MASTER'S IN INDUSTRIAL ENGINEERING

MASTER'S FINAL PROJECT

# PEER-TO-PEER ENERGY TRADING OPPORTUNITIES ANALYSIS

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Madrid

I declare, under my responsibility, that the Project presented with the title

Peer-to-Peer Energy Trading Opportunities Analysis

at the ETS of Engineering - ICAI of the Universidad Pontificia Comillas in the

Academic Year 2023/2024 is of my authorship, original and unpublished and

it has not been previously submitted for other purposes.

The Project is not plagiarism of another, either totally or partially and the information that has been

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Date: 20/07/2024

Delivery of the project authorized

THE PROJECT MANAGER

Morsy Abdelkader

Signed: Date: 20/ 07/ 2024

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# PEER-TO-PEER ENERGY TRADING OPPORTUNITIES ANALYSIS

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Collaborating Entity: Institute of Investigation and Technology

## PROJECT OVERVIEW

The transition to distributed energy resources (DERs) has significantly transformed the energy landscape, enabling small-scale power generation systems like photovoltaic (PV) panels and energy storage systems (ESS) to turn consumers into prosumers who can produce and share energy. This study evaluates the efficiency and network impact of operating a community of 55 homes participating in a peer-to-peer (P2P) energy trading scheme as either a single large entity or divided into smaller energy communities. The analysis also explores the impact of different energy storage management strategies on grid stability and operational efficiency. The results highlight the trade-offs between different configurations and management approaches, providing insights into optimizing community energy systems for economic and technical performance.

**Keywords**: Distributed Energy Resources, Peer-to-Peer Energy Trading, Energy Communities, Energy Storage Systems, Photovoltaic Panels, Grid Stability, Energy Efficiency

### 1. Introduction

Until today, the electricity market has been operated by peer-to-grid (P2G) unidirectional model, where the energy was generated in large power plants and transported through an extensive transmissions and distribution network until reaching the end consumers. However, after many years of relying on this conventional, one-way model, limitations have become increasingly apparent. These restrictions converge into a complex challenge known as the "energy trilemma" [1]. This dilemma involves balancing three crucial, yet often conflicting, goals.

1. **Environmental Sustainability:** To reduce greenhouse gas emissions and the environmental impact associated with energy generation.
2. **Energy Equity:** To ensure a reliable and sufficient energy supply to meet growing demand.

3. **Energy Security:** To ensure that all citizens have access to affordable energy, regardless of their location or socioeconomic status.

The emergence of distributed energy resources (DERs), along with peer-to-peer (P2P) energy trading, offers a promising alternative to address the energy trilemma effectively. This solution means a shift from the traditional one-way (P2G) model to a decentralized model, meaning an important change in the electric market. This new model promotes the use of renewable energy by allowing the users to participate not only in the consumption of energy, but also in its generation. It addresses directly the energy trilemma by:

1. **Enhancing Environmental Sustainability:** As the new system allows peers to trade with their surplus energy, consumers can net their demands by renewable energy, reducing greenhouse gas emissions and environmental impact.
2. **Improving Energy Equity:** It provides a more affordable and inclusive access to energy, making it more fair for all the communities to benefit from local energy resources.
3. **Boosting Energy Security:** With local power generation, communities become less dependent on large, centralized grids, making it easier to respond to outages and increasing their self-sufficiency.

## 2. Project definition

This project continues the study elaborated in previous projects such as *"Impacts of Community Energy Trading on Low Voltage Distribution Networks"* [2] and "*Mitigating the impacts of community energy trading on distribution networks by considering contracted power network charges"* [3] and emphasizes the importance of developing optimal strategies for the management of distributed energy resources (DERs).

The project under study highlights how the configuration of energy communities and energy storage management strategies can significantly influence system efficiency, grid stability and overall sustainability. The primary objectives are to analyze the impact of dividing a single large community into smaller energy communities and to evaluate how maintaining the state of charge (SoC) of batteries at the beginning and end of each day influences energy distribution and grid impact.

## 3. Description of the model/system/tool

The study uses a linear multiperiod optimization model implemented in MATLAB, considering a trading period of one month for a community of 55 houses. The model aims to minimize energy import costs from the retailer, maximize export benefits, and minimize contracted power costs. It incorporates local P2P energy trading, the flexibility of energy storage systems (ESS), and electric vehicles (EVs).

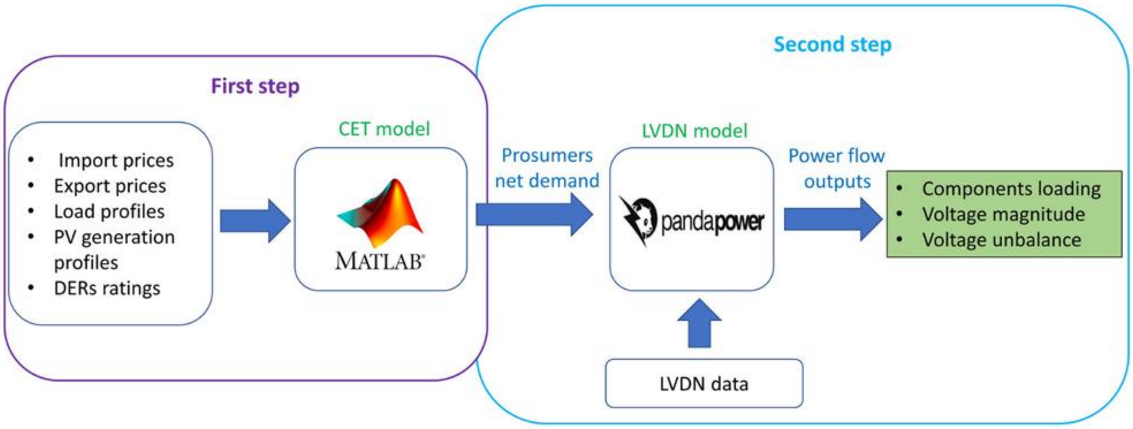

*Figure 1: Schematic diagram of community energy trading impacts evaluation [2]*

## 4. Results

First, the impact of dividing a large energy community into several smaller ones was analyzed. This analysis focused on evaluating the efficiency and stability of the network under two configurations: operating as a single large community versus subdividing into three smaller energy communities, and the following results were obtained.

- **Diversity of Demand Profiles:** Operating as a single large community showed a greater diversity of demand profiles, which favored a better ability to balance demand and energy generation. This diversity resulted in less dependence on the grid and lower operating costs, as the community was able to optimize the use of its internal resources more effectively.
- **Proportion of DERs in a Community:** The proportion of DERs in each community had a significant impact on its efficiency and stability. Communities with a higher percentage of DERs, were able to meet more of their energy demand internally, reducing the need to import energy from the grid. In contrast, communities with a

lower percentage of DERs, showed greater variability in energy import and export, increasing their dependence on the grid and associated costs.

Secondly, the impact of different energy storage management strategies on grid stability and operational efficiency was analyzed. Two scenarios were compared: one with no state-of-charge (SoC) constraints on the batteries and EVs, and one with constraints that required the batteries and the electric vehicles to maintain the same SoC at the start and end of the day.

The results under this scenario showed that depending on the value of the SoC imposed, the performance varies considerably. On the one hand, choosing to maintain a high SoC can improved stability and reduced charge and discharge cycles, prolonging the lifetime of batteries and EVs, but on the other hand, a lower SoC at the end of the day offered greater operational flexibility and reduced grid dependence, optimizing demand response but leading to higher nighttime peaks.

## 5. Conclusions

The comparison between operating as a single large community and subdividing into smaller communities showed that a greater diversity of demand profiles in a large community improves the balance between demand and generation, reducing grid dependency and operating costs. However, the proportion of DERs is crucial, as communities with more DERs can meet more demand internally. Regarding state-of-charge (SoC) management of batteries and EVs, maintaining a high SoC reduces night time peaks and prolongs lifetime, but a lower SoC offers greater operational flexibility and reduces grid dependence. Therefore, it would be interesting to investigate the possibility of dynamically adjusting the SoC according to specific system needs to achieve an optimal balance between stability and flexibility.

## 6. References

[1] Yue Zhou, Jianzhong Wu, Chao Long, Wenlong Ming,State-of-the-Art Analysis and Perspectives for Peer-to-Peer Energy Trading,Engineering,Volume 6, Issue 7,2020,Pages 739-753

[2] M. Nour, J. P. Chaves-Ávila, M. Troncia, A. Ali and Á. Sánchez-Miralles, "Impacts of Community Energy Trading on Low Voltage Distribution Networks," in IEEE Access, vol. 11

[3] M. Nour, J. P. Chaves-Ávila, M. Troncia and Á. Sánchez-Miralles, "Mitigating the Impacts of Community Energy Trading on Distribution Networks by Considering Contracted Power Network Charges," in IEEE Access, vol. 12

# PEER-TO-PEER ENERGY TRADING OPPORTUNITIES ANALYSIS

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## ABSTRACT

La transición a los recursos energéticos distribuidos (DER) ha transformado significativamente el panorama energético, permitiendo que los sistemas de generación de energía a pequeña escala, como los paneles fotovoltaicos (PV) y los sistemas de almacenamiento de energía en baterías (BESS), conviertan a los consumidores en prosumidores que pueden producir y compartir energía. Este estudio evalúa la eficiencia y el impacto en la red del funcionamiento de una comunidad de 55 hogares que participan en un sistema de comercio de energía entre iguales (P2P), ya sea como una única gran entidad o dividida en comunidades energéticas más pequeñas. El análisis también explora el impacto de diferentes estrategias de gestión de baterías en la estabilidad de la red y la eficiencia operativa. Los resultados muestran las ventajas y desventajas de las distintas configuraciones y enfoques de gestión, lo que permite optimizar los sistemas energéticos comunitarios desde el punto de vista económico y técnico.

**Palabras Clave**: Distributed Energy Resources, Peer-to-Peer Energy Trading, Energy Communities, Energy Storage Systems, Photovoltaic Panels, Grid Stability, Energy Efficiency

### 1. Introducción

Hasta hoy, el mercado de la electricidad se ha regido por el modelo unidireccional peer-to-grid (P2G), en el que la energía se generaba en grandes centrales eléctricas y se transportaba a través de una extensa red de transmisión y distribución hasta llegar a los consumidores finales. Sin embargo, tras muchos años confiando en este modelo convencional unidireccional, las limitaciones se han hecho cada vez más evidentes. Estas restricciones convergen en un complejo desafío conocido como el «trilema energético» [1]. Este dilema implica equilibrar tres objetivos cruciales, aunque a menudo contrapuestos.

1. **Sostenibilidad medioambiental:** Reducir las emisiones de gases de efecto invernadero y el impacto ambiental asociado a la generación de energía.

2. **Equidad energética:** Garantizar un suministro energético fiable y suficiente para satisfacer la creciente demanda.
3. **Seguridad energética:** Garantizar que todos los ciudadanos tengan acceso a una energía asequible, independientemente de su ubicación o estatus socioeconómico.

La aparición de los recursos energéticos distribuidos (DER), junto con el comercio de energía entre pares (P2P), ofrece una alternativa prometedora para abordar eficazmente el trilema energético. Esta solución supone un cambio del modelo tradicional unidireccional (P2G) a un modelo descentralizado, lo que significa un cambio importante en el mercado eléctrico. Este nuevo modelo fomenta el uso de energías renovables al permitir que los usuarios participen no sólo en el consumo de energía, sino también en su generación. Aborda directamente el trilema energético mediante:

1. **Mejora la sostenibilidad medioambiental:** Como el nuevo sistema permite a los compañeros comerciar con su excedente de energía, los consumidores pueden compensar sus demandas con energía renovable, reduciendo las emisiones de gases de efecto invernadero y el impacto medioambiental.
2. **Mejora de la equidad energética:** Proporciona un acceso más asequible e inclusivo a la energía, haciendo más justo que todas las comunidades se beneficien de los recursos energéticos locales.
3. **Aumentar la seguridad energética:** Con la generación local de energía, las comunidades se vuelven menos dependientes de las grandes redes centralizadas, lo que facilita la respuesta a los cortes y aumenta su autosuficiencia.

## 2. Definición del Proyecto

Este proyecto continúa el estudio elaborado en proyectos anteriores como «Impacts of Community Energy Trading on Low Voltage Distribution Networks» [2] y «Mitigating the impacts of community energy trading on distribution networks by considering contracted power network charges» [3] y hace hincapié en la importancia de desarrollar estrategias óptimas para la gestión de los recursos energéticos distribuidos (DER).

El proyecto objeto de estudio pone de relieve cómo la configuración de las comunidades energéticas y las estrategias de gestión de las baterías pueden influir significativamente en la eficiencia del sistema, la estabilidad de la red y la sostenibilidad general. Los objetivos principales son analizar el impacto de dividir una única gran comunidad en comunidades energéticas más pequeñas y evaluar cómo el mantenimiento del estado de carga (SoC) de las baterías al principio y al final de cada día influye en la distribución de la energía y en el impacto en la red.

## 3. Descripción del modelo/sistema/herramienta

El estudio utiliza un modelo lineal de optimización multiperiodo implementado en MATLAB, considerando un periodo de comercialización de un mes para una comunidad de 55 viviendas. El objetivo del modelo es minimizar los costes de importación de energía del minorista, maximizar los beneficios de exportación y minimizar los costes de energía contratada. Incorpora el comercio local de energía P2P, la flexibilidad de los sistemas de almacenamiento de energía (ESS) y los vehículos eléctricos (VE).

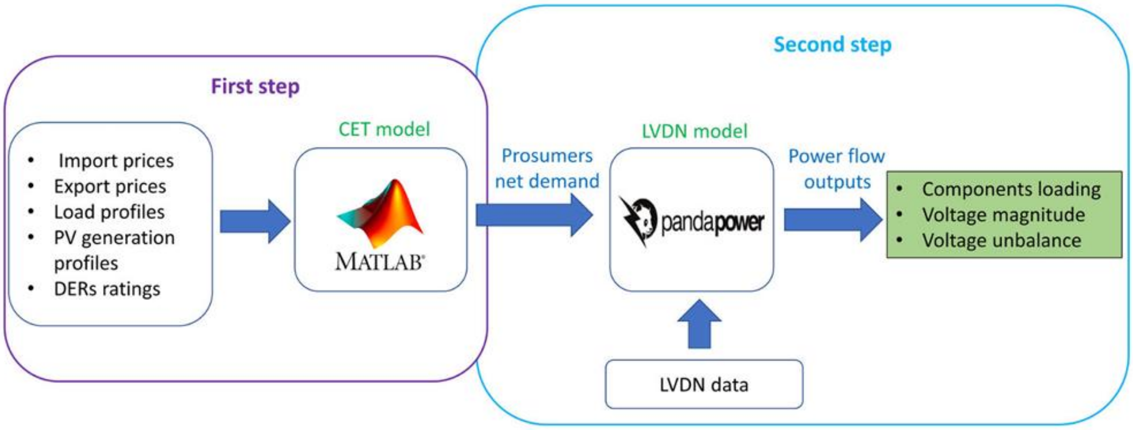

*Figure 2: Diagrama esquemático de la evaluación del impacto del comercio comunitario de energía [2]*

## 4. Resultados

En primer lugar, se analizó el impacto de dividir una gran comunidad energética en varias más pequeñas. Este análisis se centró en evaluar la eficiencia y estabilidad de la red bajo dos configuraciones: funcionando como una única gran comunidad frente a la subdivisión en tres comunidades energéticas más pequeñas, y se obtuvieron los siguientes resultados.

**- Diversidad de perfiles de demanda:** El funcionamiento como una única gran comunidad mostró una mayor diversidad de perfiles de demanda, lo que favoreció una mejor capacidad para equilibrar la demanda y la generación de energía. Esta diversidad se tradujo en una menor dependencia de la red y en menores costes operativos, ya que la comunidad pudo optimizar el uso de sus recursos internos de forma más eficaz.

**- Proporción de DER en una comunidad:** La proporción de DER en cada comunidad tuvo un impacto significativo en su eficiencia y estabilidad. Las comunidades con un mayor porcentaje de DER, fueron capaces de satisfacer más de su demanda de energía internamente, reduciendo la necesidad de importar energía de la red. Por el contrario, las comunidades con un menor porcentaje de DER, mostraron una mayor variabilidad en la importación y exportación de energía, aumentando su dependencia de la red y los costes asociados.

En segundo lugar, se analizó el impacto de diferentes estrategias de gestión de baterías sobre la estabilidad de la red y la eficiencia operativa. Se compararon dos escenarios: uno sin restricciones del estado de carga (SoC) de las baterías y los vehículos eléctricos, y otro con restricciones que exigían que las baterías y los vehículos eléctricos mantuvieran el mismo SoC al principio y al final del día.

Los resultados en este escenario mostraron que, dependiendo del valor del SoC impuesto, el rendimiento varía considerablemente. Por un lado, optar por mantener un SoC elevado puede mejorar la estabilidad y reducir los ciclos de carga y descarga, prolongando la vida útil de las baterías y los vehículos eléctricos, pero, por otro lado, un SoC inferior al final del día ofrecía una mayor flexibilidad operativa y una menor dependencia de la red, optimizando la respuesta a la demanda, pero dando lugar a picos nocturnos más elevados.

## 5. Conclusiones

La comparación entre operar como una única gran comunidad y subdividirse en comunidades más pequeñas mostró que una mayor diversidad de perfiles de demanda en una gran comunidad mejora el equilibrio entre demanda y generación, reduciendo la dependencia de la red y los costes operativos. Sin embargo, la proporción de DER es crucial, ya que las comunidades con más DER pueden satisfacer más demanda internamente. En cuanto a la gestión del estado de carga (SoC) de las baterías y los VE, mantener un SoC alto reduce los picos nocturnos y prolonga la vida útil, pero un SoC más bajo ofrece una mayor flexibilidad operativa y reduce la dependencia de la red. Por lo tanto, sería interesante investigar la posibilidad de ajustar dinámicamente el SoC en función de las necesidades específicas del sistema para lograr un equilibrio óptimo entre estabilidad y flexibilidad.

## 6. Referencias

[1] Yue Zhou, Jianzhong Wu, Chao Long, Wenlong Ming,State-of-the-Art Analysis and Perspectives for Peer-to-Peer Energy Trading,Engineering,Volume 6, Issue 7,2020,Pages 739-753

[2] M. Nour, J. P. Chaves-Ávila, M. Troncia, A. Ali and Á. Sánchez-Miralles, "Impacts of Community Energy Trading on Low Voltage Distribution Networks," in IEEE Access, vol. 11

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## Abbreviation’s List

**DERs –** Distributed Energy Resources

**P2G –** Peer to Grid

**P2P –** Peer to Peer

**PV -** Photovoltaic

**EV** – Electric Vehicles

**ESS –** Energy Storage System

**CET –** Community Energy Trading

**LVDN –** Low Voltage Distribution Network

**FIT** – Feed in Tariff

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# CHAPTER 1. INTRODUCTION

## 1.1 INTRODUCTION

During the last years, there has been a significant rise of the Distributed Energy Resources (DERs), which have transformed the energy landscape. Small-scale power generation systems, such as home photovoltaic panels (PVs) and energy storage systems (BESS), allow homes not only to consume energy but also to produce and share it with others. This revolution has made it possible to transform consumers into **prosumers**, capable of both consuming and producing energy and sharing it with other peers. This phenomenon has given rise to the emergence of decentralized power grids and peer-to-peer (P2P) energy trading, where neighbors can sell, buy or give away their surplus energy to each other. However, it remains a subject of debate about which is the most effective way to operate these new, decentralized energy systems. Is it more efficient for a community to function as a single, large entity, sharing resources across the entire network? Or would it be more beneficial to subdivide the community into smaller, self-managed energy communities?

Therefore, this study focuses on a small community of 55 homes participating in a P2P energy trading scheme, where two main aspects will be evaluated, the efficiency and impact on the network of whether it is better to operate the system as a single large entity versus dividing it into smaller energy communities and the different management of the Energy Storage Systems. This research not only addresses economic aspects of the community, but also technical and operating aspects, comparing the benefits and challenges of both approaches in the different scenarios studied.

## 1.2 P2P MARKET CONTEXT AND RELEVANCE

### 1.2.1 TRANSFORMATION OF THE ENERGY MARKET DURING THE LAST DECADES

Until today, the electricity market has been operated by peer-to-grid (P2G) unidirectional model, where the energy was generated in large power plants and transported through an extensive transmissions and distribution network until reaching the end consumers. This system, known as "generate, transmit and distribute", has made it possible to meet energy demand for decades.

However, after many years of relying on this conventional, one-way model, limitations have become increasingly apparent. These restrictions converge into a complex challenge known as the "energy trilemma" [1]. This dilemma involves balancing three crucial, yet often conflicting, goals.

4. **Environmental Sustainability:** To reduce greenhouse gas emissions and the environmental impact associated with energy generation.
5. **Energy Equity:** To ensure a reliable and sufficient energy supply to meet growing demand.
6. **Energy Security:** To ensure that all citizens have access to affordable energy, regardless of their location or socioeconomic status.

During many years, the "energy trilemma" has been a hot topic in global energy policy discussions and two main approaches have dominated the energy landscape to address this concerning issue. On the one hand, the first approach has focused on incrementing infrastructure expansion, trying to build new power plants, transmission and distribution networks on a large scale to increase the power generation and transmission capacity. On the other hand, the other approach has focused on reducing energy consumption by implementing more efficient technologies and responsible consumption practices. However, both approaches have presented big limitations and therefore, have not been significantly effective. Some of these limitations are the following.

| **Limitations of Infrastructure Expansion** | **Limitations of Energy Efficiency** |
|---|---|
| - **High Cost:** Building new energy infrastructure involves significant investments that can be a burden on consumers and governments. | - **Limited Potential:** While energy efficiency can reduce consumption, its impact may not be enough to meet growing energy demand. |
| - **Environmental Impact:** The construction of new power plants and transmission networks can have a negative impact on the environment, including the loss of natural habitats and pollution. | - **Behavioral Change:** Achieving significant changes in energy consumption patterns requires time, effort, and education, which can be challenging. |
| - **Long Term:** Building new infrastructure is a time-consuming process, which can slow down the achievement of energy goals. | - **Inequality:** Benefits of energy efficiency may not be distributed equitably, as low-income groups have less access to efficient technologies. |

However, the emergence of distributed energy resources (DERs), along with peer-to-peer (P2P) energy trading, offers a promising alternative to address the energy trilemma more effectively. This shift from the traditional one-way (P2G) model to a decentralized model means an important change in the electric market. The new model promotes the use of renewable energy by allowing the users to participate not only in the consumption of energy, but also in its generation. It addresses directly the energy trilemma by:

4. **Enhancing Environmental Sustainability:** As the new system allows peers to trade with their surplus energy, consumers can net their demands by renewable energy, reducing greenhouse gas emissions and environmental impact.
5. **Improving Energy Equity:** It provides a more affordable and inclusive access to energy, making it more fair for all the communities to benefit from local energy resources.
6. **Boosting Energy Security:** With local power generation, communities become less dependent on large, centralized grids, making it easier to respond to outages and increasing their self-sufficiency.

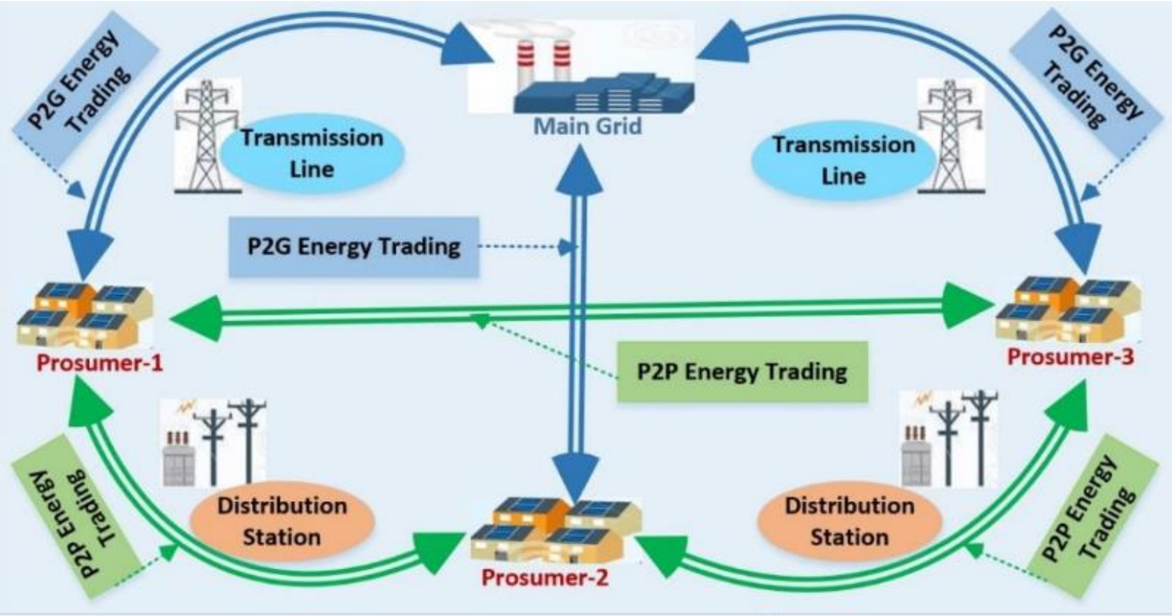

*Figure 3: Energy Trading Scheme P2G and P2P [13]*

### 1.2.2 CONCEPT AND BENEFITS OF PEER-TO-PEER (P2P) ENERGY TRADING

During recent years, Peer-to-Peer (P2P) energy trading has attracted increasing attention, as it provides an innovative new perspective on how to approach the energy market. Customers with Distributed Energy Resources (DERs) in P2P are not only able to consume but also to produce energy to the grid, bypassing traditional utility companies.

It can be understood as a "sharing economy", where it allows users to share their surplus onsite generation or the flexibility of their demand with others who need it. It is often traded at a lower cost than the energy from the bulk power grid.  This is a revolutionary new idea that presents a win-to-win situation for both producers and consumers.

- For producers: Prosumers can sell their surplus energy to other consumers in need, which not only benefits them with additional revenue steam, but also maximizes the use of their DERs.
- For consumers: P2P benefits consumers as it allows them to buy energy at lower prices compared to traditional utilities rates, especially in countries where the feed-in[1] tariff is lower than the retail price of the electricity.

Therefore, P2P energy trading offers a wide variety of benefits. As it promotes energy to be generated and consumed locally, it reduces losses in transmission making the system more dynamic. It also incentives the use of renewable energy technologies, enhancing environmental sustainability. Moreover, the diversity of generation and demand among the different customers improves the system's efficiency, as some customers may need energy in moments where others have surplus, making it a more balanced and resilient system [1].

## 1.3 MICROGRIDS AND THEIR ROLE IN COMMUNITY ENERGY

### 1.3.1 DEFINITION AND TYPES OF MICROGRIDS

A microgrid is a localized energy system that produces and distributes energy and has different operating ways. They can operate independently of the main power grid, when necessary, for example, during blackouts or storms. It can also be used to cover users' peak

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[1] A feed-in tariff (FIT) is a policy tool that provides renewable energy producers with an above-market price for what they deliver to the grid. These policies are usually designed to promote investment in renewable energy sources

demand, thus avoiding additional energy costs [4]. These grids supply a specific group of nearby users, such as homes, business centers, hospitals or factories. Their energy comes from generators or renewable sources, known as Distributed Energy Resources (DERs) such as solar panels and wind power, and they usually have energy storage systems, such as batteries.

It is interesting to understand the different types of microgrids.

| Types of Microgrid | Purpose | Main Components | Relevance |
|---|---|---|---|
| **Residential** | Serve households and small residential communities | Various DERs, including solar panels, electric vehicles and energy storage | Provide energy independence and cost savings for residents |
| **Commercial and Industrial** | Provide reliable, high-quality energy for commercial and industrial operation | Mix of renewable and conventional energy sources | Ensure continuity of critical processes and reduce long-term operational costs |
| **Institutional and Campus** | Supply energy to multiple buildings within a confined area | Solar panels and energy storage | Provide a secure and continuous energy supply for large institutions |
| **Remote and Island** | Provide energy to remote or isolated areas where grid connection is not feasible | Renewable and conventional energy sources and energy storage | Offer energy solutions in areas with difficult grid access, ensuring stable power supply |

*Table 1: Types of Microgrids [5]*

### 1.3.2 ADVANTAGES OF MICROGRIDS IN ENERGY COMMUNITIES

Over the past few years, microgrids that combine renewable energy and energy storage have become increasingly popular for several reasons. First, they have turned out to be a more environmentally friendly option and help to reduce the carbon footprint. Also, the falling prices of technologies such as solar panels and batteries, have made them become more affordable for the consumers. And finally, advances in intelligent control systems have also made them more efficient and easier to manage.

Some of the microgrids benefits are the following:

1. **Enhances Resilience:** Microgrids can keep working even if the main power grid goes down, ensuring that there is always electricity. This is especially helpful in areas where the main power grid is not reliable
2. **Facilitates Renewable Integration:** As Microgrids generate and store energy locally, it makes simpler the management of the intermittent nature of renewables, ensuring a steady supply of power even though there is no sun or wind. Therefore, this reduces the dependence on fossil fuels and helps to lower the greenhouse gas emissions, supporting a cleaner and more sustainable energy system.
3. **Improves Economic Efficiency:** This energy systems, take advantage of their own resources to save money. By generating and storing energy locally, they try to reduce the amount of energy bought during peaks when it’s most expensive. Also, they sometimes manage to earn an extra income by participating in demand response programs and providing services to the main grid.
4. **Supports the Main Grid:** They reduce the load and congestion on the main power grid, which helps make the whole system more stable and efficient.

5. **Increases Security:** Microgrids ensure that critical services, like hospitals and military bases, always have power, even if the main grid fails.
6. **Empowers Community Engagement and Autonomy:** They allow communities to manage their own energy supply, fostering independence and encouraging local solutions to energy needs.

In summary, microgrids offer significant benefits by enhancing resilience, integrating renewable energy, improving economic efficiency, and increasing energy security. They are an effective solution for improving local energy systems.

### 1.3.3 TECHNICAL AND ECONOMICS CHALLENGES OF MICROGRIDS

Even though Microgrids offer many benefits, been a technology which is still under development presents many barriers that still need to be overcome. These challenges have to be studied and addressed to ensure the progressive implementation and operation of microgrids within community energy systems.

The key challenges can be categorized into technical and economic aspects and are explained below [4].

**Technological Challenges**

- **Integration of DERs:** The management of different types of Distributed Energy Resources (DERs) can be very complicated, as each of them has different characteristics and needs. For example, solar panels only produce energy while it’s shining, or wind turbines only work while its windy. Also, batteries need careful management to charge and discharge properly. Therefore, the role of balancing all of these different sources while keeping the power grid stable and ensuring good power quality is a tricky task.
- **Control and Management:** Controlling and managing a microgrid is challenging because it involves coordinating many different parts. The system must decide the best times to use solar panels, batteries, and other energy sources. It also must handle

the switch between using the main grid and running independently during outages. This complexity requires advanced technology and precise control to ensure everything works together efficiently and reliably.

- **Protection and Security:** Protection and security are a tough job in microgrids because it involves keeping the physical and the digital systems safe. Physical equipment such as solar panels and batteries, has to be protected from damage, theft, or vandalism. The digital systems, which control the microgrid, need to be safe from hackers and cyberattacks. Ensuring everything is secure and works correctly requires strong security measures and constant monitoring.

**Economic Challenges:**

- **High Initial Cost**
- **Regulatory and Market Barriers**

# Chapter 2. PROBLEM FORMULATION

## 2.1 METHODOLOGY

The methodology shown in Figure 4 has been used to simulate the results. Firstly, the data corresponding to Import and Export prices, load profiles, PV generation profiles and DERs ratings have been exported from excel to MATLAB. Secondly, this data has been simulated with the CET model in MATLAB and the demand profiles of the houses have been exported to excel. Finally, for the analysis of the impact on the LVND, these prosumers net demand profiles have simulated in pandapower [6] with the LVDN model, and the following outputs have extracted: components loading, voltage magnitude and voltage unbalance.

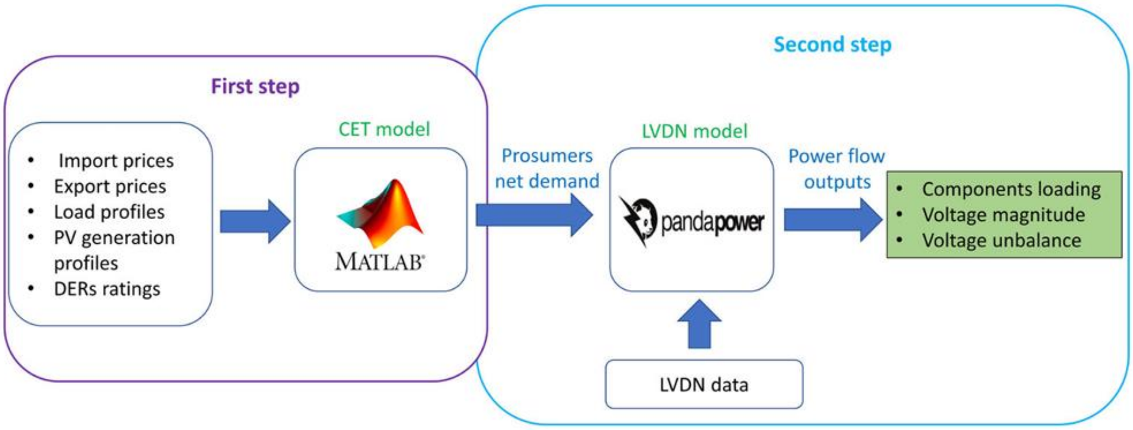


*Figure 4: Schematic diagram of community energy trading impacts evaluation [2].*

## 2.2 COMMUNITY ENERGY TRADING MARKET MODEL

### Problem's Objective Function

The proposed study is modeled as a linear multiperiod optimization problem in MATLAB, that is proposed in [7] [8]. The data used is for a trading period of 1 month and a community of 55 houses. The main objective of the problem is:

1. Minimizing the energy imports costs from the retailer [2].

2. Maximizing the energy exports benefits to the retailer [2].

3. Minimize contracted power charges [3].

$$\min \sum_{per \in P} p_{per}^{cp} * CP_{per} + \sum_{t} \sum_{h} (p_G^{(t)} * G^{(t,h)} - p_F^{(t)} * F^{(t,h)})\Delta t$$

To achieve this, local peer-to-peer energy trading within the community and the flexibility of energy storage systems (ESS) and electric vehicles (EVs) are incentivized. The community objective function is formulated considering:

- Energy balance restrictions
- DERs (Distributed Energy Resources) operation limits
- P2P trading constraints within the community

Table 2 contains the variables, scalars and parameters of the community energy trading model. The variables are written in capital letters, while the different parameters are written in lower case letters, to distinguish them easily.

| ***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 stored at ESS of home h at instant t |
| $D_{(t,h)}$ | ESS discharge power at home h at instant t |
| $D_{(t,h)\ EV}$ | EV discharge power at home h at instant t |
| $X_{(t,h)}$ | Exports to peers in the community from home h at instant t |
| $E_{(t,h)\ EV}$ | 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 |
| $C_{(t,h)\ EV}$ | EV charge power at home h at instant t |
| $I_{(t,h\ \leftarrow p)}$ | Energy imported to home h from its peer p at instant t |
| $X_{(t,h\ \rightarrow p)}$ | Energy exported from home h to its peer p at instant t |
| $CP_{per}$ | Contracted Power per house at period per |
| ***Parameters, scalars and sets*** | |
| $dem_{(t,h)}$ | Demand of house 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 |
| $n_c$ | ESS charging efficiency |
| $n_d$ | ESS discharging efficiency |
| $n_{c\ EV}$ | EV charging efficiency |
| $n_{d\ EV}$ | EV discharging efficiency |
| $\bar{C}$ and $\bar{D}$ | Upper limits of charging and discharging powers of ESS |
| $\overline{C_{EV}}$ and $\overline{D_{EV}}$ | Upper limits of charging and discharging powers of EVs |
| $\psi_{P2P}$ | P2P trade loss factor |
| $p_{per}^{cp}$ | Contracted Power Cost at period per |

*Table 2: Variables, scalars, parameters, and sets of the community energy trading model.*

### Energy Balance at Each Household Node

There must be an equilibrium between supply and demand at each instant of time t at each household node. This means that the sum of consumption from the grid $G_{(t,h)}$, the energy imports from other peers in the community $I_{(t,h)}$, the solar power generation $pv_{(t,h)}$, the discharge of the energy storage systems $D_{(t,h)}$, and the discharge of electric vehicles $D_{(t,h)\,EV}$ must be greater than or equal to the sum of exports to other peers $X_{(t,h)}$, household demand $dem_{(t,h)}$, supply to the main grid $F_{(t,h)}$, charging of storage systems $C_{(t,h)}$, and charging of electric vehicles $C_{(t,h)\,EV}$.

$$G_{(t,h)} + I_{(t,h)} + pv_{(t,h)} + D_{(t,h)} + D_{(t,h)\,EV} \geq X_{(t,h)} + dem_{(t,h)} + F_{(t,h)} + C_{(t,h)} + C_{(t,h)\,EV}$$

$$\forall t \in T, \quad \forall h \in H$$

### Operating Limits for ESSs and EVs

Energy storage systems and electric vehicles have specific limits for both charging and discharging energy. These limits are determined by the capacity of the power converter that connects the ESS or the EV to the low voltage distribution network (LVDN). The upper limits for charging and discharging are given by $\bar{C}$, $\bar{D}$ respectively for the ESS, and $\overline{C_{EV}}$, $\overline{D_{EV}}$ for the EV, while the lower limits are zero.

### ESS Charging and Discharging Limits

$$0 \leq C_{(t,h)} \leq \bar{C} \qquad \forall t \in T, \quad \forall h \in H$$

$$0 \leq D_{(t,h)} \leq \bar{D} \qquad \forall t \in T, \quad \forall h \in H$$

$$E_{min} \leq E_{(t,h)\,EV} \leq E_{max} \qquad \forall t \in T, \quad \forall h \in H$$

The energy stored in each ESS at any point is calculated considering the charging ($n_c$) and ($n_d$) discharging efficiency of the system.

$$E_{(t,h)} = E_{(t-1,h)} + n_c * C_{(t,h)} * \Delta t - \frac{1}{n_d} * D_{(t,h)} * \Delta t \quad \forall t \in T, \forall h \in H$$

- **EV Charging and Discharging Limits**

$$0 \leq C_{(t,h)\,EV} \leq \overline{C_{EV}} \quad \forall t \in T, \forall h \in H$$

$$0 \leq D_{(t,h)\,EV} \leq \overline{D_{EV}} \quad \forall t \in T, \forall h \in H$$

$$E_{EV\,min} \leq E_{(t,h)\,EV} \leq E_{EV\,max} \quad \forall t \in T, \forall h \in H$$

The energy stored in each EV at any point is calculated in a similar way to the ESSs, bearing in mind the charging ($n_{c\,EV}$) and discharging efficiency ($n_{d\,EV}$).

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

Also, for scenario 2, two new equations have been added. These constraints ensure that the state of charge (SOC) of the batteries and electric vehicles (EVs) remains the same at the beginning and the end of each day.

$$E_{(24,h)\,EV} = E_{(1,h)\,EV} \quad \forall h \in H$$

$$E_{(24,h)} = E_{(1,h)} \quad \forall h \in H$$

### P2P Energy Trading

- **P2P Trade Balance**

The energy import by the prosumer *h* from the peer *p* ($I_{(t,h\leftarrow p)}$) is equal to the export of peer *p* to prosumer *h* ($X_{(t,p\rightarrow h)}$) considering P2P trading losses ($\psi_{P2P}$).

$$I_{(t,h\leftarrow p)} = \psi_{P2P} * X_{(t,p\rightarrow h)} \quad \forall t \in T, \forall h \in H$$

- **Total Energy Exported**

The total energy exported by a household to other members of the community is calculated by adding up all the energy that household exports to each of the other households. This calculation is important to determine how much each household contributes to the energy supply within the community.

$$X_{(t,h)} = \sum_{p \neq h} X_{(t,h \rightarrow p)} \quad \forall t \in T, \ \forall h \in H$$

- **Total Energy Imported**

Similarly, the total energy imported by a household from other members of the community is calculated by adding up all the energy that household imports from each of the other households. This calculation is essential to understand how much energy each household consumes from the community grid.

$$I_{(t,h)} = \sum_{p \neq h} I_{(t,p \rightarrow h)} \quad \forall t \in T, \ \forall h \in H$$

- **Sum of Sales Equals Sum of Purchases**

The sum of all energy sold by households ($X_{(t,h)}$) must equal the sum of all energy purchased by households ($I_{(t,h)}$), considering P2P trading losses ($\psi_{P2P}$).

$$\sum_{h} \psi_{P2P} * X_{(t,h)} = \sum_{h} I_{(t,h)} \quad \forall t \in T, \qquad \forall h \in H$$

**Price Restrictions**

The CET price is capped between the import price and the export price to make it profitable for all market participants (buyers and sellers). Buyers buy energy at a lower price than the import price, and sellers sell energy at a higher price than the export price.

Considering these constraints and operating conditions, the study seeks to optimize energy trade and resource utilization within the community to achieve the objectives of minimizing import costs and maximizing export benefits.

# Chapter 3. LOW VOLTAGE DISTRIBUTION NETWORK & DER'S CHARACTERISTICS

## 3.1 LOW VOLTAGE DISTRIBUTION NETWORK

The system used in the study consists of 55 different households and a transformer. The system has a radial topology, which is typical for low-voltage networks in Europe. This means that the 55 houses are connected through lines branching off a main line, and any failure in the main line could affect a significant number of consumers. The system is connected to the main network through a transformer which reduces the voltage from 11 kV to 416 V and its capacity is 800 kVA [9].

The consumers are distributed in three electrical phases:

- Phase A (blue): 21 consumers.
- Phase B (green): 19 consumers.
- Phase C (orange): 15 consumers.

The consumption profiles are based on actual measurements of consumers in Madrid, Spain, provided by i-DE, an energy distribution company of the Iberdrola Group. Each consumer has a different consumption profile, randomly assigned from these measurements. Also, only active power trade is considered, reactive power is not included. In the power flow, it is assumed that the loads have a constant power factor of 0.95 p.u.

Figure 5 shows a schematic diagram of the distribution network.

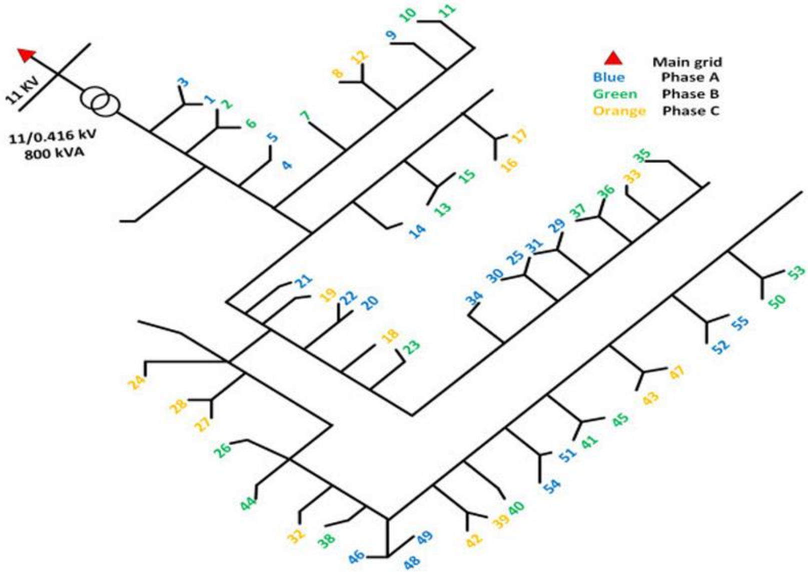


*Figure 5: Schematic diagram of the system under study [2]*

## 3.2 DER'S CHARACTERISTICS AND RETAILER PRICES

In this section, the characteristics of the different distributed energy resources (DERs) used in the study, as well as the retail prices and feed-in tariff are described. The DERs considered in this project include solar panels, energy storage systems (ESS), and electric vehicles (EV). Also, in this section the retailer prices and Feed-in Tariff (FIT) used in the analysis are also provided and explained.

### 3.2.1 PHOTOVOLTAIC

The PVs in the community have the following characteristics.

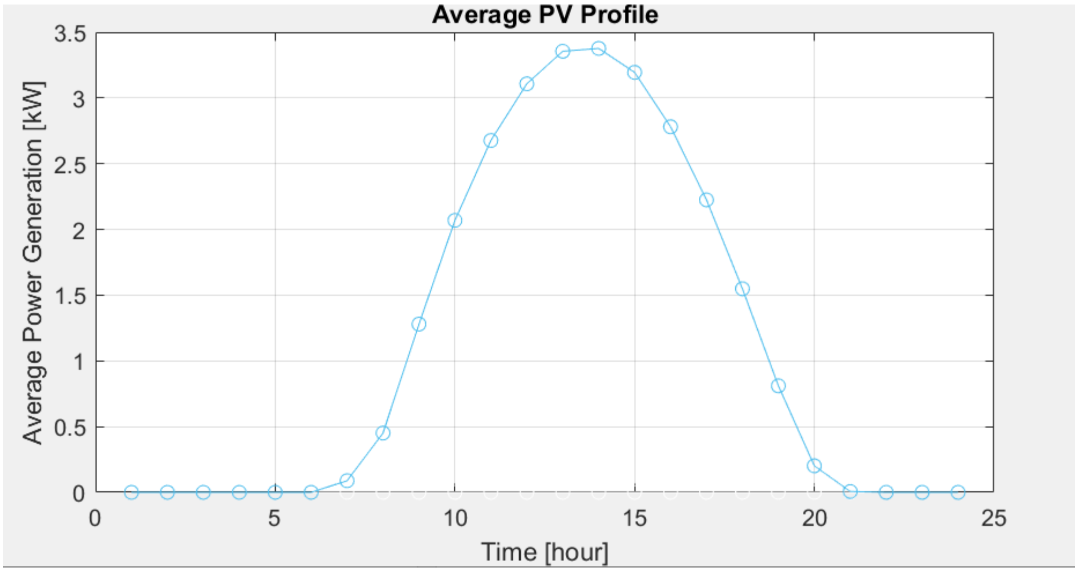


*Figure 6: PV generation profile for 1 home*

### 3.2.2 ENERGY STORAGE SYSTEMS

The Energy Storage Systems (BESS) in the community have the following characteristics.

- Capacity: 13.5 kWh
- Maximum charging power: 5 kW
- Maximum discharge power: 5 kW
- Charging efficiency: 95%

- Discharging efficiency: 95%
- Energy level lower limit: 2.7 kWh
- Upper energy level limit: 13.5 kWh

These systems allow the excess energy generated by the solar panels to be stored and used when needed, which help improve the stability and efficiency of the grid. Also, the systems have been designed in such a way that they can never be at less than 20% of their load capacity, thus ensuring longer life and performance.

In one of the scenarios studied, the system is designed to have the same state of charge at the beginning and end of the day.

### 3.2.3 ELECTRIC VEHICLES

Electric vehicles (EVs) have a significant impact on the electric system due to their characteristics. Below are described the specific charging and discharging details of the EV considered in this study (Nissan Leaf).

- Battery capacity: 24 kWh
- Energy level lower limit: 4.8 kWh
- Charger power: 3.6 kW
- Maximum discharge power: 3.6 kW
- Charging efficiency: 96%
- Discharge efficiency: 96%

All the EVs in the study have been designed to charge between 6 p.m. and 8 a.m., this is because theoretically, charging the car at night hours can take advantage of periods of lower electricity costs.

### 3.2.4 RETAILER AND FEED-IN TARIFF PRICES

This study has been carried out with the purchase and sale energy prices of Spain. The system has been designed in a way that prosumers buy power at the retail tariff and sell their surplus self-generated power at the regulated feed-in tariff (PVPC). The prices for July 2021 were obtained from the Spanish electricity system operator, “Red Eléctrica”. Details of these prices are described below:

- Retailer purchase prices: Prosumers purchase energy from the electricity grid at a price regulated by the retailer. This price may vary throughout the day, reflecting fluctuations in energy demand and supply.
- Feed-in Tariff (FIT): Prosumers who generate more energy than they consume can sell surplus energy to the grid. The feed-in tariff is the price paid for this surplus energy and is regulated by the PVPC in Spain. This tariff is generally lower than the retailer's purchase price, incentivizing self-consumption.
- Price data used: Specific prices for July 1 and 2, 2021 were obtained from “Red Eléctrica de España”. This data includes both purchase prices and feed-in tariffs, allowing for a detailed analysis of energy trading within the community.

Moreover, this study also considers the price for Peer-to-Peer energy trading. These exchange prices are within the range of the retailer's purchase prices and injection rates. In simpler terms, the prices for exchanging energy between peers are set in a way that sellers (prosumers) get more money than they would from selling back to the grid, and buyers pay less than they would if they bought from the main grid. This approach makes trading energy locally more attractive and beneficial for everyone involved.

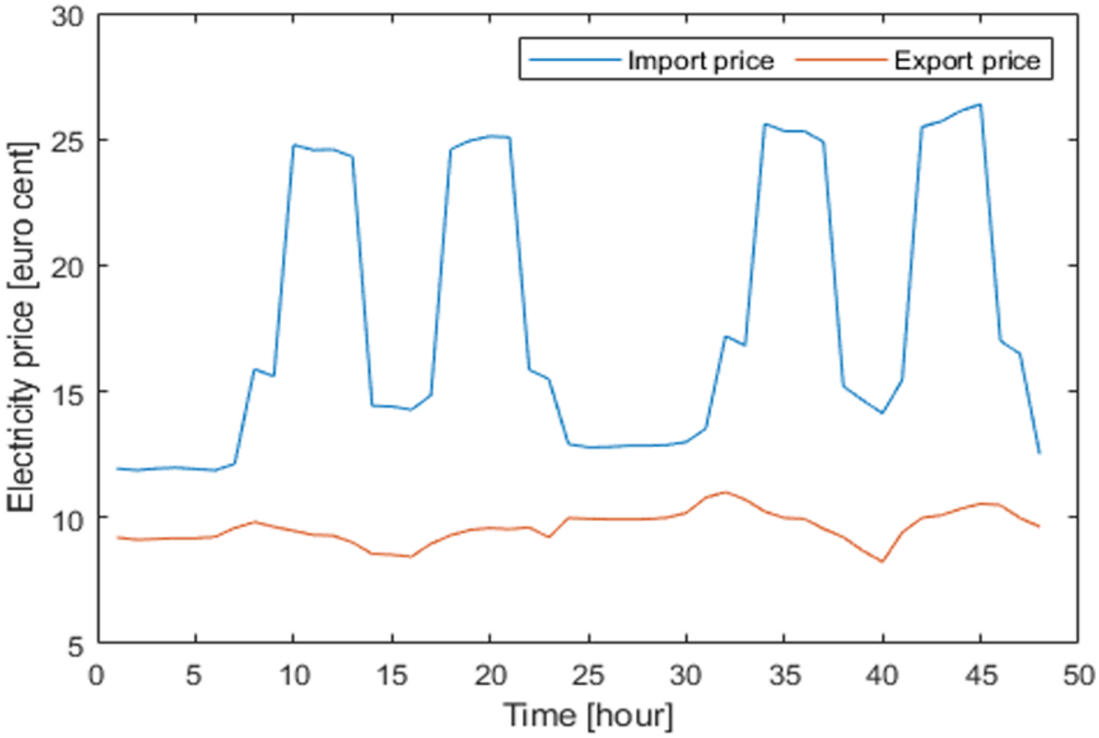


*Figure 7:Prosumers purchase/sell prices from/to retailer [2]*

## 3.3 STUDIED SCENARIOS

The study has two main objectives. First, to analyze how dividing the existing community into smaller energy communities affects energy distribution and the load on the main grid. This involves understanding the differences between operating the community as a single energy entity versus dividing it into three separate energy communities, and examining how this impacts imports from the grid, exports to the grid, or Peer-to-Peer (P2P) energy trades among others. Second, to investigate how the scheduling of the State of Charge (SoC) of batteries impacts energy distribution and its effect on the grid. This aspect aims to explore the benefits and challenges of different energy storage management strategies in maintaining grid stability and operational efficiency. To achieve these objectives, the following scenarios have been developed.

In the first scenario, the community consists of 55 houses. This study examines the impact of two different organizational structures for the energy community:

1. <u>Single Energy Community:</u> All 55 houses are grouped together to form one large energy community.
2. <u>Three Energy Communities:</u> The 55 houses are divided into three separate energy communities. Each of these smaller communities corresponds to the phase they are connected to within the electrical network. The optimization process focuses on houses connected to the same phase, ensuring that each phase-specific community is optimized independently.

This approach makes it able to compare the performance and benefits of having a single large energy community versus having multiple smaller, phase-specific energy communities.

In the second scenario, the impacts on maintaining the same state of charge of the EES and EVs at the beginning and end of each day is studied.

By comparing these scenarios, the study aims to provide a comprehensive understanding of how different community configurations and energy storage management strategies affect the overall performance, efficiency, and impact on the quality of supply indicators: voltage, unbalances and network congestions.

| *#* | *Scenario* | *DERs* | *Description* |
|---|---|---|---|
| **1** | **Diving System into Smaller Energy Communities** | PV (60% consumers)<br>BESS (40 % consumers) | Evaluates the impact of dividing a single large energy community into three smaller communities |
| **2** | **Impact of SOC for Batteries and EVs** | PV (60% consumers)<br>BESS (40% consumers)<br>EV (33% consumers) | Analyzes how the requirement to maintain the same SOC at the beginning and end of the day influences the charging and discharging cycles of both batteries and EVs. |

*Table 3: Scenarios Description*

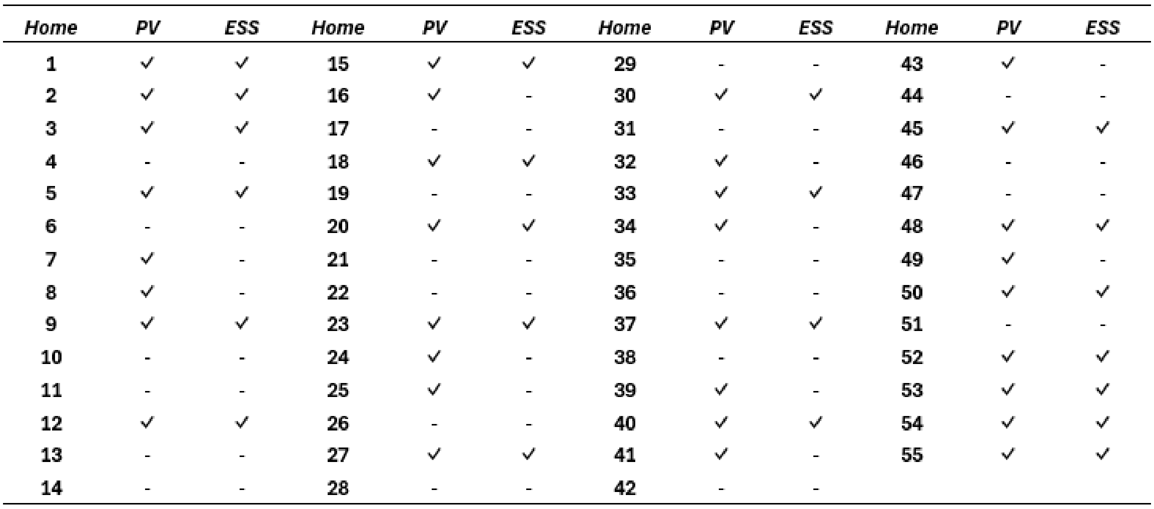
# Chapter 4. RESULTS AND DISCUSSIONS

## 4.1 DESCRIPTION OF THE STUDIED SCENARIOS

### 4.1.1 DESCRIPTION OF SCENARIO 1: ANALYSIS OF DIVIDING THE ENERGY COMMUNITY INTO SMALLER COMMUNITIES

This section describes the first scenario, which involves the division of a single energy community into three smaller, distinct communities.

- **One Energy Community:** First, the initial set up of the system, which consists of 55 houses, is described in Table 4, which provides the Distributed Energy Resources (DERs) available in each house. This set up provides 60% of the consumers with PV and 40% with energy storage systems (BESS). In this scenario, it was decided that no EVs should be used in order to simplify the results.



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

*Table 4: DERs installed at each house of the community Scenario 1, One Energy Community*

Figure 8 shows the aggregated demand of all 55 houses in the community in the first two days of the simulated month. Each colored band represents the demand contribution of an individual house. Some of the key observations are the following:

- The demand peaks appear during the morning and evening hours, corresponding to typical residential energy usage patterns. These peaks reflect increased energy consumption during times when residents are likely to be active at home. These values reach up to 80 kW.
- There are noticeable valleys in the graph during the late night and midday hours. These low demand periods seem to hover around 30-40 kW. These times reflect reduced energy usage, likely due to residents being asleep or away from home, thus not using many electrical devices.
- There is a visible variability in the demand profiles of some of the houses. This means that the community has diverse consumption patterns, while some houses consume more energy at certain times of the day others may consume less or at different times.

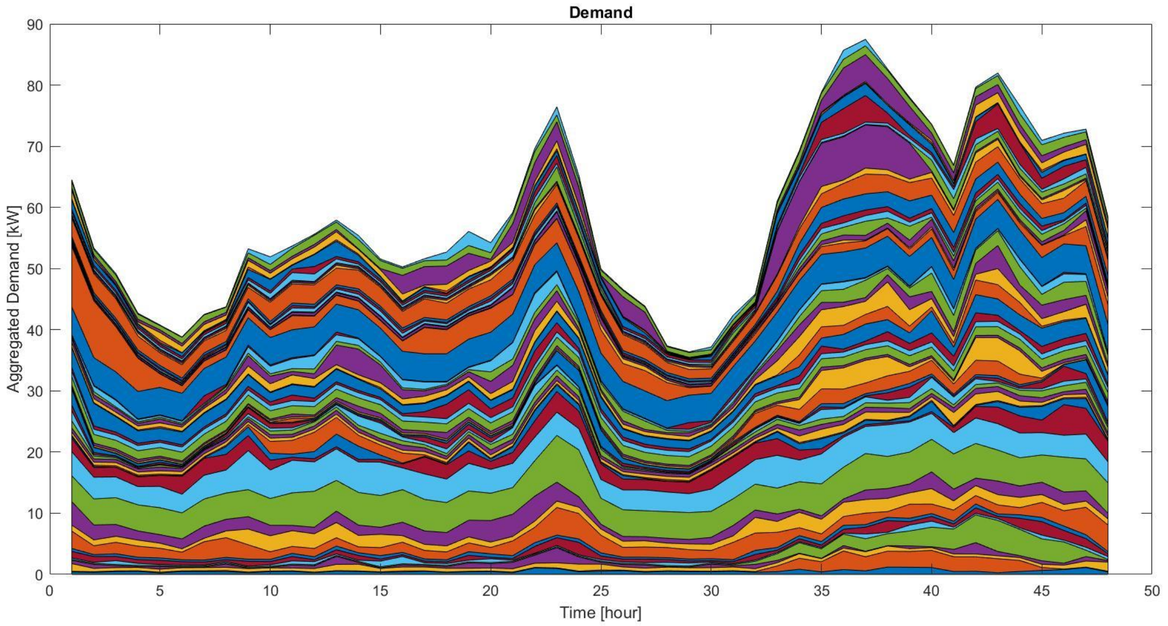
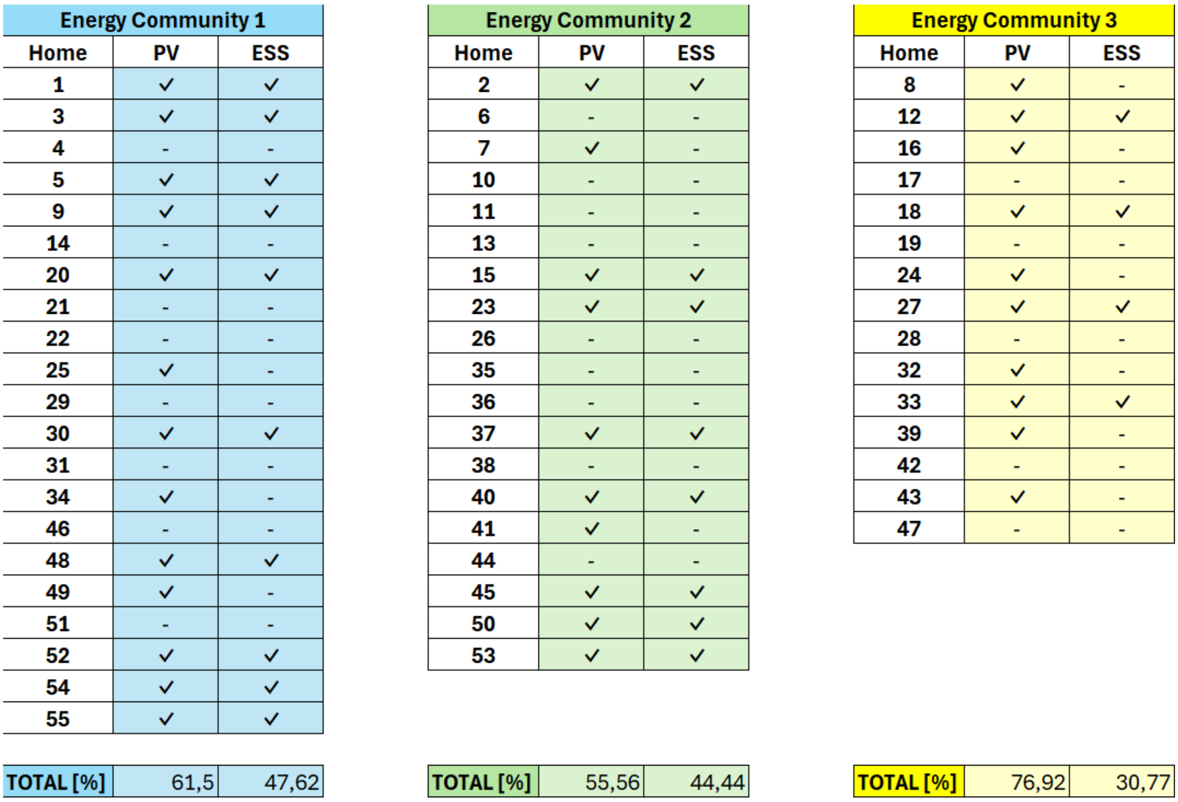


*Figure 8: Aggregated Demand Scenario 1, One Energy Community*

- **Three Energy Communities:** The initial system, consisting of 55 houses, was divided into three smaller communities for this study. This division was done by assigning houses according to the phase (A, B, or C) they are connected to in the Low Voltage Distribution Network (LVDN) Table 5 provides detailed information on the distribution of Distributed Energy Resources (DERs) within each new community.



| Energy Community 1 | | |
|---|---|---|
| **Home** | **PV** | **ESS** |
| 1 | ✓ | ✓ |
| 3 | ✓ | ✓ |
| 4 | - | - |
| 5 | ✓ | ✓ |
| 9 | ✓ | ✓ |
| 14 | - | - |
| 20 | ✓ | ✓ |
| 21 | - | - |
| 22 | - | - |
| 25 | ✓ | - |
| 29 | - | - |
| 30 | ✓ | ✓ |
| 31 | - | - |
| 34 | ✓ | - |
| 46 | - | - |
| 48 | ✓ | ✓ |
| 49 | ✓ | - |
| 51 | - | - |
| 52 | ✓ | ✓ |
| 54 | ✓ | ✓ |
| 55 | ✓ | ✓ |
| TOTAL [%] | 61,5 | 47,62 |

| Energy Community 2 | | |
|---|---|---|
| **Home** | **PV** | **ESS** |
| 2 | ✓ | ✓ |
| 6 | - | - |
| 7 | ✓ | - |
| 10 | - | - |
| 11 | - | - |
| 13 | - | - |
| 15 | ✓ | ✓ |
| 23 | ✓ | ✓ |
| 26 | - | - |
| 35 | - | - |
| 36 | - | - |
| 37 | ✓ | ✓ |
| 38 | - | - |
| 40 | ✓ | ✓ |
| 41 | ✓ | - |
| 44 | - | - |
| 45 | ✓ | ✓ |
| 50 | ✓ | ✓ |
| 53 | ✓ | ✓ |
| TOTAL [%] | 55,56 | 44,44 |

| Energy Community 3 | | |
|---|---|---|
| **Home** | **PV** | **ESS** |
| 8 | ✓ | - |
| 12 | ✓ | ✓ |
| 16 | ✓ | - |
| 17 | - | - |
| 18 | ✓ | ✓ |
| 19 | - | - |
| 24 | ✓ | - |
| 27 | ✓ | ✓ |
| 28 | - | - |
| 32 | ✓ | - |
| 33 | ✓ | ✓ |
| 39 | ✓ | - |
| 42 | - | - |
| 43 | ✓ | - |
| 47 | - | - |
| TOTAL [%] | 76,92 | 30,77 |

*Table 5: DERs installed at each house of the community Scenario 1, Three Energy Community*

In **Energy Community 1**, there are 21 houses connected to phase A. Out of these, 61.90% have photovoltaic (PV) systems, and 47.62% have energy storage systems (BESS). This Energy Community has a high proportion of PV and ESS, compared to the other communities, which can allow greater flexibility in energy management, facilitating both self-consumption and exports to the grid.

In **Energy Community 2**, there are 19 houses connected to phase B. Here, 55.56% of the houses are equipped with PV systems, and 44.44% have BESS. This energy community appears to have a less favorable balance in terms of energy resources, which could lead to a greater dependence on the grid to import energy and less capacity to export surplus

In **Energy Community 3**, consists of 15 houses connected to phase C, 76.92% have PV systems, and 30.77% have BESS. Although there is high power generation capacity (PV), the limited storage capacity (ESS) may lead to situations where the generated power is consumed internally or stored in the available ESS, reducing exports to the grid.

The following graphs, Figure 9, show the aggregated demand profiles for the three newly formed energy communities over the first two days of the simulated month. Each graph represents the demand contributions of individual houses within each community.

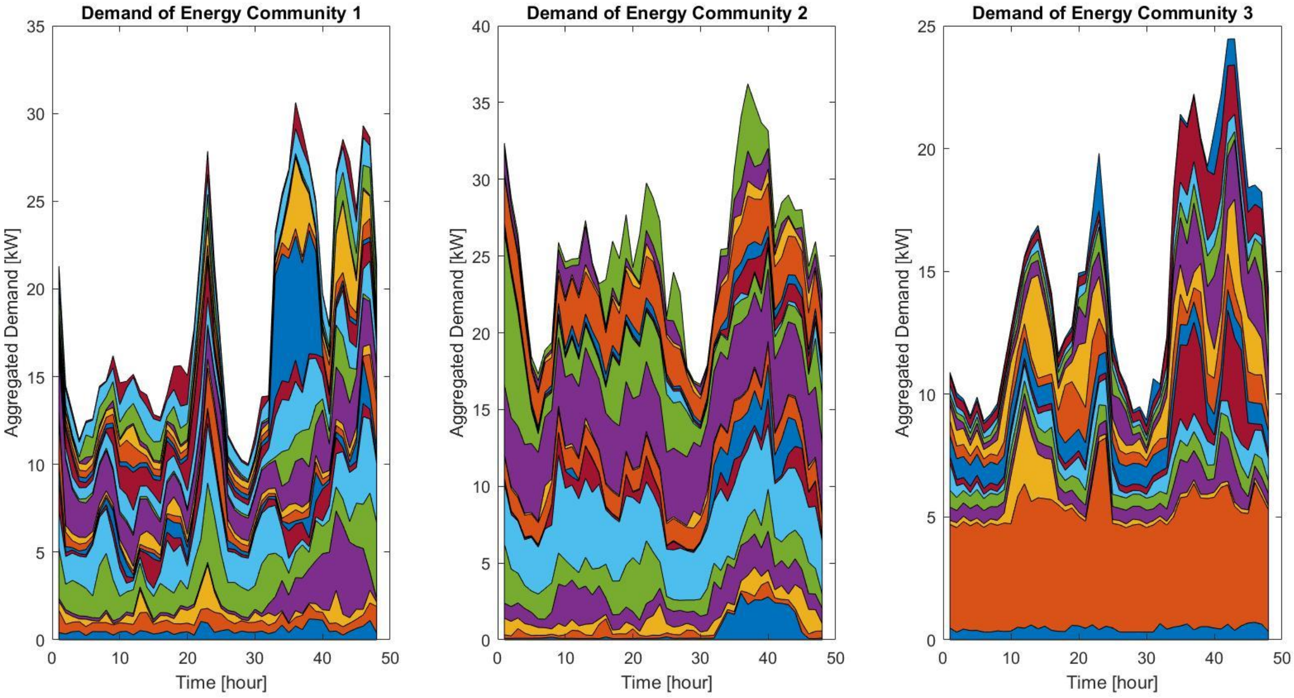


*Figure 9: Aggregated Demand Scenario 1, three energy communities*

The aggregated demand profiles for the three energy communities over the first two days of the simulated month reveal distinct consumption patterns. Energy Community 1 shows demand peaks of around 30 kW during the evening hours, with significant drops to around

10 kW during late night and midday periods. This wide range between peak and low demand highlights a high variability in consumption, indicating diverse energy usage behaviors among the houses in this community. Similarly, Energy Community 2 experiences the highest demand peaks, reaching approximately 35 kW, and slightly higher low demand periods of 15-20 kW. The pronounced peaks and higher valleys suggest a consistently higher overall energy usage compared to the other communities.

In contrast, Energy Community 3 exhibits lower peak demand values, around 25 kW, and maintains a more consistent low demand of around 10 kW. This smaller difference between peak and valley demands indicates a more stable and uniform consumption pattern among the houses in this community. The relative consistency in Energy Community 3's demand profile suggests less fluctuation in daily energy use, possibly indicating more uniform lifestyles or energy usage habits among its residents.

Overall, these demand profiles highlight the unique consumption characteristics of each community, with Community 2 showing the highest overall demand, Community 1 displaying significant variability, and Community 3 maintaining a more stable energy usage pattern.

### 4.1.2 DESCRIPTION OF SCENARIO 2: IMPACT OF SOC FOR BATTERIES AND EVS ON SINGLE COMMUNITIES

In this scenario, the impact of maintaining the same state of charge (SOC) for batteries and electric vehicles (EVs) at the beginning and end of each day is evaluated. The aim is to understand how such a constraint affects the energy distribution, storage, and consumption within the community.

The initial setup is expanded to include electric vehicles in some of the houses. The table below, Table 6, provides a detailed overview of the Distributed Energy Resources (DERs) available in each house, including the addition of EVs. Finally, the distribution of DERs is: 60% of the consumers have PV, 40% have BESS and 33,3% have EVs.

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

*Table 6: DERs installed at each house of the community [2]*

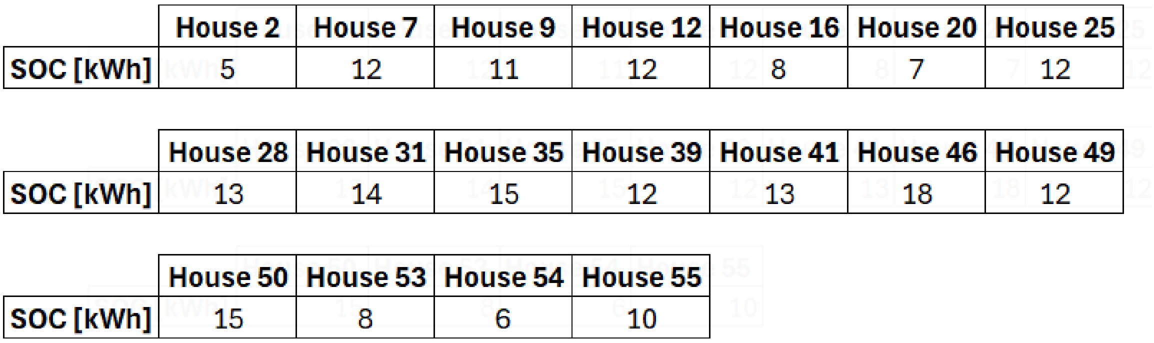
Moreover, additional constraints have been included in the system. The following tables present the initial and final state of charge (SOC) that the ESS and EVs must maintain at the initial SOC and last hour of the day.

| | **House 1** | **House 2** | **House 3** | **House 5** | **House 9** | **House 12** | **House 15** |
|---|---|---|---|---|---|---|---|
| **SOC [kWh]** | 10 | 5 | 10 | 7 | 2,7 | 3 | 9 |

| | **House 18** | **House 20** | **House 23** | **House 27** | **House 30** | **House 33** | **House 37** |
|---|---|---|---|---|---|---|---|
| **SOC [kWh]** | 5 | 6 | 6 | 8 | 8 | 4 | 4 |

| | **House 40** | **House 45** | **House 48** | **House 50** | **House 52** | **House 53** | **House 54** | **House 55** |
|---|---|---|---|---|---|---|---|---|
| **SOC [kWh]** | 8 | 6 | 6 | 5 | 3 | 10 | 10 | 7 |

*Table 7: Initial State of Charge of the Batteries*



| | House 2 | House 7 | House 9 | House 12 | House 16 | House 20 | House 25 | House 28 | House 31 | House 35 | House 39 | House 41 | House 46 | House 49 | House 50 | House 53 | House 54 | House 55 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **SOC [kWh]** | 5 | 12 | 11 | 12 | 8 | 7 | 12 | 13 | 14 | 15 | 12 | 13 | 18 | 12 | 15 | 8 | 6 | 10 |

*Table 8:Initial State of Charge of the Electric Vehicles*

The main objective of this scenario is to analyze how the requirement to maintain the same SOC at the initial and final value each day influences the charging and discharging cycles of both batteries and EVs. The new constraint added ensures that the energy storage systems operate within a controlled range, potentially impacting the overall energy distribution, peak demand periods, and the balance between energy generation and consumption.

## 4.2 OPERATION OF HOUSES UNDER DIFFERENT SCENARIOS

### 4.2.1 SCENARIO 1: ANALYSIS OF DIVIDING THE SYSTEM INTO SMALLER ENERGY SYSTEMS

In this scenario, as mentioned in previous sections, the objective is to analyze the impact of dividing a single large community into three smaller and different energy systems. Understanding this impact is important because it can reveal how smaller, localized energy systems compare to a single large system in terms of efficiency, reliability, and economic benefits.

The study was executed in two main steps. First, the initial scenario with the original setup of 55 houses was analyzed as a whole. This included evaluating the aggregated performance metrics and then zooming in to examine the detailed behavior of each phase within the single large energy system. This approach allowed for a comprehensive understanding of the system's overall performance and provided a basis for comparison with the scenario involving three smaller energy communities.

Next, the energy community was divided into three smaller energy communities, each corresponding to a different phase (A, B, or C). This division enabled a more granular analysis of the performance metrics for each smaller community. The comparison between the initial single large energy system and the three smaller systems helps to highlight the effects of the division on energy management and distribution.

The results of this scenario are presented in Table 9, providing a clear comparison of the key performance metrics between the single large energy system and the three smaller energy systems.

| | 1 Energy Community | | | | 3 Energy Community | | | |
|---|---|---|---|---|---|---|---|---|
| | Phase A | Phase B | Phase C | TOTAL | Phase A | Phase B | Phase C | TOTAL |
| **Imports from retailer (kWh)** | 6.861,40 | 9.922,08 | 4.787,29 | **21.570,78** | 5.716,85 | 12.300,03 | 4.450,05 | **22.466,93** |
| **Exports to retailer (kWh)** | 243,18 | 195,04 | 123,82 | **562,09** | 651,77 | 0 | 829,98 | **1.481,75** |
| **Total Trade (kWh)** | 6.347,4 | 4.610,43 | 4.494,44 | **15.452,30** | 5.353,86 | 5.774,9 | 3.720,8 | **14.849,56** |
| **Peak Grid Consumption (kW)** | 63,38 | 68,12 | 68,12 | **161,67** | 61,18 | 68,12 | 30,4 | **159,70** |
| **Grid Supply Percentage (%)** | 44,51 | 49,33 | 40,89 | **45,67** | 37,09 | 61,16 | 38,02 | **45,42** |
| **DERS Supply Percentage (%)** | 55,48 | 50,66 | 59,10 | **54,32** | 62,90 | 38,83 | 61,97 | **54,57** |
| **Total Cost (euros)** | 668,82 | 1.638,96 | 553.62 | **2.861,42** | 686,59 | 1.682,50 | 568,33 | **2.937,42** |
| | | | | | | | | |
| **Grid Import Cost (euros)** | 708,89 | 1.592,63 | 612,81 | **2.914,34** | 748,90 | 1.682,50 | 647,39 | **3.078,79** |
| **Grid Export Revenue (euros)** | 26,14 | 14,35 | 12,51 | **52,99** | 62,31 | 0 | 79,06 | **141,37** |

*Table 9: Comparative Analysis of Key Performance Metrics for Single vs. Three Energy Systems*

To illustrate and better understand the results presented in the table, the following graphs have been included.

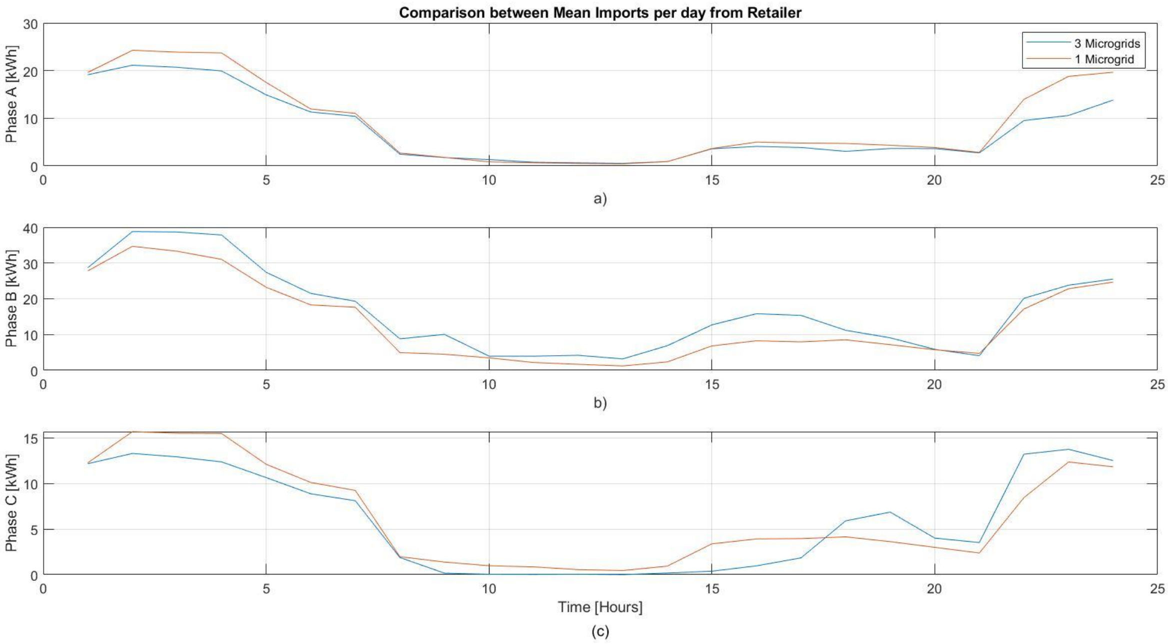


*Figure 10: Comparison between daily mean Imports from Retailer in Scenario 1 of (a) Phase A, (b) Phase B and (c) Phase C*

The mean values have been obtained as follows. For each specific hour, for example, 1 a.m., the values recorded at that hour for all the simulated days are taken. Then, the average of these values is calculated. This process is repeated for each hour of the day. In this way, an hourly mean is obtained, representing the values recorded throughout the entire simulation period.

Figure 10 provides a very valuable information on energy management in the two scenarios studied: a single energy community of 55 houses vs. three smaller energy communities.

First, in the scenario of the single energy community (represented in orange) it is interesting to point out that all their imports seem to be very uniform and predictable. This suggests that the large number of homes allows for greater balance and diversification in energy consumption and generation.

Second, in the scenario of the three different energy communities the import patterns have turned to be more variable, specially in phase B. This may be due to less diversification and balance within each smaller energy community. Also, as each energy community has to manage its own generation and consumption theirself-suffiency is more critical and the lack of adequate resources (as in Phase B) may result in higher imports.

Therefore, uneven distribution of DERs among energy communities significantly affects their ability to manage energy, as it could have been predicted. Energy communities with higher proportion of DERs (such as 1 and 3) have better self-sufficiency capabilities and lower imports, while Energy Community 2 is more dependent on imports due to its lower generation and storage capacity.

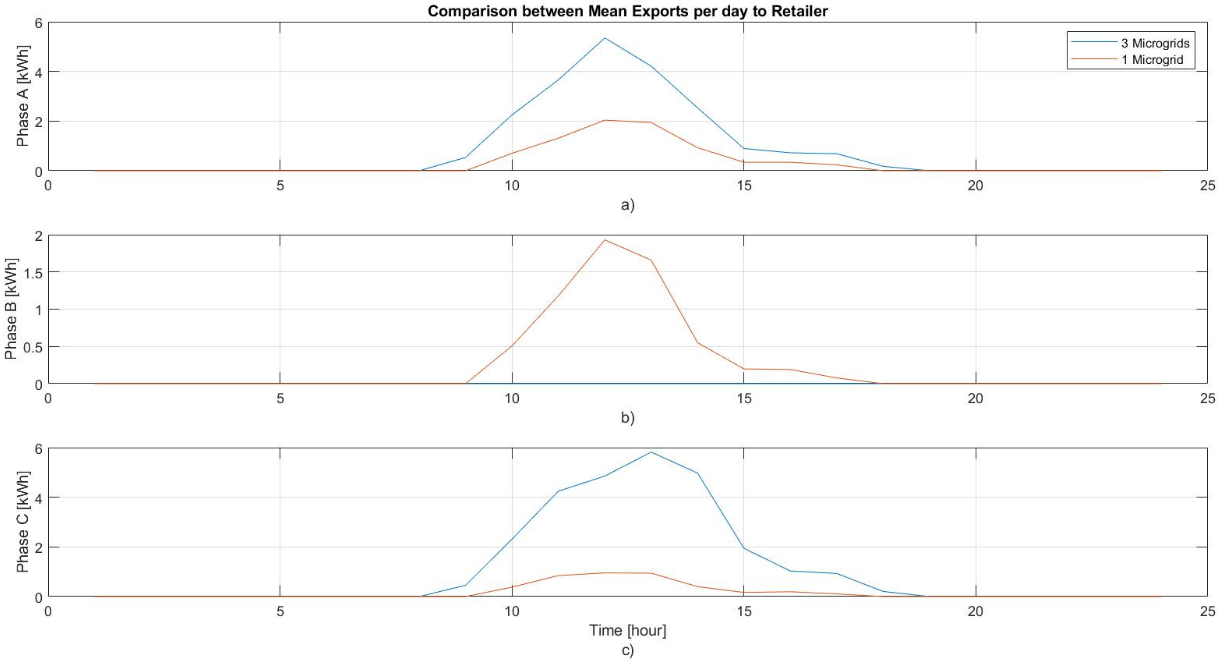


*Figure 11: Comparison between daily mean Exports to Retailer in Scenario 1 of (a) Phase A, (b) Phase B and (c) Phase C*

The export graphs show how the energy communities manage excess power generated and their ability to sell the surplus power back to the grid. An analysis of the export graphs is presented below, comparing the two scenarios of a single energy community versus three energy comunitiess.

Energy exports show a peak in the central hours of the day, coinciding with peak solar production. In the analysis of the energy communities, PV in Phase B are observed to be approximately 55%, compared to 62% in Phase A and 77% in Phase C. This lower proportion of DERs in Phase B results in less surplus energy to export, as generation and storage capacity is insufficient to meet domestic demand and generate significant surpluses.

In addition, in the three-energy communities scenario, a higher surplus of exported energy is observed compared to a single energy community. This is because the three energy communities cannot exchange energy among themselves, forcing each energy community to manage its own surpluses independently. As a result, energy communities with higher generation and storage capacity export more energy to the grid, while those with lower capacity, such as Phase B, have minimal or no exports.

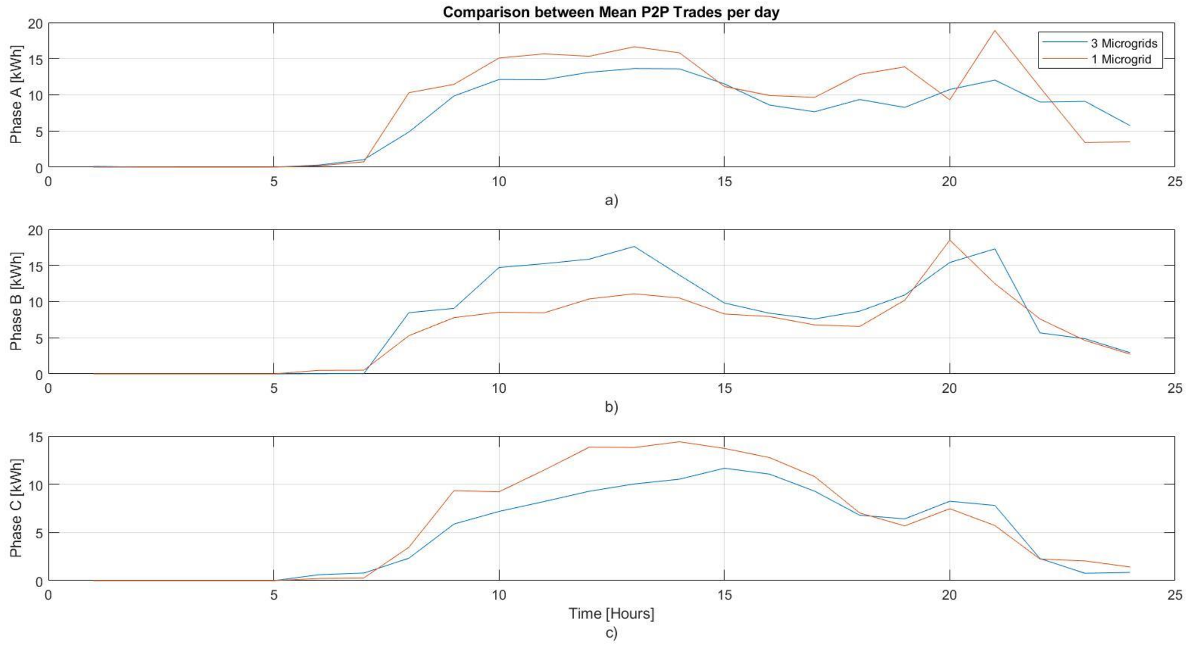


*Figure 12: Comparison between daily mean P2P trades in Scenario 1 of (a) Phase A, (b) Phase B and (c) Phase C*

P2P energy trading is a key to managing energy within energy commnities efficiently. It allows households to share their surplus energy, which optimizes resource use and improves community self-sufficiency. The main point of interest in the graph is the changing trend in P2P energy trading between the phases in the different scenarios. Sometimes there is more P2P trading in the single energy commnities scenario, while other times there is more in the three- energy commnity scenario, highlighting how the configuration and distribution of resources affect energy exchange dynamics

In the single energy commnity scenario, only 60% of the houses are equipped with PV, which means there is a greater need for energy sharing among the houses to ensure that all can meet their energy needs. This P2P trading allows houses without PV or with lower energy generation to receive surpluses from houses that do have PV, thus balancing energy demand and supply within the energy commnity.

On the other hand, in the three- energy commnity scenario, phases A and C have a higher proportion of houses with PV (62% and 77% respectively). This higher local generation capacity reduces the need for P2P trading, as more houses can meet their own energy needs with the energy they generate. Therefore, in these phases, there is less reliance on energy exchange between houses, resulting in less P2P trading activity compared to the single energy commnity scenario.

In conclusion, in this graph we have been able to observe and prove the theory that in energy communities with lower generation, there is a greater exchange of energy between houses.

### 4.2.2 SCENARIO 2: IMPACT OF SOC CONSTRAINTS FOR ESS AND EVS ON SINGLE COMMUNITIES

The objective of this section is to analyze the impact of imposing a new constraint about the state of charge (SOC) on batteries and electric vehicles (EVs) in a single community energy system. The principal aim is to understand how maintaining the same SOC at the beginning and end of each day affects the overall energy management, including imports from the grid, exports to the grid, and the use of distributed energy resources (DERs).

To understand completely the results of this scenario, the following approach was followed. First, the overall results of the simulation for both scenarios were collected and presented in Table 10. Second, a zoom into energy storage characteristics was carried out, focusing on charge and discharge profiles, SOC levels throughout the day and any noticeable differences in performance due to the new SOC constraints. Finally, the examination of the behavior of electric vehicles under both scenarios was studied. This study involves looking at their charging and discharging patterns, SOC levels, and the impact of the constraints on their overall performance and contribution to the community energy system.

- **Overall Results from the simulation:**

The results shown in Table 10 indicate that the imposition of SOC constraints leads to a slight reduction in imports from the retailer and exports to the retailer. Total trade also decreases by almost 4% under the SOC constraints scenario, suggesting less overall energy exchange. However, the most interesting result from this table is that peak grid consumption is significantly lower with SOC constraints, exactly 12,20% lower.  This reduction on peak grid consumption could indicate better load management and a reduction in peak demand stress on the grid. While the grid supply percentage and DERs supply percentage remain relatively unchanged, there is a notable increase in total cost and grid import cost in the SOC-constrained scenario, highlighting the potential financial impact of maintaining consistent SOC levels. Overall, these findings suggest that while SOC constraints can help reduce peak grid consumption and imports, they may come at a higher cost.

| | Different SOC | Same SOC |
|---|---|---|
| **Imports from retailer (kWh)** | 26.499,84 | 26.445,53 |
| **Exports to retailer (kWh)** | 776,11 | 703,67 |
| **Total Trade (kWh)** | 17.165,91 | 16.492,39 |
| **Peak Grid Consumption (kW)** | 221,97 | 194,88 |
| **Grid Supply Percentage (%)** | 56,11 | 55,99 |
| **DERS Supply Percentage (%)** | 43,89 | 44,01 |
| **Total Cost (euros)** | 3.392,79 | 3.638,08 |
| **Grid Import Cost (euros)** | 3.450,98 | 3.689,44 |
| **Grid Import Revenue (euros)** | 58,18 | 51,36 |

*Table 10: Comparison of Key Performance Metrics Under Different SOC Constraints*

Figure 13 shows the results of the table below, which are explained graphically. First, it is interesting to analyze the comparison between imports from retailer in both scenarios, and how even though in Table 10 they did not seem so different, their curves throughout the day slightly differ. On the one hand, the first scenario has a peak during nighttime, between 12 p.m. and 7 a.m., this peak corresponds to the charging period of the batteries and electric vehicles. On the other hand, the second scenario has a peak between 9 p.m. and 12 p.m., also corresponding to the charging period of the energy storage devices.

The Exports to Retailer plot for both scenarios look a lot alike, with a slight difference at the early evening. While scenario 2 does not experiment any exports, scenario 1 does, because the batteries are fully charged, and they don’t have any constraint preventing the discharge of the batteries or EVs.

Finally, the curves that correspond to the traded energy of the system in both scenarios look very similar, which makes contrast on what is shown in Table 10, as the scenario without the new constraint is about a 5% lower than scenario 2. This difference occurs during the last hours of the day, probably because while in scenario 2 the batteries cannot be discharged due to the new constraint, those in scenario 1 use that energy to meet demand instead of importing it from the grid.

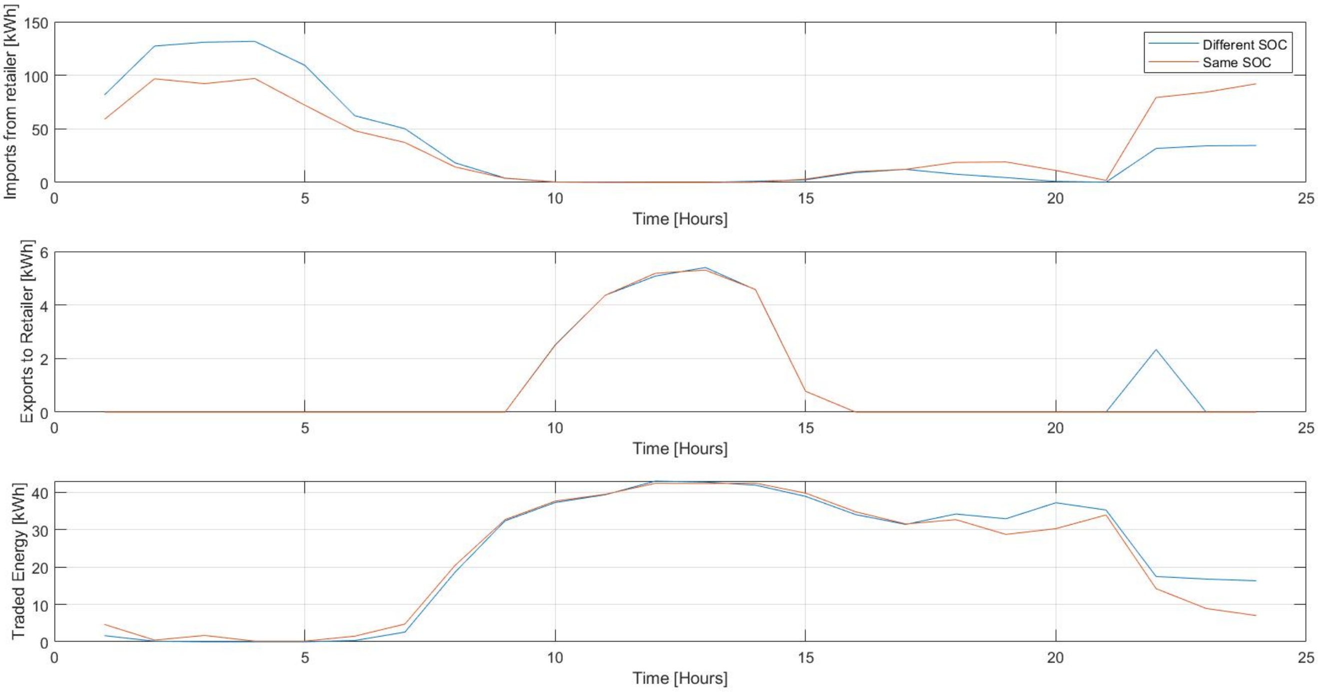


*Figure 13: Comparison of the studied scenarios in terms of imported, exported and traded energy*

- **Energy Storage Systems Analysis:**

In order to gain deeper insight into how the Energy Storage Systems operate under the two scenarios studied, the following figures focus on detailed performance and behavior of the batteries in the community.

The heatmap represented on Figure 14Figure 10, displays the energy levels for the houses that own a Energy Storage System over 24 hours, averaged across the month. The left heatmap represents the scenario with no SOC constraints, and the right heatmap represents the scenario with SOC constraints (same SOC at the initial al final value of the day for each DERs).

In the "Different SOC" scenario (left), the SOC levels show significant variability throughout the day, indicating more frequent charging and discharging cycles. The profiles show that batteries tend to be discharged by the nighttime, with their peak charging occurring around 5 PM, indicating that they use solar energy for recharging completely during the day. The pattern shown on the heatmap reflects that the batteries charge, and discharge based on the immediate availability of energy and current demand. For instance, they charge when there is sufficient solar energy available during the day and discharge when there is higher energy consumption, such as at night. In other words, the batteries are reacting quickly to the current conditions of energy supply and demand.

In contrast, in the "Same SOC" scenario (right), the SOC levels are more consistent, demonstrating the constraint to maintain the same SOC at the beginning and end of each day. This consistency results in less variability in charging and discharging patterns, ensuring a more stable energy management approach that prevents deep discharges and excessive charging cycles.

The stable SOC behavior of the scenario with the new constraint, aligns with the observed reduction in peak grid consumption seen in Table 10, as maintaining a consistent SOC likely mitigates the extreme demand spikes that occur when batteries need to be charged or discharged rapidly.

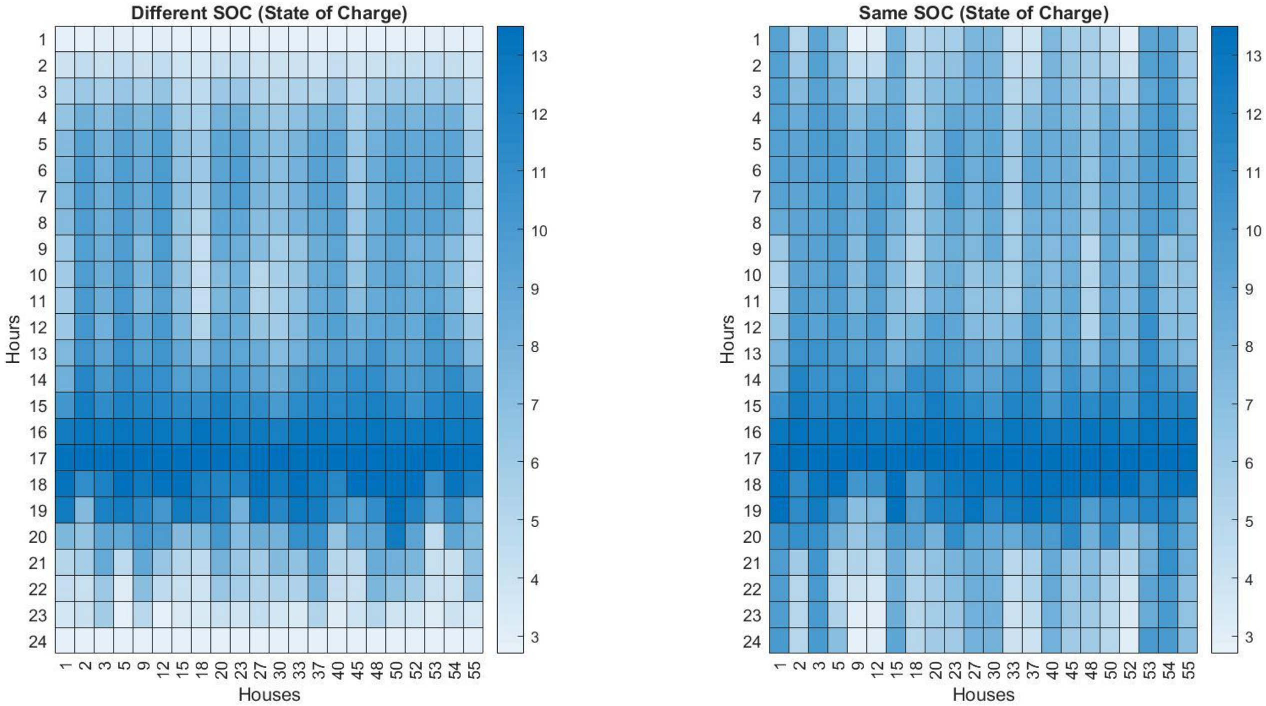


*Figure 14: Heatmap ESS State of Charge*

The aim of the histogram displayed on Figure 15 is to give a visual representation of the distribution of State of Charge (SOC) levels for the batteries across the two different scenarios. The house of the Prosumer 45 was the one chosen for the histogram, due to its DERs characteristics, it only has PV and BESS.

On the graph, the X-Axis represents the State of Charge levels of the batteries, measured in kilowatt-hours (kWh), and the Y-Axis indicates the probability or frequency of the batteries being at a specific SOC level, giving an idea of how often each SOC value occurs during the simulation period.

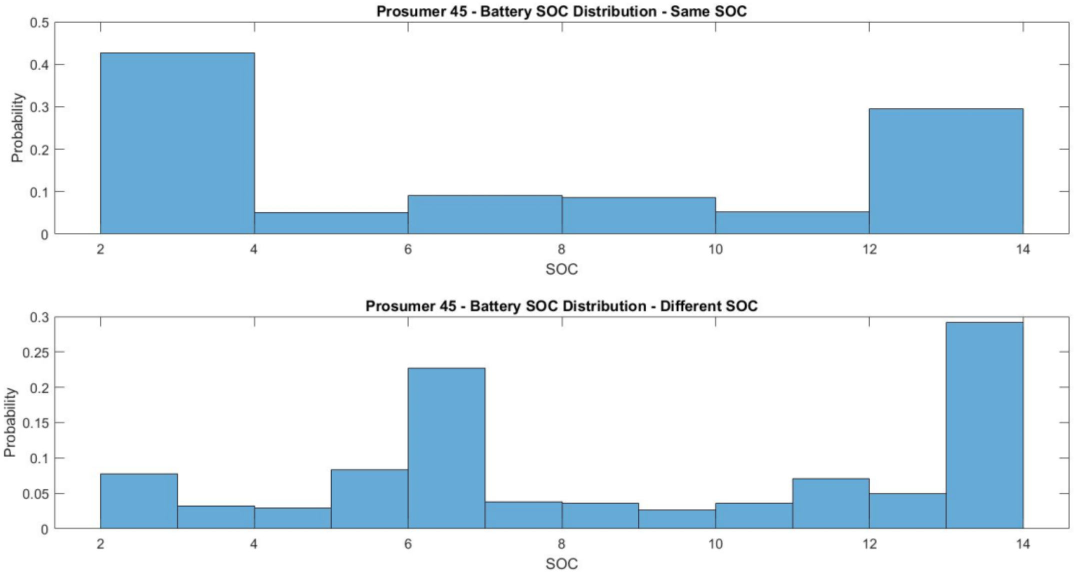


*Figure 15: Histogram ESS SOC Distribution Prosumer 45*

In the "Different SOC" scenario (bottom), the histogram shows a more spread-out distribution of SOC levels, indicating a greater variation in energy storage usage. This wider range suggests that the batteries frequently undergo charging and discharging cycles, with significant portions of time spent at both low and high SOC levels. The SOC levels often fall to the minimum at 2 kWh and reach up to the maximum at 14 kWh, reflecting a dynamic usage pattern.

Conversely, in the "Same SOC" scenario (top), the SOC distribution is more concentrated. The histogram reveals fewer fluctuations in SOC levels, with batteries maintaining more stable charge levels throughout the day. This constraint leads to less frequent deep discharges and high charge cycles, which is consistent with a more controlled and balanced energy management strategy. This behavior aligns with the observed reduction in peak grid consumption seen in the first table, as maintaining a consistent SOC likely mitigates the extreme demand spikes when batteries need to be charged or discharged rapidly.

Figure 16 shows the energy flows for House 45 in both scenarios studied on this section. The contributions from PV, grid imports, ESS discharges, P2P imports, ESS charges, P2P exports, grid exports, and demand over a day are shown on the chart.

In the energy flow graphs, the green areas represent ESS discharge, and the yellow areas represent ESS charge. In the "Different SOC" scenario (left), batteries exhibit significant peaks in discharging during the early evening and peaks in charging during midday, indicating a more reactive approach to energy availability, like mentioned with the previous Figure. In contrast, the "Same SOC" scenario (right) shows more consistent and regulated charging and discharging patterns, with fewer pronounced peaks. This consistent approach reflects the constraint to maintain the same SOC at the beginning and end of each day, leading to a smoother energy management strategy and reducing peak grid consumption.

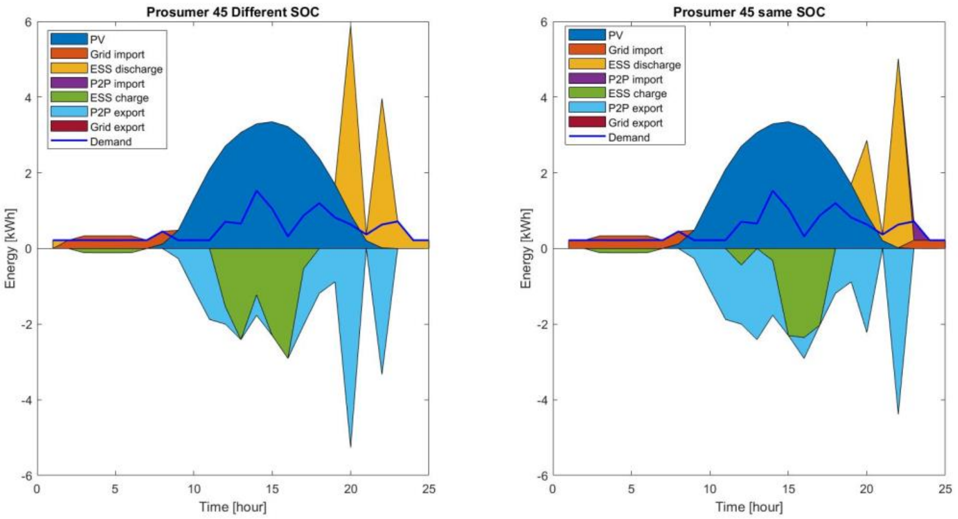


*Figure 16: Operation Home 45*

Finally, it is interesting to understand the total number of ESS cycles in each of the scenarios. A full cycle is typically defined as the complete charging and discharging of the ESS from its minimum capacity to its maximum capacity [10]. Below is shown how the total number of cycles for each scenario have been calculated.

$$Usable\ Capacity = Upper\ Limit - Lower\ Limit = 13{,}5\ kWh - 2{,}7kWh = 10{,}8\ kWh$$

$$Number\ of\ Load\ Cycles = \frac{Total\ Energy\ Charged}{Usable\ Capacity}$$

$$Number\ of\ Discharge\ Cycles = \frac{Total\ Energy\ Discharged}{Usable\ Capacity}$$

$$Number\ of\ Cycles = \frac{Number\ of\ Load\ Cycles + \ Number\ of\ Discharge\ Cycles}{2}$$

| | **Different SOC** | **Same SOC** |
|---|---|---|
| **Total Energy Charged [kWh]** | 8.598,8 | 7.205,5 |
| **Total Energy Discharged [kWh]** | 7.839,5 | 6.502,9 |
| **Number of Cycles** | 762 | 635 |

*Table 11: Total Number of Cycles of Batteries*

These findings align with the earlier results where the "Different SOC" scenario demonstrated a more immediate response to fluctuating energy demand throughout the day, leading to more frequent and larger energy exchanges. Consequently, the batteries in this scenario charged and discharged more energy overall compared to the "Same SOC" scenario, which maintained more stable and controlled energy management, resulting in fewer cycles and lower total energy movement. The result is that with the new constraint added to the simulation, the total number of cycles is reduced by almost 17%.

- **Electric Vehicles Analysis:**

Now, the focus shifts on analyzing the impact of electric vehicles (EVs) on the energy system under different state of charge (SOC) constraints. To understand it simply, it was decided to carry out a graph, Figure 17, which provides a detailed visualization of the SOC levels of EVs throughout the day in the two different scenarios studied.

Several interesting observations can be made on the heatmap in Figure 17. First, it is important to correctly understand what is shown on the graph. The X-Axis shows the number of the house which electric vehicle is studied, and the Y-Axis shows the time of the day in hours. Finally, the color bar represented on the right of the figure shows the state of charge of the vehicles, the darkest blue means full charged (24kWh) and the lightest blue means discharged (4,8kWh).

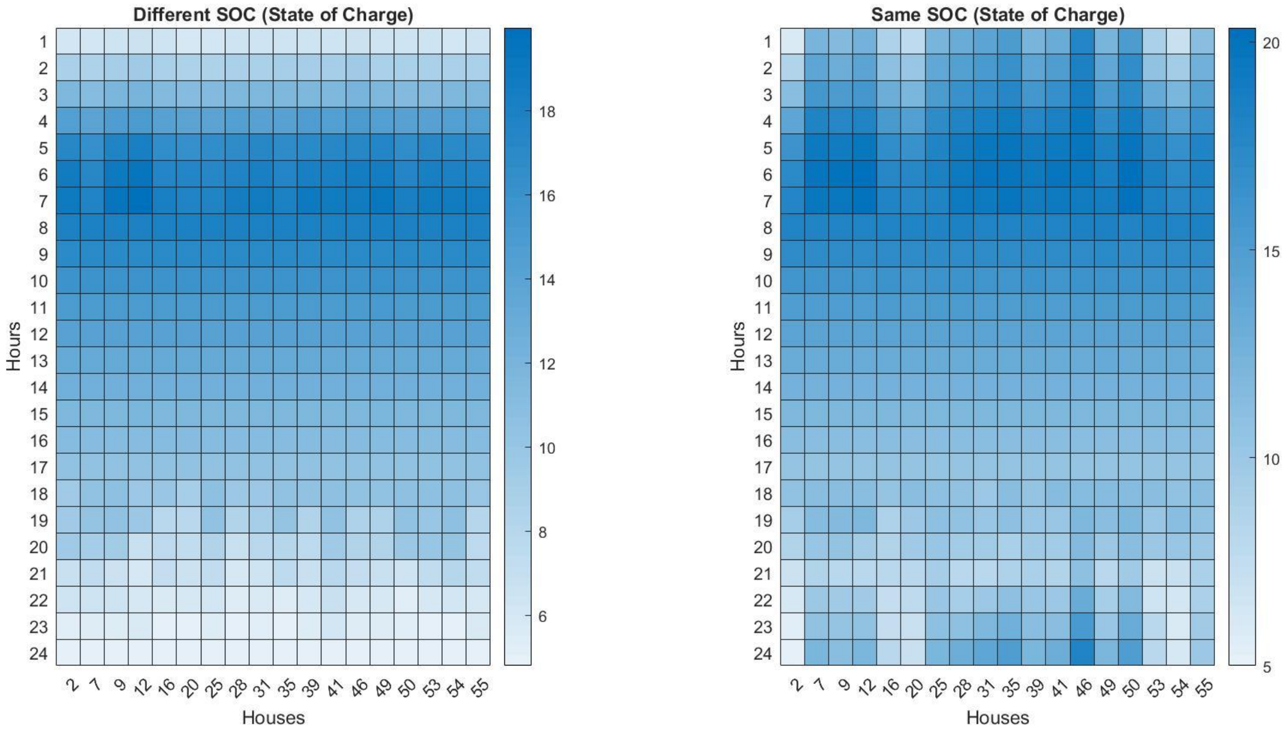


*Figure 17: Heatmap Electric Vehicles SOC*

It is observed that both subplots meet the constraint imposed in the code that at 8 am all vehicles have a SOC of 18 kW. However, as expected, the biggest difference between the two plots appears between the evening and night hours.

Among the electric vehicles in the graph on the right, with the new SOC constraint, two groups can be clearly distinguished, those with low SOC late in the day, and those with high SOC. For those vehicles whose SOC at the end of the day is low, such as vehicles in houses 2, 20 or 54, there is hardly any difference with the graph on the left. However, for vehicles with a medium or high state of charge, such as vehicles in houses 31, 35 or 46, there is a very different pattern of charge between the two scenarios.

Therefore, for the vehicles which have the constraint of been with a medium-high state of charge at the end of the day, they affect several aspects of the energy system.

1. **Reduced demand response capacity at late afternoon periods**: As they need to be charged at a certain level during midnight, they will not be able any more to use the energy stored to balance demand.
2. **Increased Grid Imports**: As they can’t use the energy from these electric vehicles to meet demand, the system will have to rely more on grid imports to cover consumption peaks.
3. **Demand Distribution**: The elimination of night electric vehicle charging could potentially lead to a more stable demand throughout the day, eliminating night peaks. This could have benefits for grid management, although it implies a greater need for imports during periods when electric vehicles are unable to contribute.

In summary, the constraint of keeping EVs charged late in the day has the benefit of eliminating nighttime peak charging, but it also reduces demand responsiveness and increases reliance on grid imports, which can increase costs and affect overall system efficiency.

## 4.3 IMPACTS OF CET ON LVDN

### 4.3.1 IMPACTS ON THE TRANSFORMER AND LINES LOADING

On this section, the impacts of the Community Energy Trading (CET) on the transformer and the power line loading will be evaluated.

Assessing transformer and line loading is crucial because it helps to understand how power is distributed on the grid and of the equipment is operating within its safe limits. Transformers and power lines have specific load limits that, if exceeded, can cause overheating, damage and possible system failure.

Maximum accepted percentages for loading a transformer are generally around 80-90% of its rated capacity under normal conditions to ensure its service life and efficient operation. However, during peak demand, up to 100-110% can be tolerated for short periods. For power lines, a similar logic is followed, where operating continuously above 100% of their capacity can lead to overloading and deterioration problems.

The analysis of load assessment is relevant because it allows network operators to:

- Prevent Overloads: Identify and mitigate risks before they cause damage.
- Optimize Power Distribution: Ensure that power is distributed efficiently without overloading any component.
- Plan Infrastructure Upgrades: Make informed decisions about when and where to upgrade or reinforce the grid.

Therefore, on this section the impacts of adding the constraint on SOC will be evaluated. By making this comparison, the effects of each configuration on the transformer loads and power lines will be assessed. This is critical to understanding the impact that different power management strategies can have on grid stability and efficiency, which can lead to determining the best way to implement and manage energy communities to ensure a reliable and secure power supply.

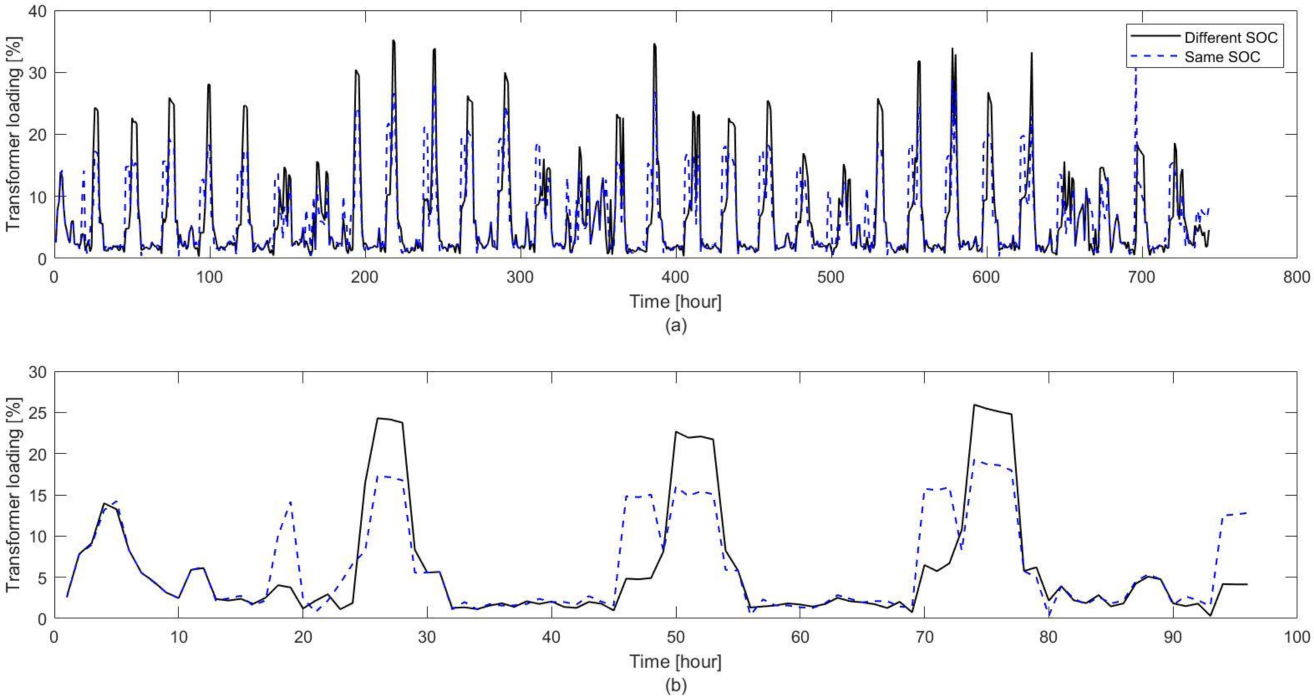


*Figure 18: Transformer loading Different SOC vs Same SOC, a) 1 month b) 4 days*

Figure 18 compares the transformer loading under two different configurations: 'Different SOC' and 'Same SOC'. In graph (a), which covers an extended period of 700 hours (1 month), it is observed that the Different SOC configuration shows higher and more frequent load peaks, reaching up to approximately 35-40% of the transformer capacity. In contrast, Same SOC presents a more stable and less variable load, with less pronounced peaks. This indicates that variability in SOC may increase the probability of transformer overload, which could lead to a higher risk of overheating and equipment deterioration.

A similar trend is observed in Figure 18  graph (b), which covers a shorter period of 100 hours (4 days). 'Different SOC' shows significant load peaks around hours 30 and 50, while 'Same SOC' maintains a more moderate load profile. These findings highlight the importance of proper SOC management to minimize load variations and ensure efficient and safe transformer operation.

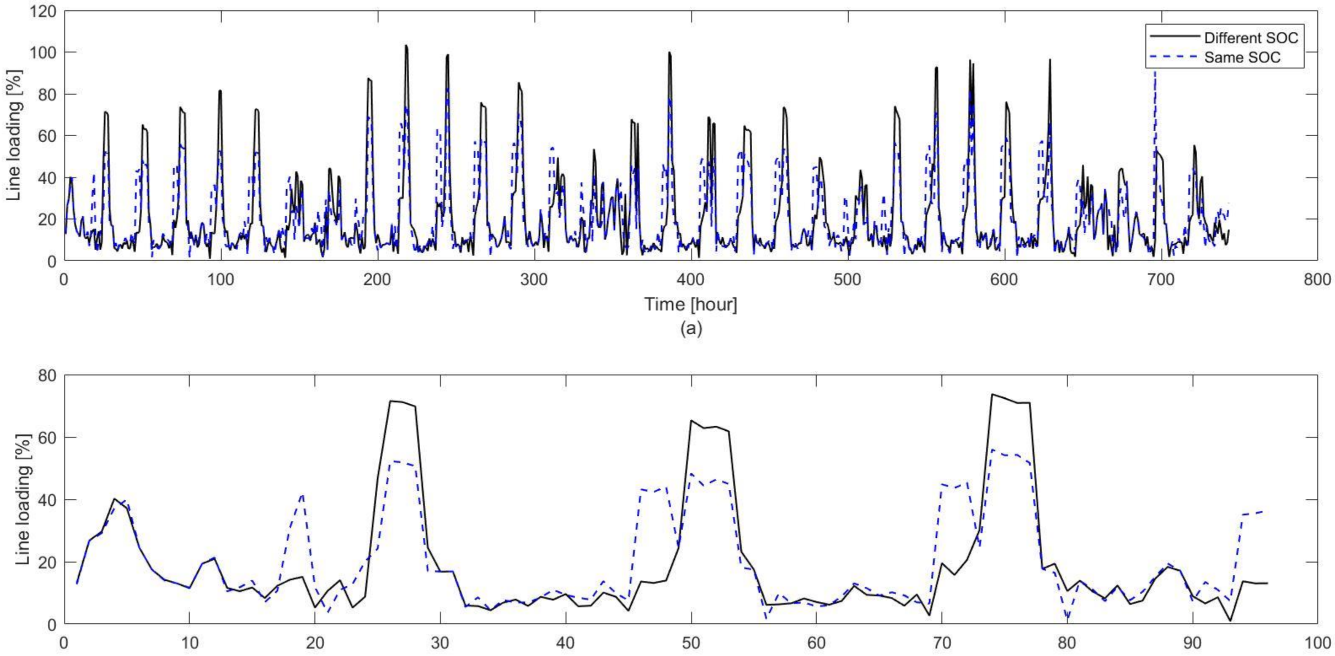


*Figure 19: Lines loading Different SOC vs Same SOC, a) 1 month b) 4 days*

Figure 19 analyzes the load of the lines under ‘Different SOC’ and ‘Same SOC’ configurations. Graph (a), which covers 700 hours, shows that ‘Different SOC’ load peaks reach up to 100% of the line’s capacity, while ‘Same SOC’ shows more moderate and less frequent peaks, staying mostly below 80%. Graph (b), which makes a zoom to the first 4 days of the month, also shows that the load peaks for ‘Different SOC’ are higher and more frequent, exceeding 60%, while ‘Same SOC’ presents a more stable and distributed load, with peaks around 40%. The most remarkable finding is that adding the SOC constraint helps to mitigate the high peaks during night hours.

These results highlight how variability in SOC significantly affects line loading, increasing the risk of overload and deterioration in the ‘Different SOC’ configurations. An optimal SOC management can help to keep lines within safe limits and prolong their lifetime.

### 4.3.2 IMPACTS ON VOLTAGE DEVIATIONS

In this section, voltage deviations in low voltage distribution lines (LVDNs) of the system are going to be evaluated. These deviations are changes in voltage levels that can affect the stability and efficiency of the power supply. LVDNs, due to their radial design and lack of voltage control devices, are especially vulnerable to these fluctuations.

It is important to study and understand why voltage deviations occur because they can be the cause of the following problems.

- System instability: If the voltage varies too much, it can cause power outages and damage connected equipment. Therefore, maintaining voltage within acceptable limits is crucial to avoid service interruptions and ensure a constant supply of electricity.
- Power quality: The operation of sensitive devices such as household appliances, medical equipment and industrial systems, can be affected by voltage fluctuations, causing damage or malfunction.
- Energy efficiency: A system that has constant voltage deviations leads to more energy losses during transmission and distribution. This is another reason why the right voltage improves efficiency, reduces operating costs and optimizes the use of energy resources.
- Renewable energy integration: Controlling voltage well is critical to integrating efficiently renewable energy sources such as solar and wind. These are variable sources and can cause voltage fluctuations, so precise control is necessary to maintain system stability.

According to the EN 50160 standard, the voltage on LVDNs must be between 0.90 and 1.10 per unit (pu), which is equivalent to a deviation of -10% to +10% from the nominal value. Maintaining the voltage within these limits is essential to ensure a stable and high-quality power supply.

Voltage deviations can be seen in two ways, voltage drop or voltage rise. The main reasons for these two types of deviations will be explained below.

- Voltage drops: When there is a high electricity demand in a specific area, the voltage tends to drop. This usually happens during the afternoon and evening times, as they are peak consumption hours, when most people are at home using appliances, lights, heating, etc. Therefore, this happens when the demand for electricity exceeds the supply capacity, causing a drop in voltage.
- Voltage rise: Contrary to the previous case, voltage increase happens when the local electricity generation is very high. This usually happens during the day in areas where there are a lot of solar panels, which produce a generate more energy than the one needed to net the demand. This leads to an increase in the grid voltage, especially near where the power is produced.

Therefore, this section seeks to evaluate how microgrid configurations and different distributed energy resources (DERs) penetration levels affect voltage deviations in LVDNs.

Table 12 summarizes the maximum and minimum values of transformer load, line load and voltage variations under ‘Different SOC’ and ‘Same SOC’ configurations.

| | **Different SOC** | **Same SOC** |
|---|---|---|
| **Maximum Transformer Loading [%]** | 35,25 | 30,97 |
| **Maximum Line Loading [%]** | 103,47 | 90,72 |
| **Lowest value of Va [pu]** | 0,94 | 0,96 |
| **Highest value of Va [pu]** | 1,10 | 1,09 |
| **Lowest value of Vb [pu]** | 0,9 | 0,91 |
| **Highest value of Vb [pu]** | 1,08 | 1,09 |
| **Lowest value of Vc [pu]** | 1,02 | 1,01 |
| **Highest value of Vb [pu]** | 1,08 | 1,07 |
| **Maximum VUF [%]** | 2,57 | 2,41 |

*Table 12: Summary of impacts of community energy trading on LVDN*

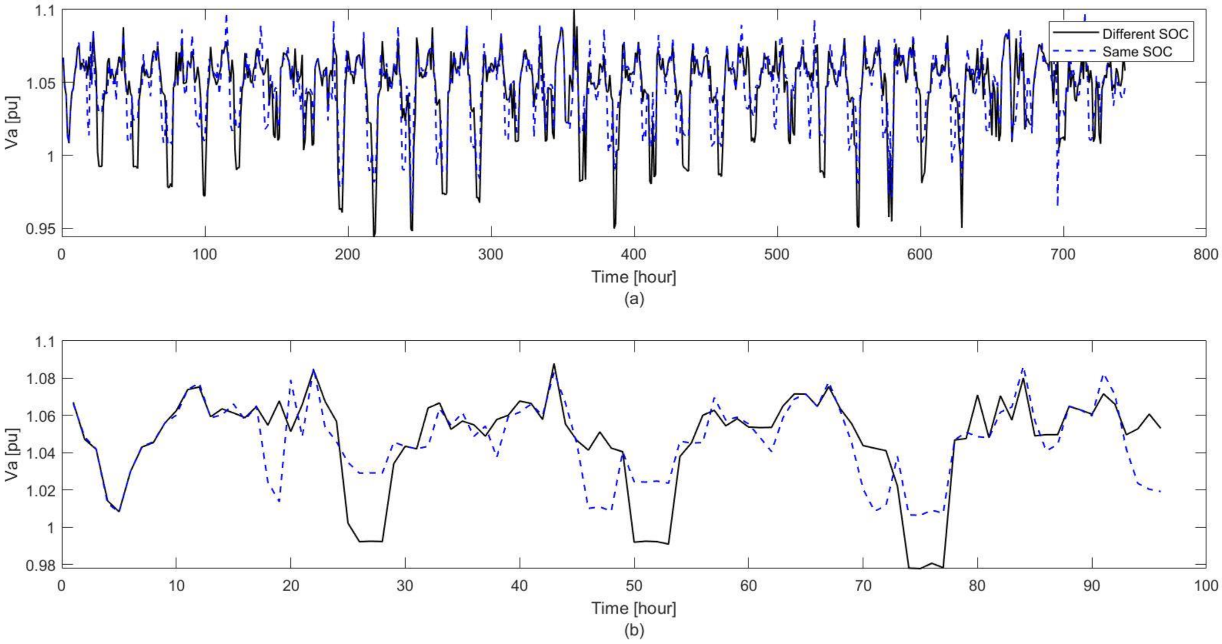


*Figure 20: Phase a voltage (Va). Different SOC vs Same SOC. (a) 1 month, (b) 4 days*

Figure 20 shows the variation of voltage Va over time under ‘Different SOC’ and ‘Same SOC’ configurations. In plot (a), which covers 700 hours, it can be observed that ‘Different SOC’ has more pronounced and frequent variations, reaching values as low as 0.94 p.u and as high as 1.10 p.u. In plot (b), which covers 100 hours, the variations are more detailed, showing that ‘Different SOC’ experiences more significant and frequent voltage drops compared to ‘Same SOC’. These results indicate that ‘Same SOC’ provides greater voltage stability.

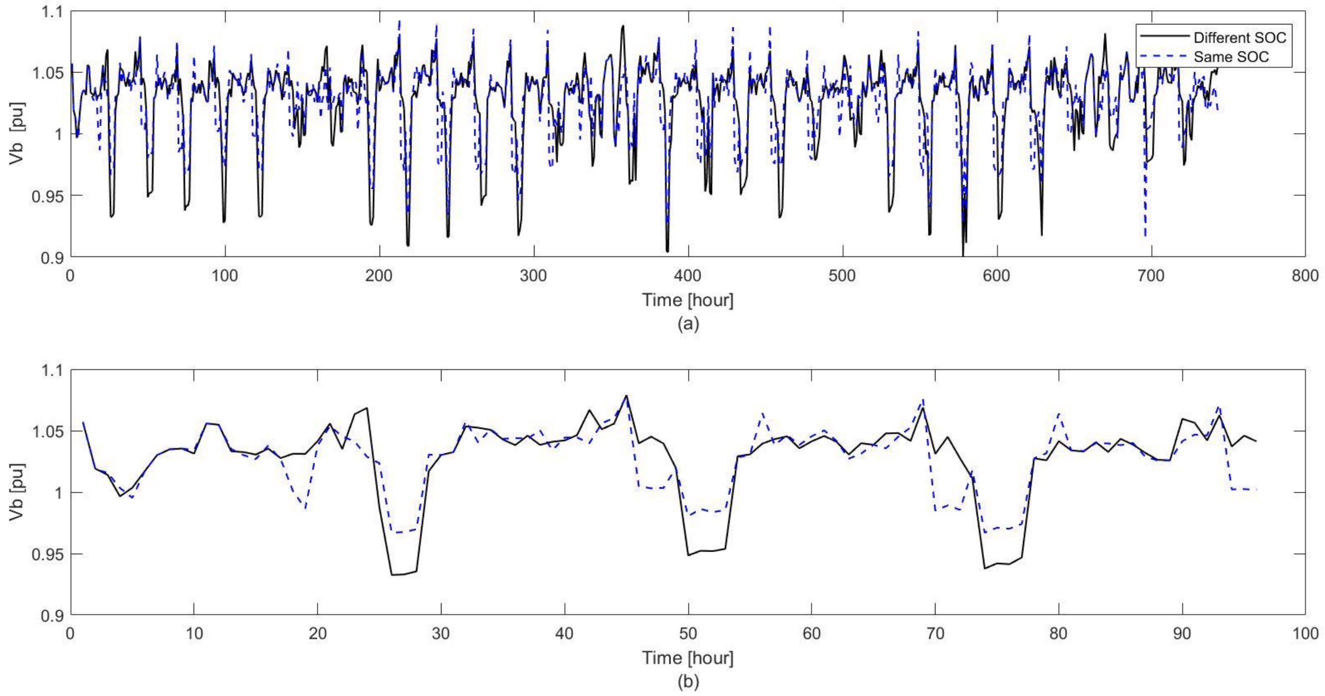


*Figure 21: Phase b voltage (Vb). Different SOC vs Same SOC. (a) 1 month, (b) 4 days*

Figure 21 analyzes the variation of the voltage in phase b, Vb. Plot (a), which covers 700 hours, shows similar fluctuations are observed between the two configurations, although ‘Different SOC’ reaches lower values of up to 0.90 p.u., which means the network is experiencing a significant voltage drop. In plot (b), ‘Different SOC’ again exhibits steeper voltage drops, while ‘Same SOC’ maintains a more stable voltage profile. These findings align with the ones mentioned on Figure 20, underling that ‘Same SOC’ helps to keep the voltage within more consistent limits.

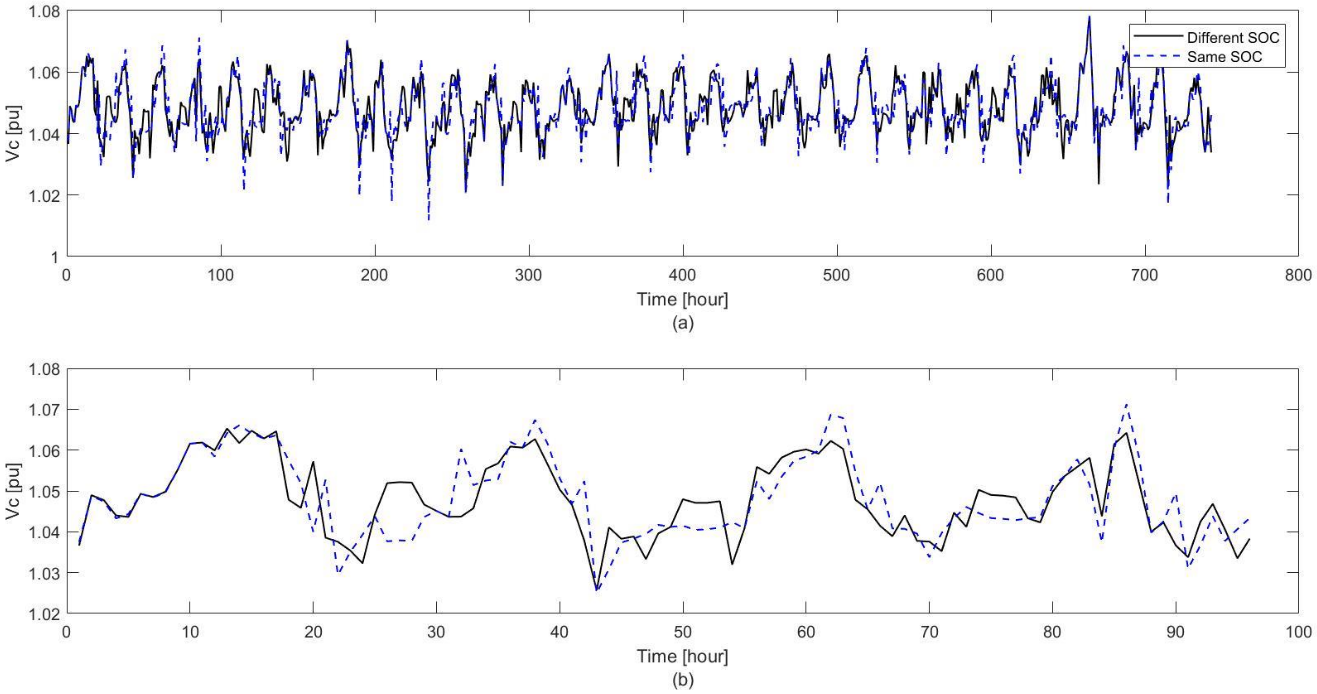


*Figure 22: Phase c voltage (Vc). Different SOC vs Same SOC. (a) 1 month, (b) 4 days*

Figure 22 shows the variation of voltage in phase c. Voltage fluctuations are less pronounced than in the other two cases (phase A and phase B), with ‘Different SOC’ and ‘Same SOC’ showing quite similar behavior. The results indicate that, although the variations in Vc are smaller, ‘Same SOC’ still offers a slight advantage in terms of voltage stability.

### 4.3.3 IMPACTS ON PHASE UNBALANCE

The Voltage Unbalance Factor (VUF) is the measurement that indicates the level of unbalance of a 3-phase system. This voltage unbalance refers to the difference in magnitude and phase angle between the three phases of the system, and it can cause different problems such as efficiency losses or damage to electrical equipment. This factor is calculated as follows:

$$VUF\ [\%] = \frac{V_2}{V_1} * 100 \quad \begin{cases} V_2 \equiv Magnitude\ of\ the\ negative\ sequence\ component \\ V_1 \equiv Magnitude\ of\ the\ positive\ sequence\ component \end{cases}$$

The aim of this subsection is to study and understand how the impact of adding a new constraint on the initial and final SOC value of each day affects the voltage unbalance in low voltage distributions networks (LVDNs).

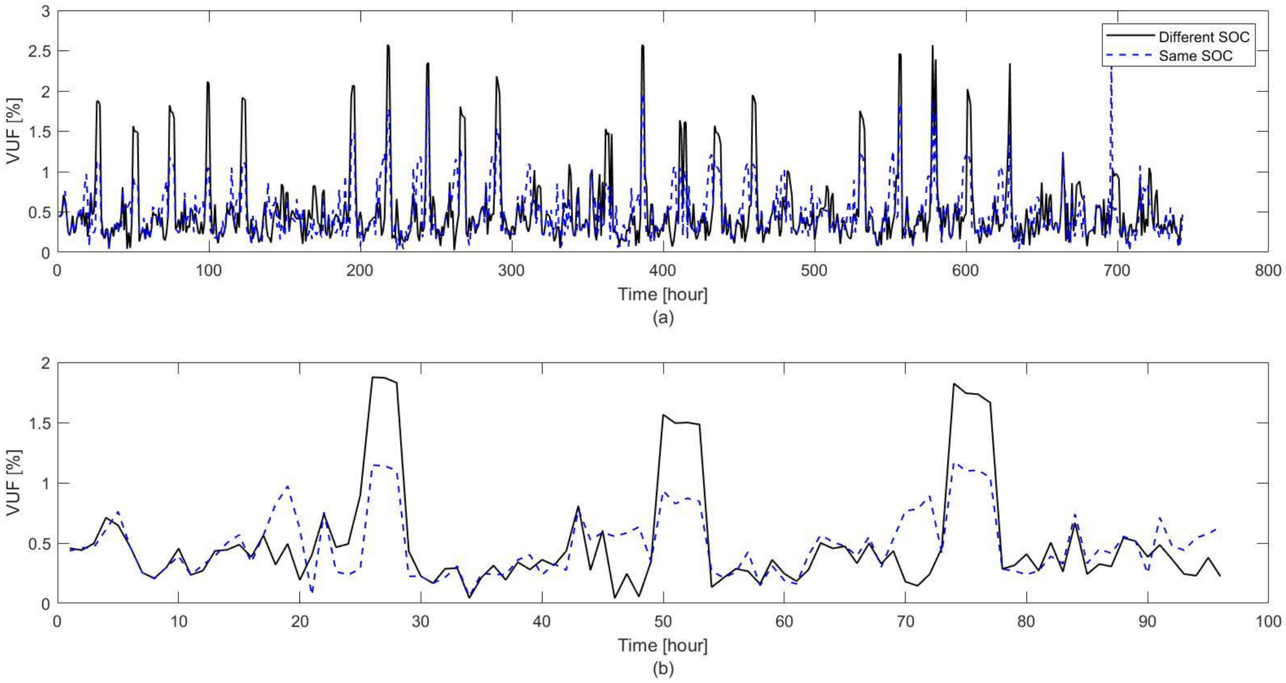


*Figure 23: Voltage Unbalance Factor VUF%. Different SOC vs Same SOC. (a) 1 month, (b) 4 days*

Figure 23 shows the Voltage Unbalance Factor (VUF) over time for the 'Different SOC' and 'Same SOC' configurations. In graph (a), which covers the whole month, the 'Different SOC' scenario shows more frequent and higher peaks that reach up to 2.5%, in contrast with the 'Same SOC' scenario, that shows more moderate peaks. In plot (b), which covers the first 100 hours of the study, a similar behavior can be seen. 'Different SOC' has more pronounced and frequent peaks compared to 'Same SOC'. These results indicate that the 'Same SOC' configuration helps to maintain a better voltage balance in the system, reducing variations and improving the stability of the power grid. The lower variability in VUF with

'Same SOC' suggests a lower probability of efficiency problems and damage to electrical equipment due to voltage unbalances.

### 4.3.4 COMPARISON OF DIFFERENT SCENARIOS WITH BOXPLOT REPRESENTATION

On this section, boxplot representation will be used to better understand the results obtained. Boxplots are very useful to understand the symmetry of the distribution, the dispersion and the possible outliers of the data [11].

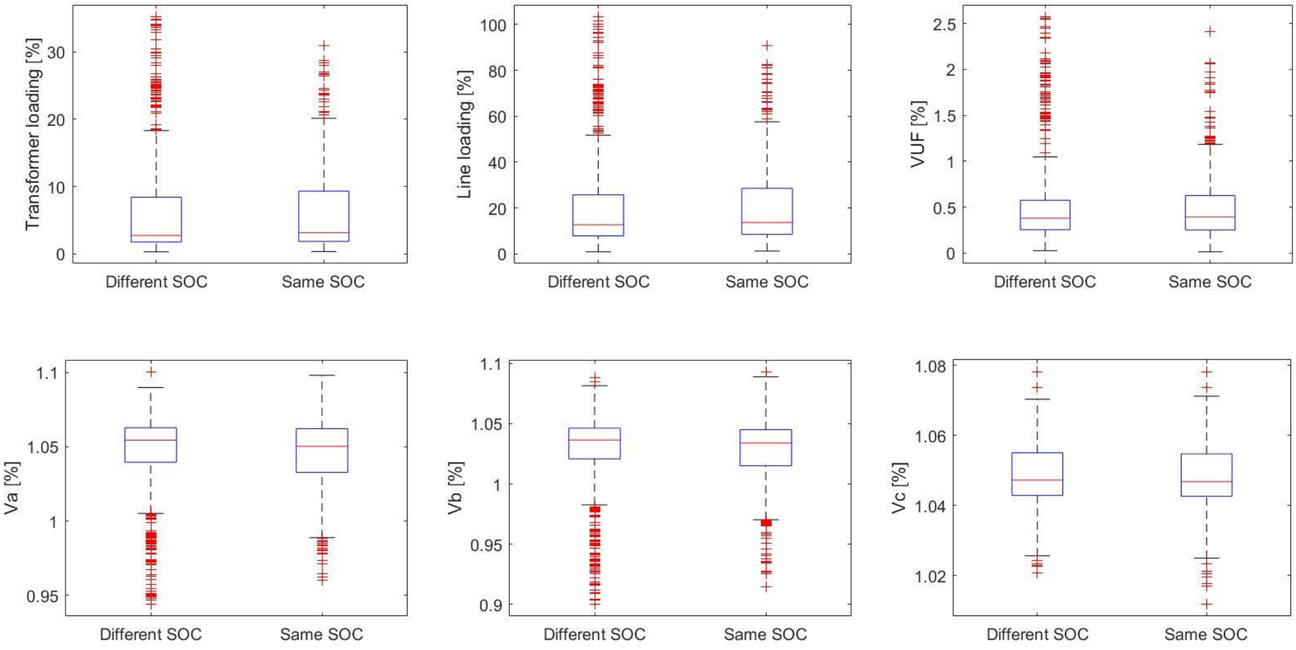


*Figure 24: Comparison of the impacts of different scenarios using boxplot representation.*

Figure 24 shows a series of boxplots comparing 'Different SOC' and 'Same SOC' for different purposes:

- Transformer loading: The transformer load has a lower dispersion in 'Same SOC' compared to 'Different SOC'. The median is similar in both cases, but the variability in load is lower in 'Same SOC', indicating that the transformer load values are more consistent and better controlled under this configuration. Outliers are also less frequent in ‘Same SOC’.

- Line loading: The line load has a higher dispersion and higher median in ‘Different SOC’ compared to ‘Same SOC’. Above the third quartile there are numerous outliers that exceed 100%-line loading in some cases. This suggests that ‘Different SOC’ is associated with higher peak loads and more variability, which could lead to higher stress on transmission lines.
- VUF: Voltage Unbalance Factor has a wider spread in ‘Different SOC’, indicating a higher voltage unbalance compared to ‘Same SOC’. ‘Same SOC’ shows a more controlled distribution and lower VUF values.
- Va, Vb and Vc: Voltages in the three phases show higher dispersion in ‘Different SOC’ scenario than in ‘Same SOC’ scenario, suggesting higher variability and lower voltage values compared with ‘Same SOC’.

# Chapter 5. ENVIRONMENTAL IMPACT

## 5.1 ANALYSIS OF DERS SUPPLY PERCENTAGE AND EMISSIONS IN DIFFERENT SCENARIOS

Table 13 presents the overall results for grid supply and DERs supply percentages in two different scenarios: a single energy community versus three smaller energy communities, and the two different SOC approches. The grid supply percentage represents the portion of the total energy demand met by imports from the grid, while the DERs supply percentage indicates the contribution of distributed energy resources (DERs) like solar panels and batteries.

For the calculation of total emissions, the energy imported from the grid and the corresponding emission factor have been taken into account. The emission factor used in this study was obtained from the electricity grid and is based on the current energy mix. This factor is 0.62 kg CO2/kWh [12], which means that for every kilowatt-hour (kWh) of energy imported from the grid, 0.62 kg of carbon dioxide (CO2) is emitted into the atmosphere. Therefore, total emissions are calculated by multiplying the amount of imported energy by this emission factor. The emission factor for the distributed energy resources has been considered as zero.

$$Total\ Emissions = Energy\ Imported\ from\ the\ grid * Emission\ Factor$$

| | Scenario 1 | | | | Scenario 2 | |
|---|---|---|---|---|---|---|
| | **Single Community** | **Phase Based Community** | | | **Different SOC** | **SOC-Contrained** |
| | | **Phase A** | **Phase B** | **Phase C** | | |
| **Grid Supply Percentage (%)** | 45,67 | 37,09 | 61,16 | 38,02 | 56,11 | 55,99 |
| **DERS Supply Percentage (%)** | 54,32 | 62,9 | 38,83 | 61,97 | 43,89 | 44,01 |
| **Total Emissions** | 13.374,02 | 3.543,92 | 7.626,00 | 2.759,00 | 16.429,38 | 16.395,90 |

*Table 13: Grid and DERs Supply percentage and Total Emissions*

- **Scenario 1:**

This scenario analyzes the impact of dividing a single large community into three smaller different energy communities.

Figure 25 shows the results of the single community, it is observed that the contribution of Grid Supply and Distributed Energy Resources (DERs Supply) are balanced, although DERs supply seem to be a little bit higher almost every day. Fluctuations in Grid Supply and DERs Supply are visible throughout the 31 days, but overall, the community maintains a balance between imported grid power and locally generated power. This stability is a result of diversification and balance in energy demand and generation within a larger community, which allows for more efficient resource management.

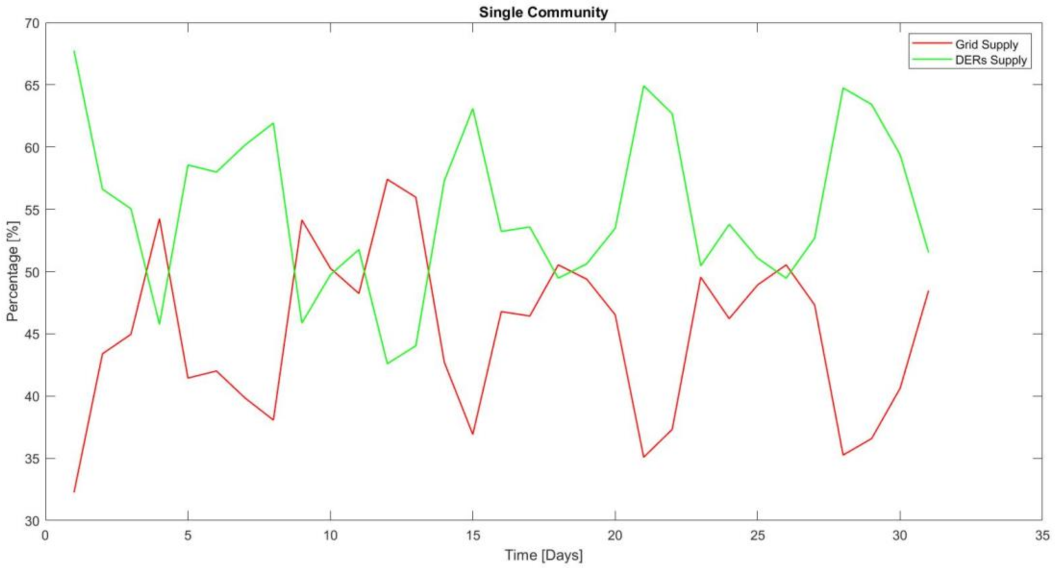


*Figure 25: Grid and DERs Supply percentage in a large community, Scenario 1*

When the larger system is divided into three different energy communities (A, B and C), there are notable differences in the behavior of each phase, mainly due to the unequal distribution of DERs.

Energy community 1 (Phase A) shows a similar pattern to the single community, with a good contribution from DERs supplying a significant part of the energy demand. Fluctuations are minor, suggesting stability comparable to that of the single community. This is mainly due to their DERs contributions are almost the same, the larger community consumers have 60% of PV and about 40% of Energy Storage systems, like energy community 1.

Energy Community 2 (Phase B) is the most disadvantaged phase in terms of DERs. It shows a greater dependence on the electrical grid (Grid Supply) and a lower contribution from DERs. This generates a greater fluctuation in the grid supply percentages, indicating greater vulnerability and less energy self-sufficiency.

Finally, Energy Community 3 (Phase C) presents a contribution of DERs slightly better than Energy Community 1, with almost 80% of consumers that own a PV. The results on this phase show a relatively stable and significant contribution from the DERs, which reduces the reliance on the grid. This is evident from the lower peaks in grid supply and higher consistency in DERs supply throughout the month. However, it is still observed that the single community scenario outperforms all individual phases in terms of overall system stability and efficiency due to the larger pool of resources and balanced energy distribution.

Dividing the community into three independent phases affects the energy self-sufficiency and stability of each phase. The single community, by pooling all resources, better optimizes locally generated energy and reduces dependence on the grid. In contrast, smaller phases show marked differences, especially in Phase B, which has fewer DERs and, therefore, greater grid dependence. This analysis highlights the importance of an equitable distribution of DERs to improve the resilience and efficiency of each micro-energy community.

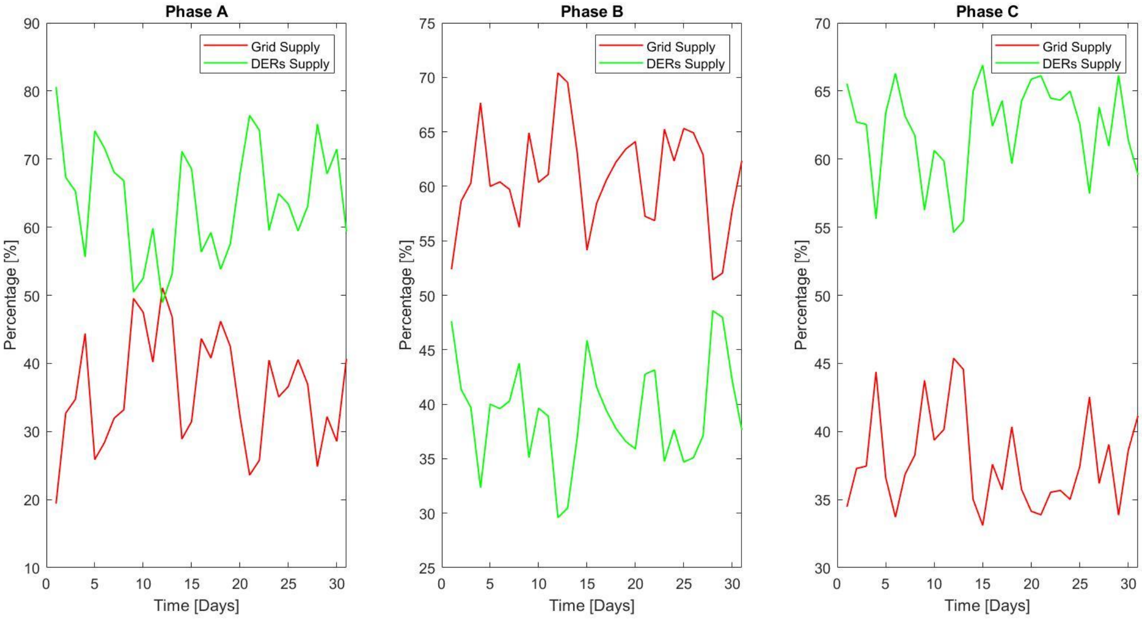


*Figure 26: Grid and DERs Supply percentage in smaller communities, Scenario 1*

- **Scenario 2:**

The comparison of the two scenarios represented in Figure 27 shows the differences in grid supply and DERs supply with and without the new SOC constraints.

In the "Same SOC" scenario, there is a notable fluctuation in the grid supply and DERs supply percentages throughout the month. The green line, representing the DERs supply, shows significant peaks and troughs, indicating a highly variable contribution from the DERs. Conversely, the grid supply (red line) compensates for this variability, often showing higher peaks where DERs supply dips. This scenario demonstrates a more dynamic response to energy demands, with batteries charging and discharging more frequently to meet immediate needs.

In contrast, the "Different SOC" scenario exhibits a slightly more stable pattern, with less pronounced fluctuations in both grid supply and DERs supply. The DERs supply still shows variability but appears more moderated compared to the non-constrained scenario. The grid supply also shows fewer and less extreme peaks, suggesting that the constraint on maintaining a specific SOC at the beginning and end of the day helps in stabilizing the overall energy supply. However, this stability comes at the cost of reduced flexibility in responding to peak demands, as the batteries cannot be fully utilized to balance the demand effectively. This is consistent with the previous findings that SOC constraints can lead to an increased reliance on grid imports during critical times.

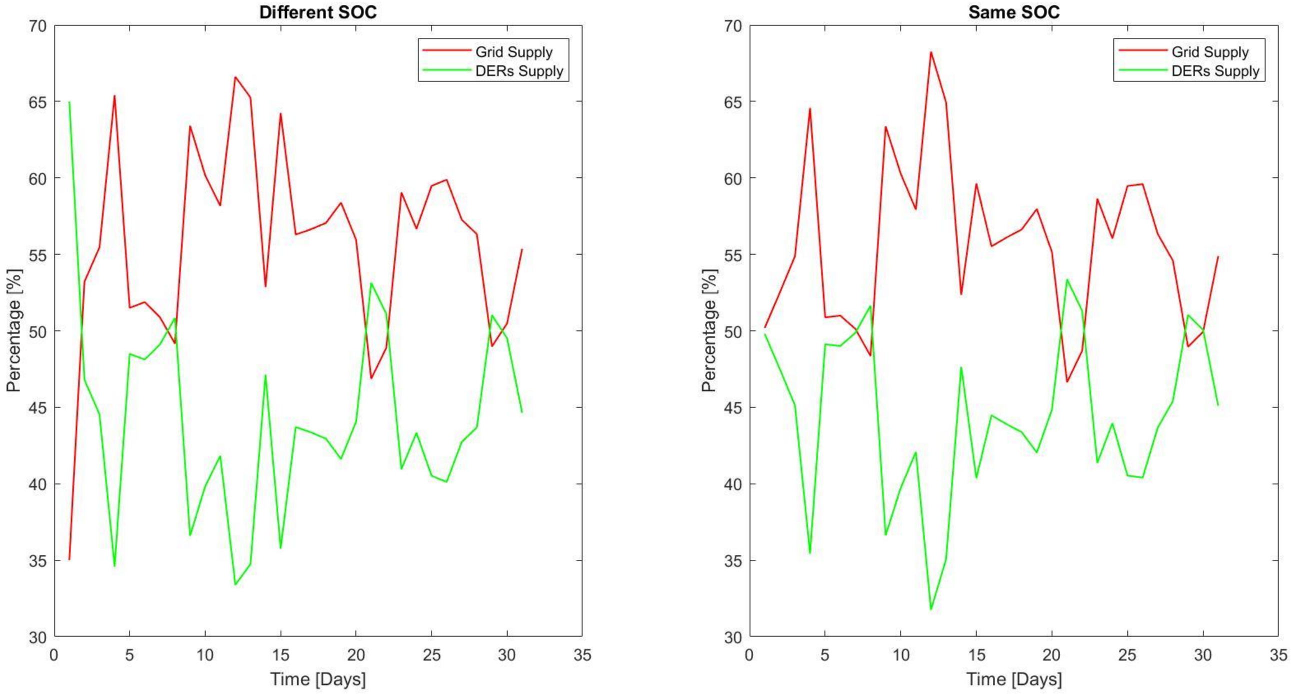


*Figure 27: Grid and DERs Supply percentage in Scenario 2*

# Chapter 6. RECOMMENDATIONS AND FUTURE STUDIES

After carrying out this study and analyzing the results obtained, some key observations were done, especially on the scenario where the management of the storage systems was explored.

From the scenario where the impacts of diving a large system into smaller, distinct communities it could be interesting to conduct further studies to determine the optimal size of energy communities, studying things such as their demand and DERs. Smaller communities might face challenges related to variability and grid reliance, whereas larger communities could benefit from more balanced energy management and increased resilience.

Also, the ESS performance in the SOC-constrained scenario, although improves the stability compared to the non-constrained scenario, these constraints limit the ability of the energy storage system to respond to peak demand during the evening, as they must maintain a specific level of charge at the beginning and end of the day. Also, this limitation can increase the dependence on the grid to meet demand at critical times and reduce overall system efficiency. Therefore, as a future study a good recommendation will be to investigate the implementation of adaptive SOC constraints for energy communities. This would involve ensuring that not all batteries in the community charge simultaneously at night, thereby preventing night-time peaks. Instead, there should be a balance where some batteries are fully charged and ready to meet the community's peak demand during the evening, while others can be set to charge during periods of lower demand. This approach would help to mitigate night-time peaks and ensure that batteries are available to satisfy the community's peak demand more effectively.

# Chapter 7. CONCLUSIONS

In this study, two main scenarios have been evaluated in the context of peer-to-peer energy trading in a community of 55 houses, and below are the most significant conclusions for both.

In the first scenario, the operation of the community as a single large entity was compared to the division into three smaller energy communities, each corresponding to a phase of the power system. The results showed that operating as a large community allows for a greater diversity of demand profiles, which facilitates a better balance between energy generation and consumption. This reduces grid dependency and operating costs, as the community can optimize the use of its internal resources more efficiently. However, the proportion of distributed energy resources (DER) in each community is crucial; communities with a higher percentage of DER can meet more of their demand internally, reducing the need to import energy from the grid. In contrast, communities with less DER showed greater variability in energy import and export, increasing their dependence on the grid and associated costs.

In the second scenario, the impact of maintaining the same state of charge (SOC) of batteries and electric vehicles (EVs) at the initial and final value of each day was analyzed. The results indicated that imposing this constraint can improve stability and reduce charge/discharge cycles, prolonging the lifetime of batteries and EVs. However, a higher SOC at the end of the day can also provide greater operational flexibility and reduce grid dependence, optimizing demand response, although it can lead to higher peaks during the night. Maintaining a constant SOC helps reduce peak grid consumption, which can alleviate stress on the grid and improve load management, but at the cost of greater rigidity in day-to-day operation.

In summary, the comparison of these two scenarios highlights the importance of energy community configuration and SOC management on grid efficiency and stability. An optimal strategy could involve dynamically adjusting the SOC according to the specific needs of the system to achieve a balance between stability and flexibility.

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# ANNEX I

## SUSTAINABLE DEVELOPMENT GOALS

1. SDG 7: Affordable and Non-Polluting Energy

   As mentioned in the introduction of the project, P2P energy trading and the incorporation of DERs is the solution for addressing the "Energy Trilemma". As it promotes the use of renewable energy and enhances energy efficiency. By optimizing the distribution and use of energy within the communities, energy efficiency is improved, and energy losses are reduced.

2. SDG 11: Sustainable Cities and Communities

   The implementation of energy communities reduces carbon emissions by promoting the use of local and clean energy. Also, the project supports the creation of resilient and sustainable infrastructure that can adapt to future energy demands and environmental challenges.

3. SDG 9: Industry, Innovation and Infrastructure

   This project motivates the study of new methods to optimize and improve energy use within communities.

4. SDG 13: Climate Action

   By reducing dependence on non-renewable energy sources and improving energy efficiency, the project contributes to climate change mitigation.

## 5. SDG 17: Partnerships to Achieve the Goals

The project involves cooperation between different people, who share their resources to build a more sustainable infrastructure. Consumers can easily turn into prosumers, being able to both consume and generate and share their surplus energy with other peers in the community, unifying the community towards a same goal.

*Figure 28: Sustainable Development Goals*