 kW	**228,9620 kW**	228,9620 kW	215,4215 kW	215,4215 kW	215,4215 kW	228,062 kW	-

Table 8: Results obtained in MATLAB for Model 2

MODEL 3													
Indicator	**Value**												
	January	**February**	**March**	**April**	**May**	**June**	**July**	**August**	**Semptember**	**October**	**November**	**December**	**TOTAL**
Total energy cost for the community	6116,40 €	6116,40 €	5026,9 €	3369,30 €	3369,30 €	3369,30 €	**4165,60 €**	4165,60 €	3369,30 €	3369,30 €	4398 €	6116,40 €	52951,8 €
Average total energy cost per household	111,2078 €	111,2078 €	91,3982 €	61,2609 €	61,2609 €	61,2609 €	**75,7378 €**	75,7378 €	61,2609 €	61,2609 €	79,9644 €	111,2078 €	962,7661 €
Total cost of energy imported from the grid	6390,90 €	6390,90 €	5782,9 €	4321 €	4321 €	4321 €	**5486,3 €**	5486,3 €	4321 €	4321 €	4756,9 €	6390,90 €	62290,1 €
Revenues generated by exporting energy to the grid	274,4899 €	274,4899 €	756,0349 €	951,6184 €	951,6184 €	951,6184 €	**1320,7 €**	1320,7 €	951,6184 €	951,6184 €	358,8097 €	274,4899 €	9337, 806 €
Total energy exchanged between households (imported and exported)	0 kWh	0 kWh	0 kWh	0 kWh	0 kWh	0 kWh	**0 kWh**	0 kWh	0 kWh	0 kWh	0 kWh	0 kWh	0 kWh
Total amount of energy imported from the grid	45588 kWh	45588 kWh	40982 kWh	31087 kWh	31087 kWh	31087 kWh	**38724 kWh**	38724 kWh	31087 kWh	31087 kWh	34493 kWh	45588 kWh	445122 kWh
Total amount of energy exported to the grid	2877,3 kWh	2877,3 kWh	7998,5 kWh	10032 kWh	10032 kWh	10032 kWh	**14040 kWh**	14040 kWh	10032 kWh	10032 kWh	3754,5 kWh	2877,3 kWh	98624,9 kWh
Percentage of energy supplied from the grid	96,5268%	96,5268%	86,7723%	87,7615%	87,7615%	87,7615%	**81,9919%**	81,9919%	87,7615%	87,7615%	97,3786%	96,5268%	-
Percentage of energy supplied by distributed energy resources (DERs including exchanges between households)	3,4732%	3,4732%	13,2277%	12,2385%	12,2385%	12,2385%	**18,0081%**	18,0081%	12,2385%	12,2385%	2,6214%	3,4732%	-
Maximum power consumption from the grid at any given time	208,1412 kW	208,1412 kW	174,2804 kW	144,8068 kW	144,8068 kW	144,8068 kW	**159,8371 kW**	159,8371 kW	144,8068 kW	144,8068 kW	179,7299 kW	208,1412 kW	-

Table 9: Results obtained in MATLAB for Model 3

5.2. Methodology

The different steps to be carried out for the analysis of the proposed scenarios are explained below.

5.2.1 Economic assessment through economic indicators

To conduct the economic study, a period of 20 years will be considered [22], which corresponds to the lifespan of a photovoltaic installation. For this purpose, it will be assumed that the data obtained for one year will be used for all the years of the project's lifespan.

- Cost assessment

First, it will be necessary to know what the **initial costs** of the total energy community have been, including infrastructure, permits and licenses.
For the **cost of the infrastructure**, it must first be taken into account that not all homes have photovoltaic panels. In the energy community under study, only 60% of the houses have photovoltaic installations. To compute the infrastructure cost, several pieces of data need to be known, being this the number of PV panels and the photovoltaic generation capacity of a specified kWp. With this data, it is now possible to estimate the price of each residential solar panel. Assuming 100% efficiency, the total cost of the infrastructure for the entire energy community will be computed accordingly:

$$Total\ cost\ of\ PV\ infraestructure = nº\ PV\ panels * Cost\ of\ 1\ PV\ panel$$

Equation 22: Total cost of PV infrastructure

In addition to the infrastructure costs, it will be necessary to check if a **grid access and connection permit** is required. These permits are required for installations with more than 15kW of power, as dictated by Article 7 of Royal Decree 244/2019 [23]. Prices for residential permits for access and connection to the electrical grid range from 100 to 1000 euros [24]. This makes the total initial costs:

$$\begin{aligned} &Total\ initial\ costs \\ &\qquad = Cost\ of\ PV\ infraestructure \\ &\qquad + \text{Cost of grid access and connection permit} \end{aligned}$$

Equation 23: Total initial costs

In addition to these initial costs, it will be required to know the **operation and maintenance** costs. Although the initial investment is quite significant, solar energy systems are more affordable in the long run. With regular maintenance, PV panels may last up to 30 years, supplying a reliable electricity source. This power source carries low operating costs as it involves very little intervention and functions autonomously [25]. Annual O&M costs will be 2% of the initial investment [26], resulting in the following O&M cost for each year:

$$O\&M\ cost = 2\% * Investment\ cost$$

Equation 24: Operation and maintenance cost

- Income assessment

In order to perform the income analysis, the results obtained from each case will be compared to the data obtained with the reference case.

To calculate the income that each energy community will have every year, first, it will be required to know the income generated each year from exporting excess energy to the grid. These revenues obtained from the sale of surpluses will be computed as follows:

$$Grid\ exports\ revenue = \sum_{month=1}^{12} Revenue\ generated\ by\ esporting\ energy\ to\ the\ grid$$

Equation 25: Grid export revenue

Once the income is known, it will need to be compared with the income of the reference case to determine the annual savings generated, using the next expression:

$$\begin{aligned} Energy\ cost\ savings &= Total\ cost\ of\ energy\ imported\ from\ the\ grid\ in\ the\ reference\ case \\ &- Total\ cost\ of\ energy\ imported\ from\ the\ grid\ for\ each\ model \end{aligned}$$

Equation 26: Energy cost savings

- Cash flow analysis

In order to carry out the cash flow analysis, for the first step, it will be necessary to calculate the **annual net income** with the following expression:

$$Annual\ net\ income = Annual\ revenues - Annual\ operating\ costs$$

Equation 27: Annual net income

Next, the **Return on Investment** (ROI) will be calculated to assess the profitability of the investment. This metric helps determine which investments are worthwhile and provides insights into how to optimize existing ones for better performance. Consequently, it allows for evaluating how specific initiatives contribute to the company's overall results [27]. The expression used to compute this index will be as follows:

$$ROI = \frac{Income - Initial\ investment}{Initial\ investment} * 100$$

Equation 28: ROI

Next, the point at which the investment is recovered for each model will be computed, known as the **payback period**. The payback period is the time required for the return on an investment to repay the initial investment cost. It indicates how long it will take for an investment to generate enough cash flows to cover its initial expense.

- Evaluation of economic benefits

To evaluate the economic benefits of each scenario, the next step is to calculate the net present value. Calculating the **Net Present Value** (NPV) is crucial for the project, as it provides a detailed assessment of the long-term financial viability. The NPV allows determining the present value of future cash flows, discounted at a specific interest rate, accurately reflecting the real return on investment. This is critical to the project, as it allows me to compare the expected benefits with the initial investment and other investment alternatives, ensuring that resources are allocated efficiently and cost-effectively. In addition, calculating NPV helps identify potential financial risks and make informed decisions to maximize economic returns throughout the project life cycle [28]. The expression to compute is the following:

$$NPV = -Io \sum_{t=0}^{20} \frac{Rt}{(1+i)^t}$$

Equation 29: NPV

Being Io the initial investment, Rt the net inflow-outflow during period t, i the discount rate and t the number of periods. For this study, a discount factor of 3% was chosen to analyze the Net Present Value of energy community projects for several key reasons. First, 3% is a rate that adequately reflects the opportunity cost of capital in moderate to low-risk investment scenarios, such as renewable energy and energy community projects. This rate is consistent with reference interest rates used in financial analyses and evaluations of similar projects in the energy sector. In addition, the 3% rate considers current economic and financial conditions, providing a solid basis for evaluating the long-term economic viability of projects. Another index that is essential to calculate when performing an economic viability analysis is the IRR. The **Internal Rate of Return** (IRR) is a metric that estimates the expected annual growth rate of an investment. It is calculated similarly to the Net Present Value (NPV), but with the particularity that it is adjusted so that the NPV equals zero. The main purpose of the IRR is to identify the discount rate that balances the present value of all nominal annual cash flows with the initial outlay of the investment [29]. The following expression is used for its calculation:

$$IRR = -Io \sum_{t=0}^{20} \frac{Rt}{(1+i)^t} = 0$$

Equation 30: IRR

5.2.2 Technical assessment through technical indicators (Impact on the electric grid)

To conduct the technical analysis, the impact on the transformer and lines loading, the impact on voltage deviations, and the impact on phase unbalance we will study. To obtain the values of the variables necessary for this analysis, the prosumers DERs demand dispatch obtained in the first step of the model was used to perform the power flow. This data will be compared to the reference data, which is the case with no DERs installed.

- Impact on the transformer and lines loading

Analyzing the impact on transformer and lines loading is crucial for ensuring the reliability and consistency of the power distribution network. Transformers and lines are vital components that must operate within their specified limits to prevent overheating, inefficiencies, and potential failures. By evaluating the loading conditions, potential overloads can be identified and measures to mitigate risks can be implemented, ensuring the system can handle peak demands and maintain continuous service. This analysis helps in optimizing the performance, prolonging the lifespan of equipment, and improving the overall efficiency of the power distribution network. The best way to conduct this analysis is by representing the different voltage values in graphical form.

- Impact on voltage deviations

Due to their radial topology and lack of voltage control devices, Low Voltage Distribution Networks (LVDNs) often experience higher voltage deviations compared to other parts of the power system. Therefore, it is crucial to conduct a detailed analysis. Each phase's voltage is presented individually, given that the LVDN studied is unbalanced and each phase has prosumers with different characteristics. To examine the impact on voltage deviations, the first step was to select the household to be analyzed. Since feeder end nodes typically exhibit higher voltage deviations than nodes closer to the transformer, household 53 was chosen as it is connected at the end of the node on phase B. Additionally, it is important to consider that, according to EN 50160 [30], the voltage in Low Voltage Distribution Networks (LVDNs) must remain within the range of 0.90 to 1.10 pu. The best way to conduct this analysis is by representing the different voltage values in graphical form.

- Impacts on phase unbalance

Since phase unbalances can lead to inefficiencies, increased losses, and potential damage to equipment it is important to analyze it. By doing so, it can be ensured that the loads are evenly distributed across all phases, thereby enhancing the consistency and performance of the network. In this analysis, household 53 was chosen. This detailed analysis will help in identifying and mitigating issues related to phase unbalance, ensuring a more reliable and efficient power distribution system. The best way to conduct this analysis is by representing the different voltage values in graphical form.

5.2.3 Environmental impact

To evaluate the environmental impact that each of the models will cause, the annual reduction of CO2 emissions is calculated for each case. This calculation requires knowing the CO2 reduction for each kilowatt-hour (kWh) of bulk power system generation. According to the available data, the emission is estimated to be 0,41 kg of CO2 for each kWh of energy produced [31]. Once this data is known, it will be necessary to know how many kWh are generated by CO2 emitting technologies in each of the scenarios, considering only imported from the grid, as the energy generated in the energy community has zero CO2 emissions since based on renewable energy sources. For each of the models, the CO2 emission reduction will be computed using the following expression, under the assumption that, without the local RES generation, this electricity has to be generated by the bulk power system generation sources:

$$CO2\ emission\ reduction = \frac{0{,}41kg\ of\ CO2}{1KWh} * Energy\ supplied\ by\ DERs$$

Equation 31: CO2 emission reduction

5.3. Results

5.3.1 Economic assessment through economic indicators

Analyzing the data obtained and taking into account the base case, being July, the total costs of all community energy are higher in Model 3, reaching €4165.60. This is mainly due to the fact that all the energy demanded comes from renewable sources from the house itself or from the grid, as there is no energy exchange between houses. The lack of internal energy exchange causes high dependence on the grid and results in higher costs by not maximizing the use of internally generated resources. In contrast, Model 1, which has total costs of €3446.60, allows for energy exchange between households in the community, which reduces the need to import energy from the grid and contributes to greater self-sufficiency. However, Model 2 achieves the lowest total costs of €3007.30 due to an efficient combination of minimizing the cost of imported energy and maximizing revenue from exporting surplus to the grid, as well as allowing an optimal internal energy exchange of 16796 kWh. The main reason why the costs of Model 1 are higher than those of Model 2 is that, although energy exchange between households is allowed, no revenue is generated from exporting energy to the grid, thus limiting the possibilities of offsetting import costs. In addition, Model 2, by allowing energy export, generates additional revenue (€88,4209), which contributes significantly to the reduction in total net costs to the community.

- Cost assessment

First, it will be necessary to know what the **initial costs** of the total energy community have been, including infrastructure, permits and licenses.

For the **infrastructure cost**, it has to be taken into account that only 23 houses out of 55 have a photovoltaic installation. As stated in Section 4.1, the energy community counts with 33 solar panels with a photovoltaic generation capacity of 5 kWp. Assuming 100% efficiency and estimating a cost of 6.500€ [32] for each residential solar panel, the total cost of the infrastructure for the whole energy community will be computed as follows:

$$Total\ cost\ of\ PV\ infraestructure = 33\ panels * 6.500€ = 214.500\ €$$

Regarding the **grid access and connection permit**, as this energy community comprises numerous buildings, the total power capacity exceeds 15 kW. Hence, it is mandatory to obtain this permit from the distribution company. The cost for residential access and connection permits typically ranges from 100 to 1000 euros. For this study, we consider the worst-case scenario of 1000 euros [24]. Therefore, the total initial costs are calculated as follows:

$$Total\ initial\ costs = 214.500\ € + 1000\ € = 215.500\ €$$

The **operation and maintenance** costs entail an annual expenditure equivalent to 2% of the initial investment. This results in the following yearly O&M costs:

$$O\&M\ cost = 2\% * 214.500€ = 4.290\ €/\text{year}$$

- Income assessment

In order to perform the income analysis, the results obtained from each case will be compared to the data obtained with the reference case.
To calculate the income that each energy community will have every year, first of all, the revenues obtained from the sale of surpluses to the grid will be computed for each of the cases:

$$Grid\ exports\ revenue_{MODEL\ 1} = 0\ \text{€/year}$$

$$Grid\ exports\ revenue_{MODEL\ 2} = 560{,}4878\ €/year$$

$$Grid\ exports\ revenue_{MODEL\ 3} = 9337,806\ €/year$$

Next, knowing the grid exports revenue, and comparing it with the income of the reference case to determine the annual savings generated, obtaining the following results for each of the cases:

$$Energy\ cost\ savings_{MODEL\ 1} = 80.035{,}68€ - 47.957{,}80€ = 32.077{,}88\ \text{€/year}$$

$$Energy\ cost\ savings_{MODEL\ 2} = 80.035{,}68€ - 42.878{,}40€ = 37.157{,}28\ \text{€/year}$$

$$Energy\ cost\ savings_{MODEL\ 3} = 80.035{,}68€ - 62.290{,}10€ = 17.745{,}58\ \text{€/year}$$

- Cash flow analysis

The first step to carry out the cash flow analysis is to calculate the **annual net income**, Obtaining the following results:

$$Annual\ net\ income_{MODEL\ 1} = (0\ € + 32.077{,}88€) - (4.290\ €) = 27.787{,}88\ \text{€/year}$$

$$Annual\ net\ income_{MODEL\ 2} = (560{,}4878\ € + 37.157{,}28€) - (4.290\ €) \\ = 33.427{,}77\ \text{€/year}$$

$$Annual\ net\ income_{MODEL\ 3} = (9.337,806\ € + 17.745{,}58€) - (4.290\ €) \\ = 22.793{,}39\ \text{€/year}$$

Next, the **Return on Investment** (ROI) will be calculated. The following results were obtained when evaluating the ROI considering the revenues during the entire life of the project:

$$ROI_{MODEL\ 1} = \frac{(27.787{,}88\ € * 20\ \text{years}) - (214.500\ € + 1000€)}{(214.500\ € + 1000€)} * 100 = 157{,}89\ \%$$

$$ROI_{MODEL\ 2} = \frac{(33.427{,}77\ € * 20\ \text{years}) - (214.500\ € + 1000€)}{(214.500\ € + 1000€)€} * 100 = 210{,}23\ \%$$

$$ROI_{MODEL\ 3} = \frac{(22.793{,}39\ € * 20\ \text{years}) - (214.500\ € + 1000€)}{(214.500\ € + 1000€)} * 100 = 111{,}54\ \%$$

Evaluating the ROIs, it can be seen that in Model 1, with an ROI of 157.89%, it successfully recovers the initial investment over the entire duration of the project and generates a significant profit. Similarly, Model 2, with an ROI of 210.23%, not only recovers the initial investment but also yields the highest profit among all models. Model 3, with an ROI of 111.54%, also recovers the initial investment and generates a profit, although less than Models 1 and 2. Next, **payback period** will be computed. The following graphs presents the annual cash flows for each model, starting with the initial investment in year 0. It also shows the cumulative cash flow over the project's 20-year lifetime, highlighting how the financial performance accumulates each year. This type of visualization allows us to see both the yearly net gains or losses and the overall trend towards recovering the initial investment and generating profit. Here are the graphs for each of the models:

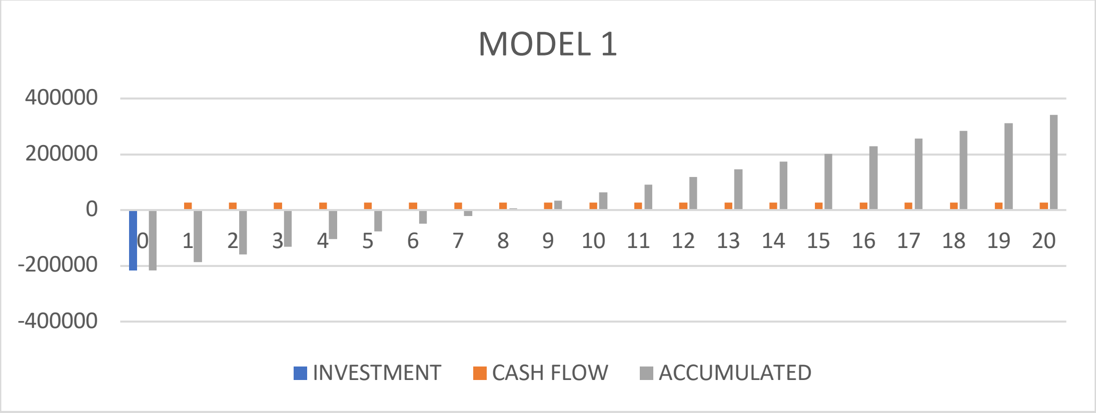


Figure 8: Model 1 investment and cashflows

In the first case illustrated in Figure 8, the investment is fully recovered by year 8. This positive outcome results from the model's balanced approach of managing imports from and exports to the grid. By effectively utilizing the revenue generated from selling energy to the grid, the total income becomes sufficient to cover expenses and recoup the initial investment within the project's timeframe.

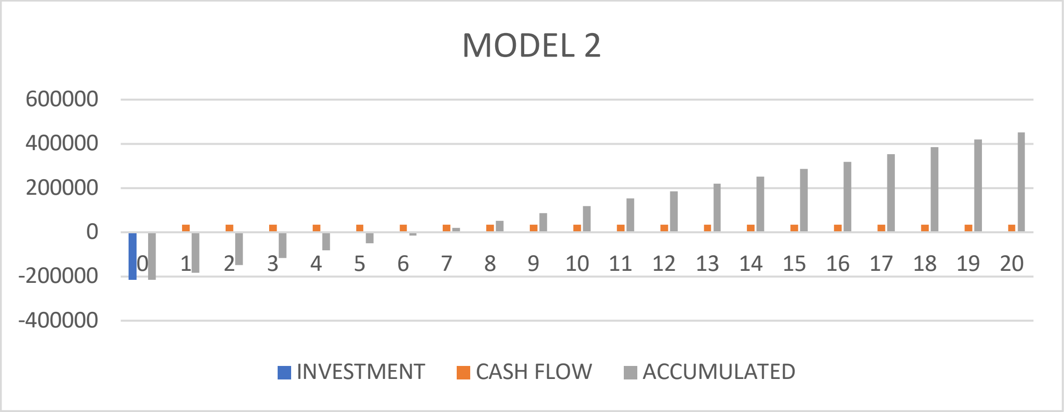


Figure 9: Model 2 investment and cashflows

In the second case, as illustrated in Figure 9, the investment is recovered by year 7 thanks to a significant income stream, obtaining some profit from year 7 onwards.

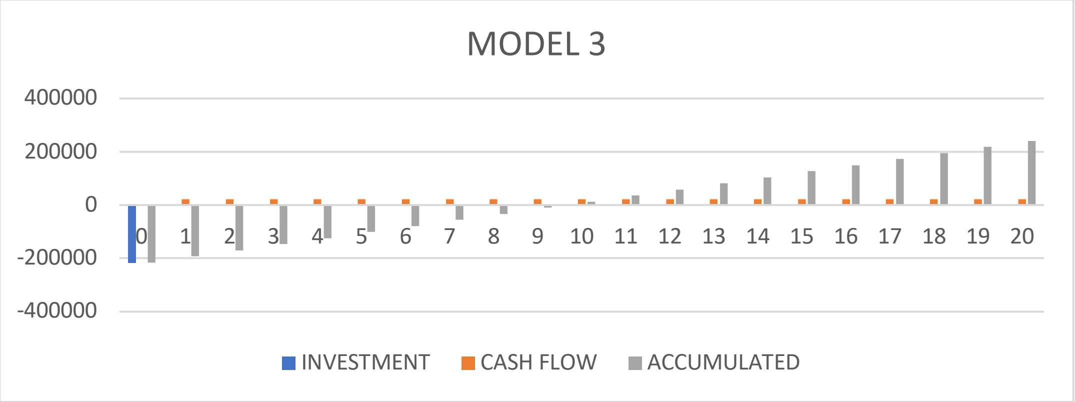


Figure 10: Model 3 investment and cashflows

Finally, in Model 3, the investment is fully recovered by year 10, as shown in Figure 10. This result is attributed to the model's ability to manage costs effectively, despite not enabling energy exchange with other households within the same energy community. By relying on the household's own PV generation and strategic use of grid energy, the model successfully meets demand and recoups the initial investment within the project's timeframe.

- Evaluation of economic benefits

To evaluate the economic benefits of each scenario, the next step is to calculate the **Net Present Value** (NPV). The Net Present Values obtained for each of the models are the following:

$$NPV_{MODEL\ 1} = 197.913,48\ €$$

$$NPV_{MODEL\ 2} = 281.820{,}77\ €$$

$$NPV_{MODEL\ 3} = 123.608{,}03\ €$$

The positive NPV values of Model 1, Model 2, and Model 3 indicate that each project generates a net present value, suggesting that the project's future cash flows are sufficient to offset the initial investment and the applied 3% discount rate. This aligns with the ROI calculations discussed in the previous section. Specifically, for Model 1, the NPV indicates a significant return over the initial investment. For Model 2, the NPV is even higher, demonstrating the highest return among the models. Model 3 also shows a positive NPV, confirming its financial viability over the project's duration.

Next, the **Internal Rate of Return** (IRR) will be computed. For each of the scenarios, the following results for the discount rate are obtained:

$$IRR_{MODEL\ 1} = 11\%$$

$$IRR_{MODEL\ 2} = 14\%$$

$$IRR_{MODEL\ 3} = 9\%$$

Analyzing the results for the calculated IRRs, it can be observed that Model 2, with an IRR of 14%, indicates that the project will generate an annual return of 14% on the initial investment. For Model 1 and Model 3, the IRRs are 11% and 9%, respectively, demonstrating that these scenarios also provide positive annual returns on the initial investment. These IRRs suggest that all three models are expected to yield returns that exceed the initial investment costs. Table 10 shows all the results obtained in the economic analysis for each of the scenarios:

RESULTS	**MODEL 1**	**MODEL 2**	**MODEL 3**
INITIAL COSTS	215.500€	215.500€	215.500€
ANNUAL TOTAL COST	4.290€	4.290€	4.290€
ANNUAL TOTAL REVENUES	32.077,88€	37.717,76€	27.083,31€
ANNUAL NET INCOME	27.787,88 €	33.427,77 €	22.793,39 €
ROI	157,89%	210,23%	111,54%
NPV	197.913,48€	281.820,77€	123.608,03€
IRR	11%	14%	9%

Table 10: Compilation of the results obtained for each of the models

Analyzing all the results gathered by the economic assessment it can be states that Model 1 is economically viable, with sufficient revenue to cover annual costs and a solid long-term financial outlook. It successfully reduces dependence on external energy sources, aligning well with its objective of minimizing grid interactions. On the other hand, Model 2 is the most profitable and economically viable option among the three. It not only minimizes costs effectively but also maximizes revenue, making it a highly lucrative choice for implementation. And lastly, looking at Model 3, although the model is economically viable, its profitability is the lowest among the three, primarily due to its restriction on energy exchange. This limitation reduces its potential for optimizing energy efficiency and maximizing revenue, making it less flexible compared to the other models.

To summarize the current findings, Model 2 stands out as the most profitable and economically viable option, effectively minimizing costs while maximizing revenue. Model 1 is also viable, successfully balancing income and costs to minimize interactions with the grid. Meanwhile, Model 3, despite being viable, offers the lowest profit margins and the least flexibility due to its restriction on energy exchange. To enhance the profitability of Model 3, it would be beneficial to explore ways to increase revenues or reconsider the policy on energy exchange to improve its efficiency and financial performance. This analysis provides a detailed perspective based on the new results, enabling informed decisions regarding the implementation of these business models for energy communities.

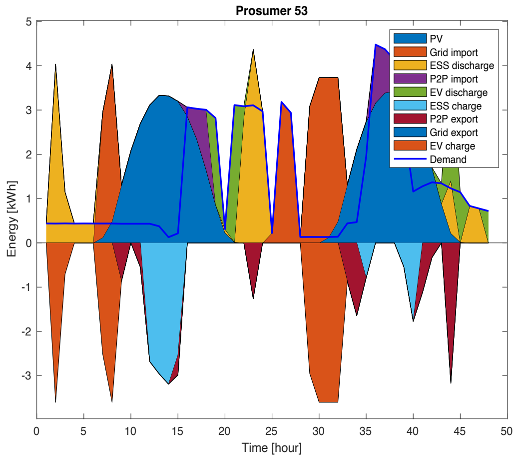
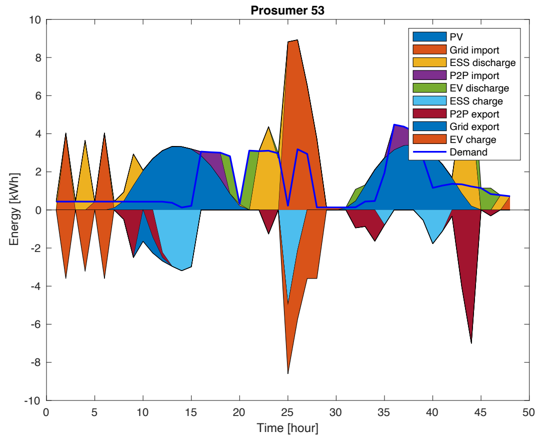
5.3.2 Technical assessment through technical indicators (Impact on the electric grid)

When running the second part pf the model, in which the power flow is permorfed, the following results were obtained for each of the cases, as can be seen in Table 11:

RESULTS	REFERENCE	MODEL 1	MODEL 2	MODEL 3
Maximum transformer loading [%]	14,96%	19,50%	35,67%	24,70%
Maximum line Loading [%]	46%	45,57%	102,68%	73,53%
Lowest value of Va (pu)	1,007	1,006	0,946	0,970
Highest value of Va (pu)	1,053	1,055	1,107	1,111
Lowest value of Vb (pu)	0,983	0,981	0,891	0,932
Highest value of Vb (pu)	1,033	1,116	1,088	1,117
Lowest value of Vc (pu)	1,013	1,012	1,014	1,016
Highest value of Vc (pu)	1,051	1,072	1,073	1,073
Maximum VUF (%)	0,901%	0,979%	2,758%	1,791%

Table 11: PandaPower results

For a more precise and detailed analysis, graphs depicting the energy consumption and generation from each source of prosumer 53 will be provided for each in Table 12:

MODEL 1	MODEL 2
	

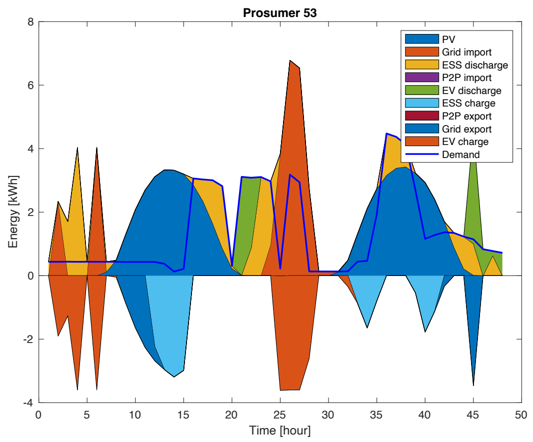
MODEL 3	
	

Table 12: Prosumer 53 graphs

- Impact on the transformer and lines loading

As previously mentioned, analysis becomes clearer when examining graphical representations. Therefore, Figure 11 below illustrates the transformer loading across each case throughout the month of July, while Figure 12 depicts transformer loading over three days to provide a more detailed perspective.

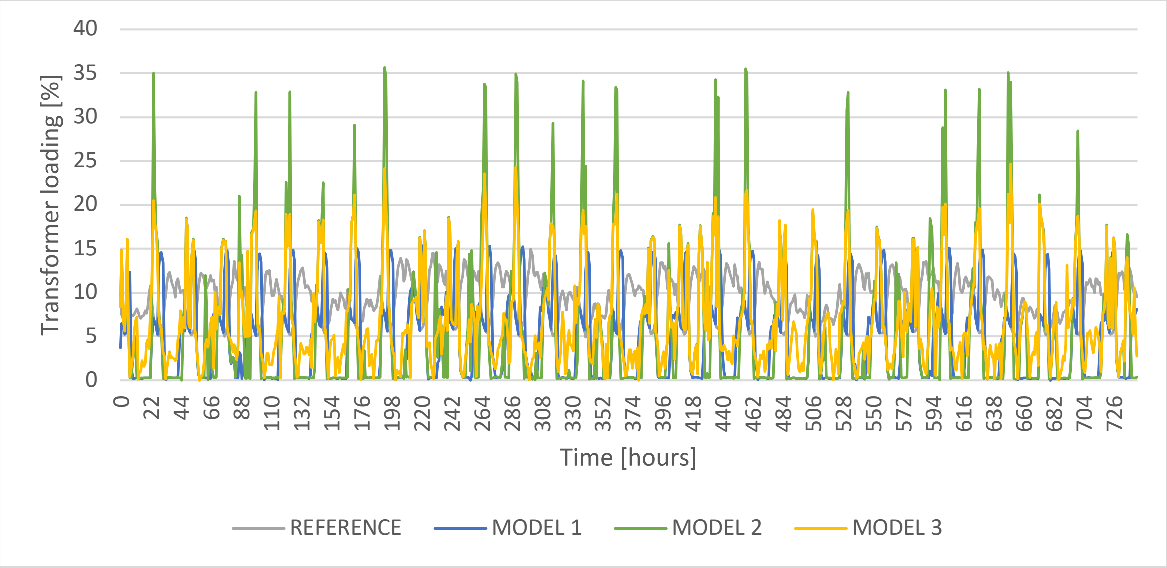


Figure 11: Transformer loading (1 month)

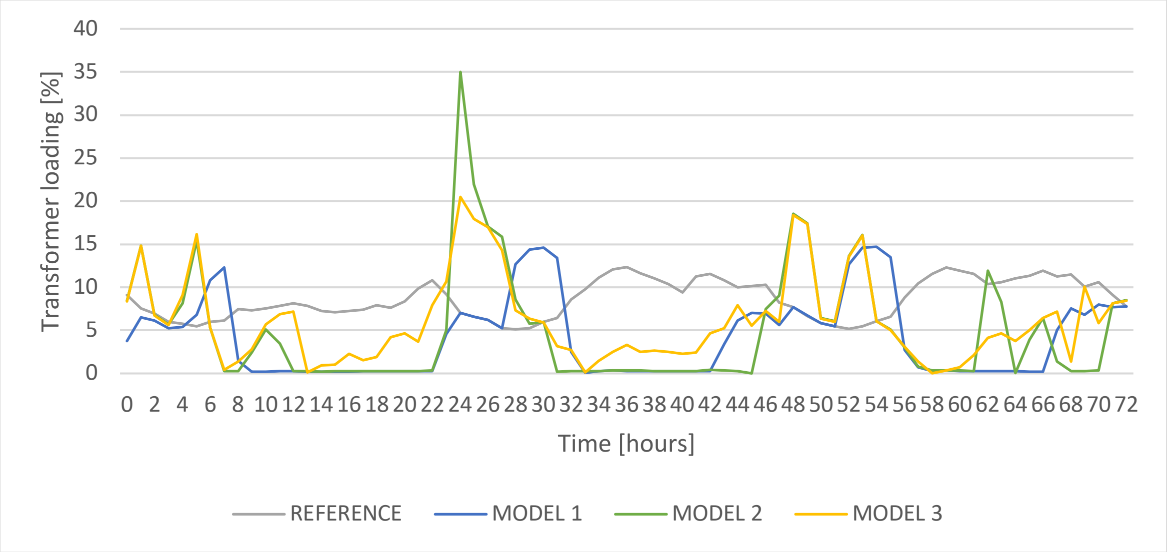


Figure 12: Transformer loading (3 days)

Looking at these figures it can be seen that in the reference case, since there are no DERs, there might be less variability in energy generation and consumption patterns. This consistency could lead to lower overall transformer loading compared to scenarios where active management of energy flows (like DERS integration) is not present. For Model 1, by optimizing internal energy generation and consumption within the community, there might be a slight increase in transformer loading due to more localized energy flows, but still relatively low compared to other models. On the other hand, Model 2 reaches the highest transformer loading out of all the cases. The objective of minimizing total costs can lead to decisions that prioritize cost-efficient energy generation without necessarily optimizing for transformer loading. This could happen because system operates closer to its capacity limits to achieve cost savings. In Model 3, where energy exchange between houses within the community is not allowed, there could be instances where individual households are drawing more power simultaneously, leading to higher transformer loading. The restriction on energy exchange might lead to less flexibility in load balancing across the community, affecting transformer loading. The points where the transformer loading is at its maximum for all models correspond to the moments when the battery is charged and the EV is charged, and energy needs to be imported from the grid to do so, as it can be seen in Table 12.

Next, the line loadings will be analyzed using Figure 13 , for the whole month and Figure 14 for 3 days.

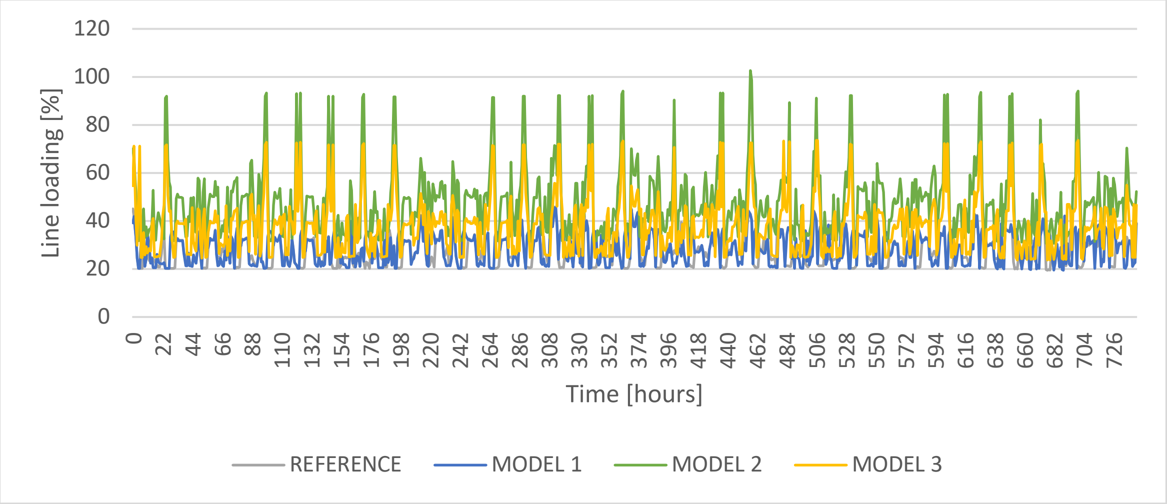


Figure 13: Line loading (1 month)

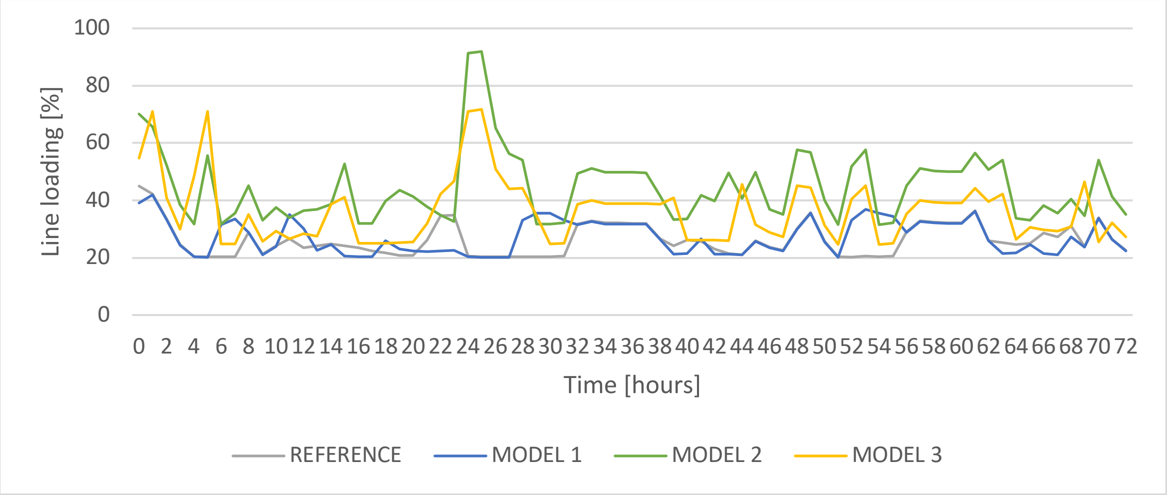


Figure 14: Line loading (3 days)

By examining the figures presented above, it can be seen how in the reference case, without DERs, the energy distribution within the community might be more stable and predictable, resulting in lower line loadings. This consistency ensures that the lines are not heavily loaded, as energy flows are managed within manageable limits. In Model 1, similarly to the reference scenario, the focus on minimizing energy imports and exports to the grid may lead to efficient internal energy distribution. This can result in comparable line loading to the reference scenario, as energy flows are optimized within the community without excessive strain on the lines. For Model 2, since the objective of minimizing total costs may lead to decisions that prioritize cost-efficient energy generation, potentially resulting in higher line loading. Strategies to minimize costs might involve operating closer to the line capacity limits to avoid costly infrastructure upgrades or operational inefficiencies. Finally, for Model 3, restrictions on energy exchange between houses within the community could lead to instances where individual households draw more power simultaneously. This could result in higher line loading as the distribution network may experience peaks in demand that strain the lines more than in scenarios with energy sharing between households. The same thing happens as in the transformer loading analyses, where the points where the line loading is at its maximum for all models correspond to the moments when the battery is charged, and the EV is charged.

- Impact on voltage deviations

The following step will be to analyze the voltage deviations by looking at Figure 15 where the voltage of phase B is represented during the month of July, and Figure 16 where only the first 3 days of July are represented.

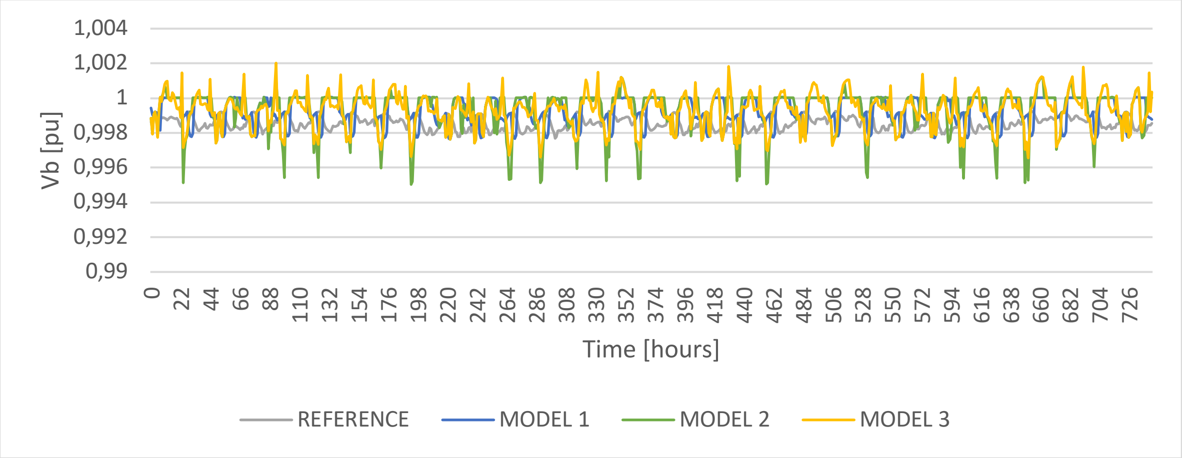


Figure 15: Phase b voltage (1 month)

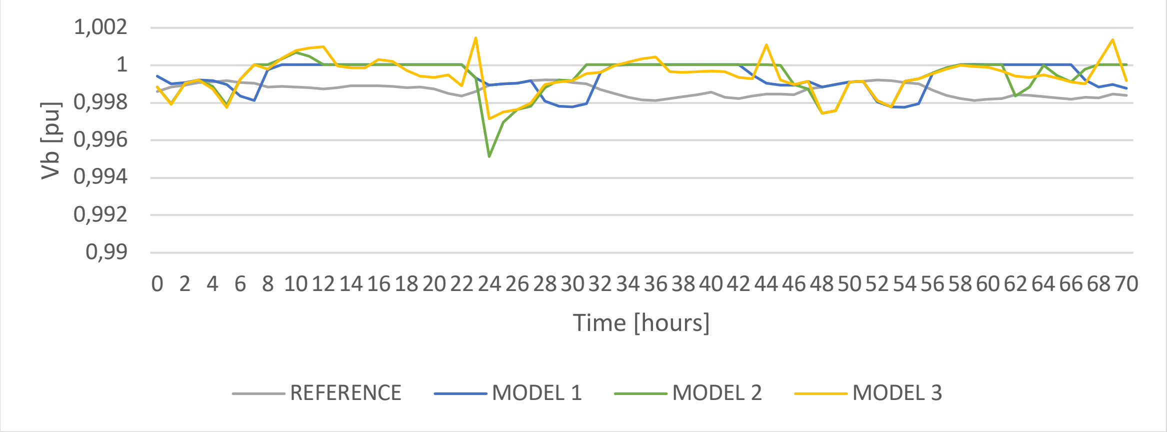


Figure 16: Phase b voltage (3 days)

Firstly, it can be seen, thar in all the models the voltage limits of 0.90 to 1.10 pu are not surpassed. In Model 1, the voltage is quite stable, since minimizing imports and exports implies that the system tries to maintain the energy balance internally within the local grid. By avoiding large energy exchanges with the external grid, power fluctuations that can cause voltage variations are reduced. In Model 2 it can be seen that there are frequent fluctuations in the value of the voltage. To minimize costs, the system may choose to import energy when it is cheaper and export when prices are high. These frequent and variable exchanges of energy with the grid can cause voltage fluctuations, as demand and supply are not constantly balanced. In Model 3, the absence of energy exchange between houses may result in more stable voltages, although some fluctuations are observed. Without the possibility of exchanging energy between houses, imports and exports of energy to the external grid are the main ways of balancing supply and demand. Although this may cause some fluctuations, they are likely to be less extreme compared to those in Model 2 due to the lack of internal exchange.

Looking at all the models as a whole, the lowest voltage values are reached at the time when the most is imported from the network, as these actions directly affect the voltage consistency in the network.

- Impacts on phase unbalance

The following step will be to analyze the phase unbalance by looking at Figure 17 where the phase unbalance of prosumer 53 is represented during the month of July, and Figure 18 where only the first 3 days of July are represented.

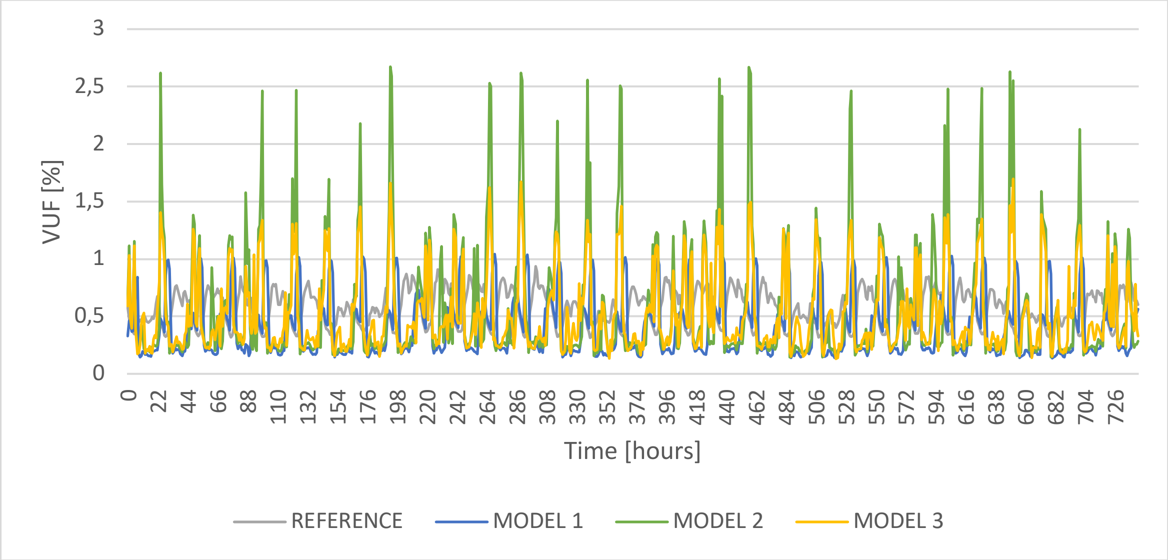


Figure 17: Voltage unbalance factor (1 month)

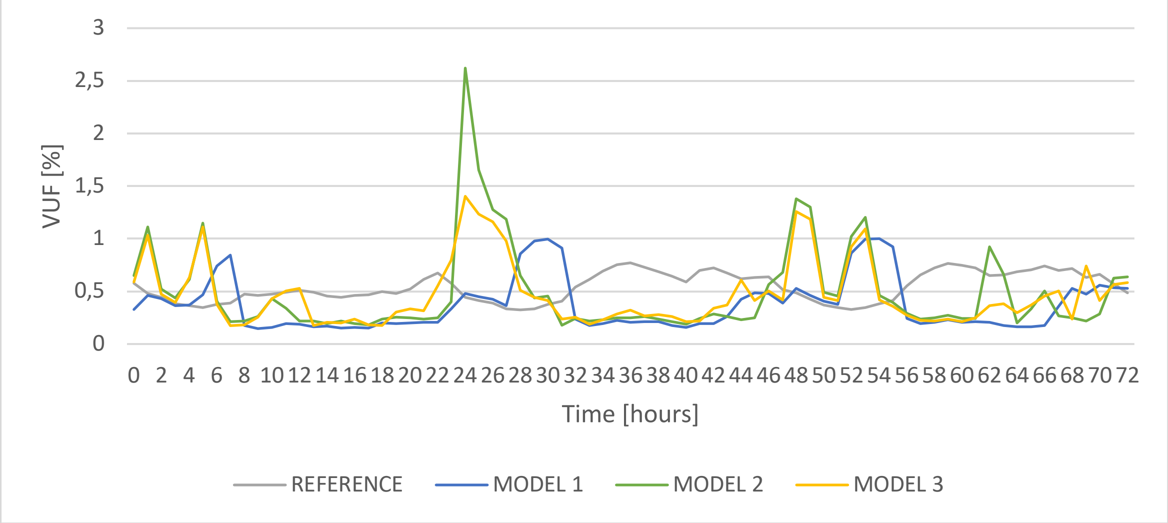


Figure 18: Voltage unbalance factor (3 days)

The reference model has a very low maximum VUF (0.901%), indicating that the system is fairly balanced without the integration of distributed energy resources. In Model 1, the maximum VUF is also low (0.979%), similar to the reference model. This suggests that the strategy of minimizing both imports and exports to the grid does not significantly affect the voltage balance in the grid. In Model 2, which aims to minimize costs, reaches a maximum VUF of 2,758% surpassing the maximum allowable VUF, which is 2%. Minimizing costs could imply significant changes in load and generation in different parts of the grid, leading to higher voltage unbalance. Finally, Model 3, which also seeks to minimize costs but does not allow power exchange between houses, has a maximum VUF of 1,791%. While still higher than the reference and Model 1 models, it is lower than Model 2, suggesting that not allowing power exchange could help reduce voltage unbalance compared to Model 2.

5.3.3. Environmental impact

To assess the environmental impact of each model, the annual reduction in CO2 emissions will be calculated for each case, yielding the following results:

$$CO2\ emission\ reduction_{MODEL\ 1} = \frac{0{,}41kg\ of\ CO2}{1KWh} * 146.778{,}98\ kWh = 60.179\ kg\ CO2$$

$$CO2\ emission\ reduction_{MODEL\ 2} = \frac{0{,}41kg\ of\ CO2}{1KWh} * 131.621{,}94\ kWh = 53.964\ kg\ CO2$$

$$CO2\ emission\ reduction_{MODEL\ 3} = \frac{0{,}41kg\ of\ CO2}{1KWh} * 50.782{,}71\ kWh = 20.820\ kg\ CO2$$

While the Model 3 shows the smallest reduction in CO2 emissions, at 20,820 kg (20.82 metric tons), it's important to put this figure into perspective to fully appreciate its impact. To illustrate, 20 metric tons of CO2 is equivalent to the annual electricity consumption of 4 average households. This means that even in the least favorable scenario, the community energy model still achieves a substantial environmental benefit by offsetting the CO2 emissions comparable to the electricity usage of four homes for an entire year [33].

Analyzing the results obtained, Model 1 has achieved the highest CO2 reduction among the three. The reason behind this may be that by minimizing exports and imports, the houses are maximizing the use of locally generated energy, through renewable sources such as solar panels. This suggests high efficiency in energy storage and use, minimizing the need to rely on the conventional power grid, which has a larger carbon footprint. With Model 2, although it has achieved significant CO2 reduction, it is lower than Model 1. Total cost optimization may involve decisions that do not always prioritize maximum energy efficiency, such as using the grid at times of low local generation to minimize operating costs. Finally Model 3 has the lowest CO2 reduction, which can be attributed to the lack of energy sharing between homes. The inability to share energy means that each home must rely on its own generation and storage, which can lead to less efficient use of available resources. In situations where one house generates a surplus and another has a deficit, the use of locally generated energy cannot be optimized, resulting in greater use of the grid.

6. Conclusions

The objective of this thesis is to explore various local electricity sharing models for energy communities, focusing on leveraging the potential of Distributed Energy Resources (DERs). Additionally, it aims to conduct a comprehensive techno-economic evaluation of these energy distribution models to identify their feasibility and cost-effectiveness.

After analyzing the proposed scenarios, which have the following objectives: Model 1 aims to minimize imported and exported energy with the grid, Model 2 aims to minimize costs, and Model 3 aims to minimize costs but without allowing energy exchange between houses, the results reveal significant insights.

The **economic analysis** conducted on the three energy community models has revealed important differences in terms of feasibility and cost-effectiveness. Model 1, has proven to be economically viable. This model achieves an appropriate balance between revenues and costs, reducing dependence on external energy sources and aligning well with its goal of minimizing interactions with the grid. While not the most cost-effective, its focus on energy self-sufficiency makes it a sustainable option in the long term.

Model 2, stands out as the most cost-effective and economically viable option among the three. This model not only effectively reduces costs, but also maximizes revenues, making it a highly cost-efficient option for implementation in energy communities. Its ability to optimize both efficiency and profitability makes it particularly attractive, highlighted by its robust financial performance.

On the other hand, Model 3, offers the lowest cost-effectiveness of the three models. This restriction on energy exchange limits its ability to optimize energy efficiency and maximize revenue, reducing its flexibility compared to the other models. However, it remains a viable option and could be improved by exploring ways to increase revenue or reconsidering the energy exchange policy.

Regarding the economic analysis, it can be concluded that Model 2 is the most profitable and economically viable, minimizing costs and maximizing revenues, which makes it the most cost-effective option for implementation in energy communities. Model 1 is also economically viable, aligning with its objective of reducing imports and exports from the grid, although it does not reach the same profitability as Model 2. On the other hand, Model 3, although viable, presents the lowest profitability due to the restriction in the exchange of energy between houses, which limits its efficiency and flexibility.

In terms of the **technical analysis**, or Model 1, the optimization of power generation and consumption within the community leads to a slight increase in transformer load (19.50%) and a line load comparable to the reference case (45.57%). This model demonstrates efficient management of internal power flows without putting excessive strain on grid components, and maintains voltage consistency (with values within the acceptable range), which helps reduce fluctuations that can cause voltage variations.

Model 2 has the highest transformer loading (35.67%) and line loading (102.68%). The prioritization of cost-effective power generation, without necessarily optimizing transformer loading, leads to operations close to capacity limits to achieve cost savings. This strategy, although efficient in economic terms, can significantly increase the load on grid components and cause voltage fluctuations due to variable power imports and exports. The violation of network constraints in line loading, by exceeding 100%, indicates that congestion management is necessary, or the network must be reinforced to increase its capacity.

In Model 3, transformer loading (24.70%) and line loading (73.53%) are observed to be higher than in Models 1 and the baseline. The lack of flexibility in load balancing within the community results in demand peaks that further stress the network. This constraint limits the ability to efficiently distribute power, affecting operational consistency and causing some voltage fluctuations, although not as extreme as in Model 2.

Looking at the **environmental impact**, although all models have environmental benefits by reducing CO2 emissions, Model 1 stands out for its greater share of RES production of renewable energy and its ability to minimize dependence on the conventional power grid.

In conclusion, the evaluation of the three energy community models reveals that each has its own strengths and weaknesses in economic, technical and environmental terms. Model 1, although not the most profitable, achieves an adequate balance between revenues and costs, and stands out for its energy self-sufficiency and efficiency in reducing CO2 emissions. Model 2 is shown to be the most profitable and economically viable, maximizing revenues and reducing costs, although at the cost of a higher load on the grid components and higher voltage fluctuations. On the other hand, Model 3, although viable, is the least cost-effective due to the restriction on power exchange between houses, which limits its efficiency and flexibility. However, all models contribute significantly to the reduction of CO2 emissions, highlighting the positive impact of energy communities on the environment. The choice of the appropriate model depends on the specific priorities of each community, whether economic, technical or environmental, offering different advantages depending on the approach adopted.

While the study provides valuable insights into the economic, technical, and environmental aspects of the three energy community models, it is important to acknowledge its limitations and suggest future research directions to build upon these findings. The study is based on specific data sets that may not capture all the nuances of real-world energy consumption patterns and generation capacities. The granularity and quality of the data could affect the accuracy of the simulation results. In addition, the models are evaluated based on data from a specific region, which may not be generalizable to other areas with different climatic conditions, energy policies, or even market dynamics.

Economic and policy constraints also present limitations. The study assumes certain regulatory and policy frameworks that may not be applicable to other countries. Variations in local regulations could impact the implementation and success of the models. Additionally, the economic analysis is based on current market incentives and tariffs, which could change, thereby affecting the cost-effectiveness and feasibility of the models.

The environmental impact assessment primarily focuses on CO2 emissions, which limits the scope of the analysis. Other environmental factors such as land use, water consumption, and biodiversity impacts are not considered in this study.

Future research should be more accurate and should carry out a broader data collection and analysis through long-term studies to capture the dynamic nature of energy consumption, technological advancements, and market changes. Expanding the analysis to include diverse geographic regions would also improve the generalizability of the findings.

Further economic and policy analysis is necessary to assess the impact of different regulatory frameworks and policies on the feasibility and performance of energy community models. Studying the effects of evolving market incentives, tariffs, and energy pricing on the economic viability of the models will provide deeper insights.

A comprehensive environmental impact assessment should incorporate a wider range of environmental metrics to evaluate the broader ecological impacts of energy community models. Performing lifecycle assessments of DERs and other technological components will help understand their environmental footprint from production to disposal.

Finally, it is important to consider community engagement and social impact. Investigating the role of community engagement, social acceptance, and behavior change in the success of energy community models is essential. Analyzing the social implications of energy sharing models to ensure equitable access and benefits for all community members will also be valuable.

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