COMILLAS
UNIVERSIDAD PONTIFICIA
ICAI

MASTER’S DEGREE IN INDUSTRIAL ENGINEERING

MASTER’S THESIS

MODELLING ELECTRIC VEHICLES FOR EMERGING MARKETS AND DEMAND RESPONSE MECHANISMS

Author: Alejandro Paniagua Gutiérrez

Director: José Pablo Chaves Ávila

Co-Director: Matteo Troncia

Madrid

July 2024

Declaro, bajo mi responsabilidad, que el Proyecto presentado con el título

“Modelling electric vehicles for emerging markets and demand response mechanisms”

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Alejandro

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ABSTRACT

1. Introduction

Energy prices have been rising due to high gas prices and the Ukrainian War, exacerbating Europe's dependence on Russian gas for over 40% of its supply and causing extreme electricity prices. Additionally, the growing cost of CO_2 emission rights and frequent grid constraints due to Distributed Energy Resources (DERs) necessitate new energy efficiency methods [1]. The European Union's sustainability policies aimed at combating climate change are pushing all sectors, particularly transportation, towards a net-zero emissions model. This transition will increase the penetration of electric vehicles (EVs), alter traditional electricity consumption patterns, and raise overall energy costs for end users [2]. Optimized energy management will be crucial to prevent grid constraints from high electricity demand.

To reduce electricity bills, many citizens have installed rooftop solar PV systems, though this is not always optimal due to potential energy surpluses. Battery storage could help optimize this energy use. The integration of EVs poses additional challenges to grid operations and capacity, with "dumb charging" methods risking grid safety. Efficient management of renewable energy, storage facilities, and EVs is essential. Community Energy Trading (CET) has emerged as a reliable solution to manage the growing DERs in the grid. While studies often focus on PV self-consumption, more research is needed on using these systems in local energy communities with various distributed energy resources, such as energy storage systems and EVs [3].

2. Methodology

This Master's Thesis aims to study the impact of the growth of electric vehicles on low voltage distribution networks. The main objectives are to estimate the most efficient allocation of

energy in an energy community, assess if community energy trading is a valid measure to optimize energy efficiency and compare which of the scenarios entails the best results for costs minimization. There are several scenarios considered with different DERs distributions:

1. Case 1: base case, with no DERs.
2. Case 2: including PV as DERs.
3. Case 3: including PV and ESS as DERs.
4. Case 4: including PV, ESS and EV charging as DERs.
5. Case 5: including PV, ESS and EV charging and discharging as DERs.
6. Case 6: including PV, ESS and EV charging and discharging as DERs. The difference between cases 5 and 6 is the availability of EVs, which are connected to the grid four more hours every day in case 6.
7. Case 7: including PV, ESS and EV charging and discharging as DERs. In this last case, 100 % EV integration is considered (all customers have EVs).

The model used for performing the simulations is taken from the research article "Impacts of Community Energy Trading on Low Voltage Distribution Networks" and used, modified and adapted to the former cases [3]. This model is based on MATLAB and uses PV and load profiles, energy import and export prices and the characteristics of DERs as an input to obtain the dispatch of the customers' DERs and the demand profile. Thus, the impact of DERs on the grid, grid consumption, grid exports, grid imports and costs are studied.

3. Results

In the following graphs in Figure 1, the energy allocation during the first 48 hours of the simulation is represented. On the top left corner, the scenario without DERs is displayed. Since there are no DERs, all the energy must be imported from the grid. The rest of scenarios depicted include DERs, changing the EV charging/discharging conditions.

On the top right, the scenario considering only EV charging is represented. During the day, the energy from the PV facilities is used to meet the demand of customer 53. The energy surplus is either traded with other members of the community that cannot cover their demand with PV or stored in batteries for future use. When the PV production decreases, energy is imported from other peers or ESS discharge. During the nights, the EV and ESS are charged mainly using imports from the grid as electricity prices are at their lowest, creating high peaks of consumption.

The third scenario represented includes DERs and EV charging and discharging, shown on the bottom left. The patterns are similar to the previous scenario: the PV covers the demand, charges the ESS and the surplus is traded. At night, the EV and ESS are charged from the grid due to low prices. The difference is in the periods of high energy prices, when the EV is discharged to support the energy needs of customer 53 and the whole energy community, reducing the imports during expensive hours. The results are similar for the last case represented on the bottom right graph, as the EVs remain 4 hours longer connected to the grid, reducing the need for importing energy at higher prices.

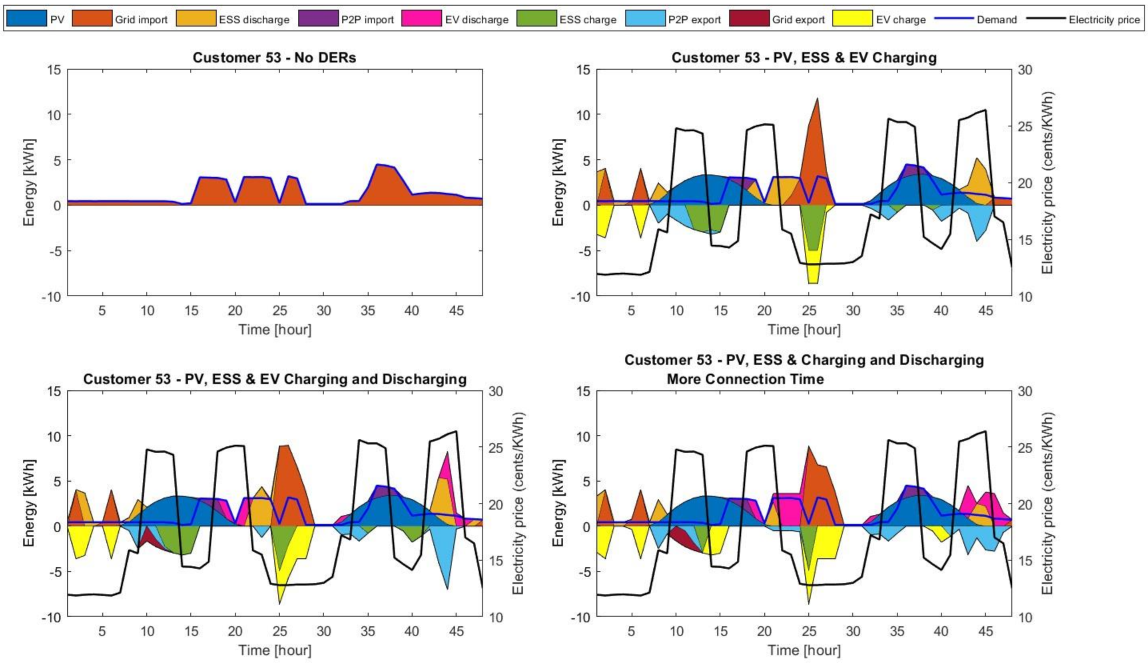

Figure 1. Customer 53 for scenarios a) No DERs b) PV, ESS and EV Charging c) PV, ESS and EV charging and discharging and d) PV, ESS and EV charging and discharging – More Connection Time

In Table 1, the results for the base case and the main scenarios concerning EVs are presented. The scenario that minimizes the cost for the energy community is the scenario that includes DERs and the EVs have more availability. Thus, the energy imports are also minimized and take place when there are low electricity prices. Consequently, the 46% of the overall demand is met by DERs, the maximum for the simulations considering EVs. Traded energy also reaches its maximum. However, the reduction in costs in all the scenarios concerning DERs is significant, and the peak grid consumption is considerably high, but stable through the simulations.

Results	No DERs	DERs - EV Charging	DERs EV Charging & Discharging	DERs EV Charging & Discharging - More Connection Time
Grid Imports (kWh)	47.229,00	26.323,00	26.621,00	25.522,00
Grid Exports (kWh)	0,00	851,91	927,17	1.342,50
Total Trade (kWh)	0,00	15.678,00	16.796,00	17.356,00
Peak Grid Consumption (kWh)	105,91	228,96	228,96	228,96
Grid Supply Percentage (%)	100,00	55,73	56,37	54,04
DERs Supply Percentage (%)	0,00	44,27	43,63	45,96
Total Cost (€)	7.622,40	3.106,35	3.007,28	2.767,72
Grid Import Cost (€)	7.622,40	3.186,90	3.095,70	2.896,20
Grid Export Revenue (€)	0,00	80,55	88,42	128,48

Table 1. Results of the simulations

4. Conclusions

The integration of distributed energy resources (DERs) presents both challenges and opportunities for power systems. While various approaches exist for efficient operation of distribution networks incorporating DERs, the consensus is that DERs offer significant economic and energy efficiency benefits to end-consumers, especially when forming energy communities. This thesis explores seven different DER integration scenarios, focusing on a realistic low voltage distribution network (LVDN) in Madrid, to identify optimal energy allocation strategies. The findings highlight that DERs, including photovoltaics, batteries, and electric vehicles, can substantially reduce total energy costs by minimizing grid imports, leveraging low electricity prices, and maximizing the use of storage systems and EV batteries for intra-community energy trading.

The analysis demonstrates that scenarios without electric vehicles show a cost reduction of over 50%, primarily due to the introduction of photovoltaics. When combined with energy storage systems (ESS), costs decrease by an additional 22%, achieving the best results across all simulations. Although scenarios incorporating electric vehicles entail higher costs due to increased demand, the most cost-effective scenario considering EVs involves PV, ESS, and EV charging/discharging with extended connection times to the LVDN. This approach utilizes the storage capacity of EVs to provide grid services, resulting in a 47% cost reduction compared to initial simulations without DERs. Overall, without taking into account investments, the thesis underscores the value of DERs in reducing energy costs and enhancing grid efficiency, emphasizing Community Energy Trading as a viable alternative for energy communities.

5. References

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MODELIZACIÓN DE VEHÍCULOS ELÉCTRICOS PARA MERCADOS EMERGENTES Y MECANISMOS DE RESPUESTA A LA DEMANDA

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RESUMEN DEL PROYECTO

1. Introducción

En los últimos años, los precios de la energía han ido subiendo debido a los elevados precios del gas y a la guerra de Ucrania, lo que ha agravado la dependencia europea del gas ruso en más del 40% de su suministro y ha provocado precios extremos de la electricidad. Además, el coste creciente de los derechos de emisión de CO_2 y las frecuentes restricciones de la red debidas a los recursos energéticos distribuidos (DERs) hacen necesarios nuevos métodos de eficiencia energética [1]. Las políticas de sostenibilidad de la Unión Europea destinadas a combatir el cambio climático están empujando a todos los sectores, en particular al transporte, hacia un modelo de cero emisiones netas. Esta transición aumentará la penetración de los vehículos eléctricos (VE), alterará los patrones tradicionales de consumo de electricidad y elevará los costes energéticos globales para los usuarios finales [2]. La gestión optimizada de la energía será crucial para evitar las restricciones de la red derivadas de la elevada demanda de electricidad.

Para reducir las facturas de electricidad, muchos ciudadanos han instalado módulos fotovoltaicos en sus tejados, aunque no siempre es la estrategia óptima, debido a los posibles excedentes de energía. El almacenamiento en baterías podría ayudar a optimizar este uso de la energía. Además, la integración de los vehículos eléctricos plantea retos adicionales para el funcionamiento y la capacidad de la red, ya que los métodos de "dumb charging" ponen en peligro la seguridad de la red. Es esencial una gestión eficiente de las energías renovables, las instalaciones de almacenamiento (ESS) y los vehículos eléctricos. El comercio comunitario de energía (Community Energy Trading) ha surgido como una solución fiable para gestionar las crecientes fuentes de energía renovables en la red. Aunque los estudios suelen centrarse en el autoconsumo fotovoltaico (FV), es necesario investigar más sobre el uso de estos sistemas en comunidades energéticas locales con diversos recursos energéticos distribuidos [3].

2. Metodología

Esta tesis tiene como objetivo estudiar el impacto del crecimiento de los vehículos eléctricos en redes de distribución de baja tensión. Los principales objetivos son estimar la distribución de energía más eficiente en una comunidad energética, evaluar si el comercio comunitario de energía (Community Energy Trading) es una medida válida para optimizar la eficiencia energética y comparar cuál de los escenarios conlleva los mejores resultados para la minimización de costes. Se consideran varios escenarios con diferentes distribuciones de DERs:

1. Caso 1: caso base, sin DERs.
2. Caso 2: incluyendo FV como DERs.
3. Caso 3: incluyendo FV y ESS como DERs,
4. Caso 4: incluyendo FV, ESS y carga de VEs como DERs.
5. Caso 5: incluyendo FV, ESS y carga y descarga de VEs como DERs.
6. Caso 6: incluyendo FV, ESS y carga y descarga de VEs como DERs. La diferencia entre los casos 5 y 6 es la disponibilidad de los VEs, que están conectados a la red cuatro horas más cada día en el caso 6.
7. Caso 7: incluyendo FV, ESS y carga y descarga de VE como DERs. En este último caso, se considera una integración del 100% de VEs (todos los clientes tienen VEs).

El modelo utilizado para realizar las simulaciones se toma del artículo de investigación "Impacts of Community Energy Trading on Low Voltage Distribution Networks" y se usa, modifica y adapta a los casos anteriores [3]. Este modelo se basa en MATLAB y utiliza perfiles de FV y consumo, precios de importación y exportación de energía y las características de los DERs como entrada para obtener la asignación de los DERs de los clientes y el perfil de demanda. Así, se estudiará el impacto de los DERs en la red, el consumo de la red, las exportaciones e importaciones de la red y los costes.

3. Resultados

En los siguientes gráficos de la Figura 1 se representa la asignación de energía durante las primeras 48 horas de la simulación. En la esquina superior izquierda, se muestra el escenario sin DERs. Dado que no hay DERs, toda la energía debe ser importada de la red. Los escenarios restantes representados incluyen DERs, cambiando las condiciones de carga/descarga de los vehículos eléctricos.

En la parte superior derecha, se representa el escenario que considera solo la carga de los VE. Durante el día, la energía de las instalaciones fotovoltaicas (FV) se utiliza para satisfacer la demanda del cliente 53. El excedente de energía se intercambia con otros miembros de la comunidad que no pueden cubrir su demanda con FV o se almacena en baterías para uso futuro. Cuando la producción de FV disminuye, se importa energía de otros miembros o se descargan las baterías (ESS). Durante la noche, el VE, así como el ESS, se carga principalmente utilizando importaciones de la red, ya que los precios de la electricidad están en su punto más bajo, creando picos altos de consumo.

El tercer escenario representado incluye DERs y la carga y descarga de los VE, mostrado en la parte inferior izquierda. Los patrones son similares al escenario anterior: la FV cubre la demanda, carga el ESS y el excedente se intercambia. Por la noche, el VE y el ESS se cargan de la red debido a los bajos precios. La diferencia está en los períodos de altos precios de la energía, cuando el VE se descarga para apoyar las necesidades energéticas del cliente 53 y de toda la comunidad energética, reduciendo las importaciones durante las horas caras. Los resultados son similares para el último caso representado en el gráfico inferior derecho, ya que los VE permanecen conectados a la red 4 horas más, reduciendo la necesidad de importar energía a precios más altos.

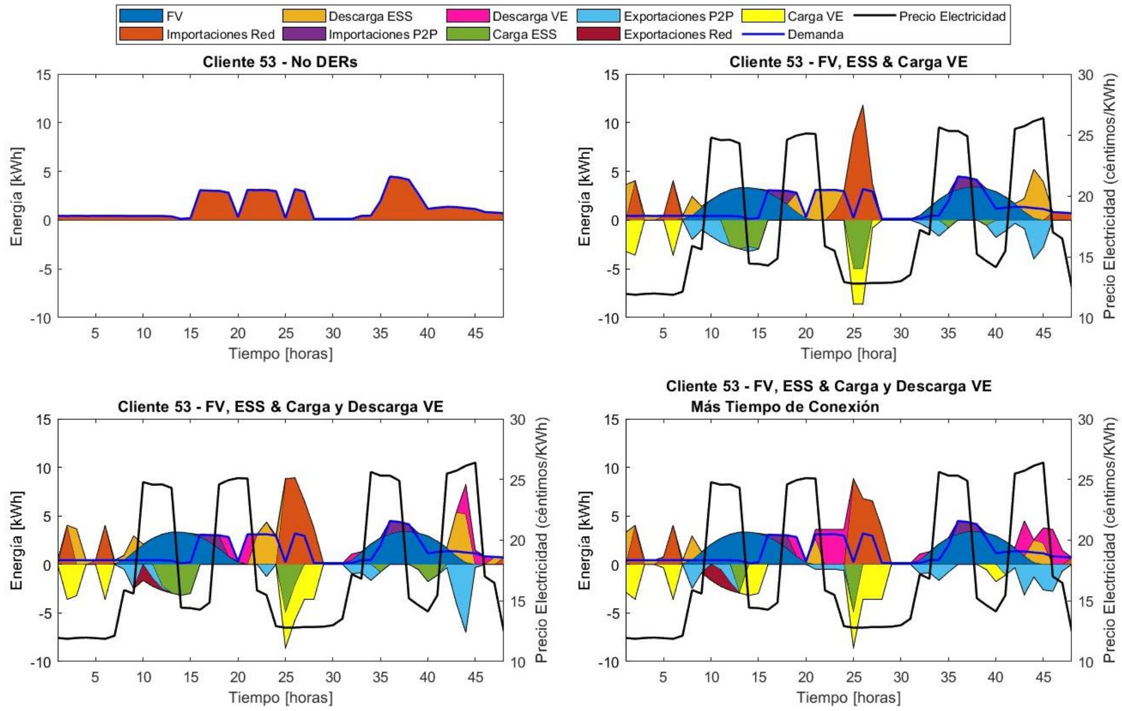

Figura 1. Cliente 53 para escenarios a) No DERs b) FV, ESS y carga VE c) FV, ESS y carga y descarga VE y d) FV, ESS y carga y descarga VE – Más Tiempo de Conexión

En la Tabla 1, se presentan los resultados del caso base y los principales escenarios relacionados con los VE. El escenario que minimiza el coste para la comunidad energética es el que incluye DERs y los VE tienen mayor disponibilidad. De este modo, las importaciones de energía también se minimizan y se realizan cuando los precios de la electricidad son bajos. En consecuencia, el 46% de la demanda total se satisface con DERs, el máximo para las simulaciones que consideran VE. La energía intercambiada también alcanza su máximo. Sin embargo, la reducción de costes en todos los escenarios relacionados con DERs es significativa, y el consumo máximo de la red es considerablemente alto, pero estable a lo largo de las simulaciones.

Resultados	**No DERs**	**DERs - Carga VE**	**DERs Carga y Descarga VE**	**DERs Carga y Descarga VE – Más Tiempo de Conexión**
Importaciones de la Red (kWh)	47.229,00	26.323,00	26.621,00	25.522,00
Exportaciones de la Red (kWh)	0,00	851,91	927,17	1.342,50
Intercambio Total de Energía (kWh)	0,00	15.678,00	16.796,00	17.356,00
Consumo Pico de la Red (kWh)	105,91	228,96	228,96	228,96
Porcentaje de Suministro de la Red (%)	100,00	55,73	56,37	54,04
Porcentaje de Suministro DERs (%)	0,00	44,27	43,63	45,96
Coste Total (€)	7.622,40	3.106,35	3.007,28	2.767,72
Coste de Importaciones de la Red (€)	7.622,40	3.186,90	3.095,70	2.896,20
Ingresos de Exportaciones a la Red (€)	0,00	80,55	88,42	128,48

Tabla 1. Resultados de las simulaciones.

4. Conclusiones

La integración de recursos energéticos distribuidos (DERs) presenta tanto desafíos como oportunidades para los sistemas eléctricos. Si bien existen diversos enfoques para la operación eficiente de redes de distribución que incorporan DERs, el consenso es que los DERs ofrecen beneficios significativos en términos económicos y de eficiencia energética para los consumidores finales, especialmente al formar comunidades energéticas. Esta tesis explora siete escenarios diferentes de integración de DERs, centrándose en una red de distribución de baja tensión real en la ciudad de Madrid, para identificar estrategias óptimas de asignación de energía. Los hallazgos destacan que los DERs, incluyendo fotovoltaica, baterías y vehículos eléctricos, pueden reducir sustancialmente los costes totales de energía al minimizar las importaciones de la red, aprovechar los bajos precios de la electricidad y maximizar el uso de sistemas de almacenamiento y baterías de vehículos eléctricos para el intercambio de energía dentro de la comunidad.

El análisis demuestra que los escenarios sin vehículos eléctricos muestran una reducción de costes de más del 50%, principalmente debido a la introducción de fotovoltaica. Cuando se combina FV con sistemas de almacenamiento de energía, los costes disminuyen en un 22% adicional, logrando los mejores resultados en todas las simulaciones. Teniendo en cuenta que los escenarios que incorporan vehículos eléctricos implican mayores costes debido al aumento de la demanda, el escenario más rentable con VEs implica la combinación de fotovoltaicas, ESS y la carga/descarga de vehículos eléctricos con tiempos de conexión más largos a la red. Este enfoque utiliza la capacidad de almacenamiento de los vehículos eléctricos para proporcionar servicios a la red, resultando en una reducción de costes del 47% en comparación con las simulaciones iniciales sin DERs. En general, sin tener en cuenta los costes de inversión, la tesis subraya el valor de los DERs en la reducción de costes de energía y la mejora de la eficiencia de la red, destacando el comercio comunitario de energía (Community Energy Trading) como una alternativa viable para las comunidades energéticas.

5. Referencias

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[2] International Energy Agency, "World Energy Outlook 2023 – Analysis," IEA. Acceso: Jul. 08, 2024. [Online]. Disponible en: https://www.iea.org/reports/world-energy-outlook-2023

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1. Introduction

1.1.Motivation

Lately, energy prices have been following an increasing trend, which has been worsened due to high prices of gas and the crisis generated by the Ukrainian War. Furthermore, Europe's dependence on Russian gas on more than 40% of these resources and the uncertainty of supply have led to extreme electricity prices in recent years. The price of compensation for CO_2 emission rights has also grown [1]. These events, combined with the grid constraints that become more and more frequent as a consequence of Distributed Energy Resources (DERs), have resulted in the need for new energy efficiency methods to handle the changes in the electricity sector.

Additionally, sustainability policies introduced by the European Union to face climate change and temperature increase are leading all of the sectors, especially the transportation sector, towards a net-zero emissions model. These policies will result in higher penetration for electric vehicles (EVs), which will modify the electricity consumption curves that have been traditionally studied, increasing the total consumption of energy by end users and incurring higher costs. Considering the growing demand for electricity in the coming years due to electrification and electric vehicles' penetration, optimized energy management will be decisive [2]. The most efficient way to allocate this without leading to grid constraints due to high demands is to implement these measures to reduce the risk of transmission lines saturation.

In the quest for reducing the electricity bill, many citizens have started to install solar PV in their rooftops. Although this measure has helped lowering the electricity costs, it's not optimal, as there may be energy surplus that is not used due to lower consumption when there is high renewable production. For this reason, storage in batteries could optimize the usage of this energy. Furthermore, the penetration of EV may entail significant challenges in grid operations and capacity, and the dumb charging methods may result in violations of grid safety parameters. It's essential to evaluate the most efficient way of dealing with renewable energy and storage facilities, combined with EVs integration on the network.

Finally, Community Energy Trading (CET) has proven to be one of the most reliable solutions to face the increasing growth of DERs in the grid. Most of the published studies consider PV self-consumption [3]. However, further analysis is still needed on how these systems could be used in local areas, such as energy communities, with a wider variety of distributed energy resources, such as energy storage systems (ESS) or EVs.

1.2. Project Objectives

This document describes the work addressed in the context of a Master's Thesis aimed to study the impact of the growth of electric vehicles on low voltage distribution networks. Several different scenarios are studied to develop a profound analysis of the problem, focused on community energy trading. The objectives of the thesis are the following:

- Estimate the most efficient allocation of energy in an energy community with different distributed energy resources within their members.
- Estimate the effect on energy allocation and cost variation in the different scenarios, such as longer EV connection periods to the distribution network.
- Evaluate the impact on market models of different volumes of EV's penetration in the grid.
- Assess if CET is a valid measure to optimize energy efficiency and management.
- Compare which option entails the best results for cost minimization and energy optimization.

2. State of the art

The increase of global temperatures and the effects of climate change has compelled governments to take action and implement measures to confront these challenges. The starting point to start making progress towards a climate-neutral world was the Paris Agreement, signed by 196 parties in 2015. Since the Paris Agreement, economic, social and technological measures have been taken to reduce greenhouse gas emissions with the objective of limiting the temperature increase by less than 2ºC, by 1.5ºC in the best scenario [4].

Nowadays, many countries are aware and focused on their commitment to the environment. Despite the efforts of countries to decrease greenhouse gas emissions and achieve the net-zero scenario, global greenhouse gas emissions kept increasing in 2022, reaching higher levels than in 2019 before the COVID-19 crisis. As shown in Figure 1, in the European Union, the main sectors that generate emissions are transport and power industries [5], although they have been slightly decreasing over the years.

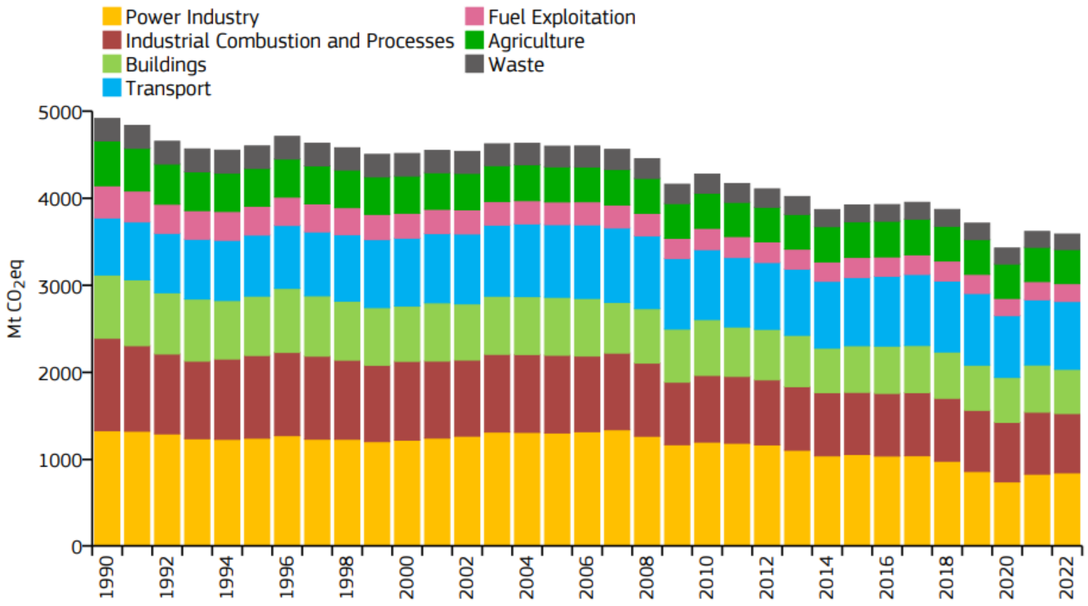

Figure 1 Greenhouse gas emissions per sector in the EU [5]

As a result of the Paris Agreement, the member states of the European Union have signed the European Climate Law, which establishes a legal obligation to achieve net zero emissions by 2050 through a series of medium-term objectives. The target of 2030 includes the reduction of, at least, the 55% of net emissions compared to preindustrial levels [6].

Under this context, the EU is working to enhance the development of clean energy sources, such as solar, wind energy or hydrogen, promote the integration of energy systems across the EU and develop interconnected energy infrastructure creating energy corridors [7]. In addition to the decarbonization objectives, the outbreak of the Russian War against Ukraine has resulted in a faster energy transition to a clean future to become independent from Russian oil and gas [8]. Considering the future expectations of renewable energy sources' penetration, the energy system must be designed to allocate the energy supply and demand efficiently and provide the flexibility that fossil fuels currently hold [9].

Two of the leading renewable technologies are wind and solar, which represented the 29.9% and 18.2% of the total renewable energy consumed in the EU in 2022 respectively [10]. These are Variable Renewable Energy (VRE) sources, which can only produce when the conditions are favorable. In order to face the flexibility challenge, Distributed Energy Resources (DERs) rise as a promising alternative. DERs are small generation units, typically renewable, located "behind-the-meter" on the consumer side of the demand. They are connected to the distribution network at low or medium voltage levels and enable the production of energy in almost any place. DERs include photovoltaic systems for self-consumption (PV), wind energy or combined heat and power technologies. However, in recent years DERs have expanded to feature electric vehicles and chargers (EV), battery energy storage systems (BESS), smart metering and home energy management systems (HEMS), which may provide balancing services and demand control on the grid [11].

DERs can be helpful to manage the energy allocation problem that may arise due to the lack of flexibility that VRE sources cannot provide. VRE, especially solar and wind energy, have become two of the technologies with the lowest levelized cost of energy (LCOE), without even considering governmental subsidies. Following a contribution of the 22% to the EU electricity supply, VRE sources production is expected to increase according to the decarbonization scenarios proposed by the EU [9]. As VRE supply is dependent on the weather conditions, the difference between its production and the electricity demand, known as residual demand, can create two situations which will help understand the primordial role of DERs in the electricity system.

If VRE is lower that the electricity demand, there is a VRE deficit, so demand is covered by increasing the production of the residual technology on the market, normally combined cycle gas turbine (CCGT) power plants, importing cheaper generation from other markets, injecting stored energy into the grid or directly reducing demand. On the contrary, in situations of VRE production excess, energy can be exported to other markets or stored in batteries, generation from controllable and expensive units can be decreased or, as a last resort measure, VRE production can be curtailed [9].

Considering both situations, there has been a paradigm shift from "load following", in which the generation followed the electricity demand to provide all the grid users with supply, to a "generation following", in which the demand and other resources are adjusted to make the most of the production of VRE sources, trying to adapt to the sudden changes in generation given their variable origin. DERs may provide the flexibility needed to face these variations in generation by modifying its production or consumption patterns almost in real-time [12].

The optimal management of distributed energy resources is a main priority to achieve an efficient allocation of energy resources, maximizing the benefits for the network and minimizing costs for end-users. The increasing insertion of DERs into the network are also creating new restrictions in the operation of the distribution network in terms of congestion of the lines, reverse flows and voltage problems. Furthermore, renewable energy sources, combined with DERs are slowly decreasing the presence of fossil-fuel power plants on the electricity market, which are the main source of flexibility right now. If DERs are managed efficiently, the physical effects on the grid can be avoided by controlling the production and consumption patterns and while also providing flexibility by the controllability of the resources [12].

The introduction of DERs in the European Union has been progressive since the Paris Agreement in 2015. The European Climate Law established that every European country must create their own plans on how to work on the sustainability objectives approved in the Paris Agreement and guarantee their compliance by 2050 [6]. These plans are subject to periodic updates according to the objectives and forecasts of the EU. In Spain, the plan is divided into different phases. The current phase corresponds to the goals and guidelines included in the National Energy and Climate Plan 2021-2030 (NECP).

Spain's NECP addresses challenges and opportunities across five dimensions of the Energy Union: decarbonization (including renewables), energy efficiency, energy security, the internal energy market, and research, innovation, and competitiveness. The country's long-term objective is to achieve carbon neutrality by 2050, with a specific target of reducing total gross greenhouse gas (GHG) emissions by at least 90% compared to the 1990 baseline. The last update of the NECP rises the reduction of emissions up to 32% in 2030, increases the total share of renewable energy to 48% and enhances energy efficiency up to 44%. Consequently, the estimation of capacity installed of solar PV by 2030 rises to 76,4 GW, including 19 GW of self-consumption, wind capacity rises to 62 GW, and 22 GW of storage capacity (together with thermo solar storage) [13]. The evolution of gross installed electric power capacity is shown in Table 1.

Generation PNIEC 2023-2030 Scenario. Gross Capacity (MW)					
Technology	**Years**	**2019**	**2020**	**2025**	**2030**
Wind		25.583	26.754	42.144	62.044
Solar PV		8.306	11.004	56.737	76.387
Solar Thermal		2.300	2.300	2.300	4.800
Hydro		14.006	14.011	14.261	14.511
Biogas		203	210	240	440
Other RES		0	0	25	80
Biomass		413	609	1.009	1.409
Coal		10.159	10.159	0	0
Combined Cycle		26.612	26.612	26.612	26.612
Cogeneration		5.446	5.276	4.068	3.784
Fuel & Fuel/Gas		3.660	3.660	2.847	1.830
Waste & others		600	609	470	342
Nuclear		7.399	7.399	7.399	3.181
Storage		6.413	6.413	8.828	18.543
Total		**111.100**	**115.016**	**166.940**	**213.963**

Table 1 Evolution of gross installed electric power capacity [13]

To ensure sustainable electricity production, the government is advocating for various measures to boost the use of renewable energies and enhance energy efficiency. These measures include the establishment of new renewable energy generation facilities, adaptation of electricity grids for renewable integration, promotion of self-consumption with renewables, incorporation of renewables in the industrial sector, adoption of advanced biofuels in transportation, encouragement of renewable gases, implementation of biomass programs, public procurement of renewable energies, and the regulation of local energy communities [13]. Additionally, there is an emphasis on fostering an active role for citizens in the decarbonization process.

Furthermore, the plan highlights the importance of guaranteeing consumers the right to produce, consume, store, and sell their own renewable energy. It aims to assess both the obstacles and the development potential of renewable energy communities, emphasizing citizen participation in the transition towards decarbonization [13].

The Spanish NECP also contemplates an increase in the electrification of the economy over the decade as one of the key drivers for decarbonization rising to a 34% in 2030. Regarding electric vehicles, forecasts expect the fleet to increase up to 5,5 million electric vehicles by 2030, 10% higher than the previous target. This progress in electrification is facilitating, not only the penetration of renewables in areas where the use of fossil fuels still predominates, but also significant energy saving in energy consumption for end-users. These measures are supported by complementary mechanisms to facilitate broad access by society and businesses, and therefore, the possibility of taking advantage of the costs savings they entail [13].

2.1.Electric Vehicles

Electric Vehicles are vehicles with one or more electric motors powered by electricity stored in batteries. As a result of the strong policies and regulations introduced by the European authorities, EVs have become one of the key assets to improve energy efficiency and manage energy allocation. The expected growth in EVs will allow them to become new resources for energy dispatch.

Sales of electric vehicles have witnessed a potential increase in recent years. In 2020, only 5% of newly sold cars in the world were electric. This figure increased to 9% in 2021 and further rose to 14% in 2022, resulting in more than 10 million cars. According to the 2024 Global EV Outlook, this number neared 14 million by the end of 2023, reaching 18% of the total sale of cars. The outlook for EV sales share is favorable considering the current regulatory framework, growing up around 23% annually from 2023 to 2035 [14]. As a result, it is projected that the demand for EV will have severe consequences on both energy market and climate objectives.

In Europe, the electric car sales have also been increasing since 2021, when 2,4 million electric cars were sold. In 2023, this number reached 3,2 million electric cars. As represented in Figure 2, the exponential growth in the electric car stock in European countries is substantial over the past few years. At the end of 2023, the European electric car stock exceeded 11 million cars, combining battery electric vehicles (BEV) and plug-in hybrid electric vehicles (PHEV) [14].

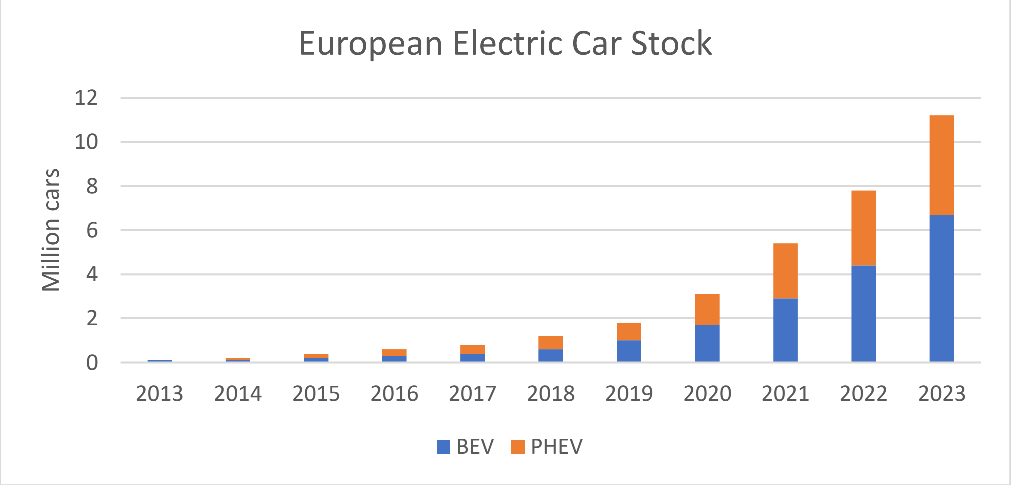

Figure 2 European electric car stock [14]

The growing demand of electric vehicles into the market has led to a consistent integration of EVs into the grid, allowing them to act as active or passive resources according to the network's needs. The functionalities of EVs, including unidirectional and bidirectional control as well as power flow capabilities have enabled grids to optimize energy usage patterns and enhance support in grid services [15]. Several aspects for the widespread integration and effective utilization of EVs are outlined below:

- Electrifying the transport and mobility sector is considered a viable solution to address challenges related to greenhouse gas emissions and the limited availability of carbon-based resources.
- Since a significant proportion of vehicles remains parked at charging infrastructure for around the 90% of the time, they can stay connected to the network and actively participate in energy management programs, acting as battery resources through the concept of Vehicle-to-Grid (V2G).
- Mass-scale adoption of electric vehicles has the potential to provide grid support during incidents, offering ancillary services such as frequency and voltage control or peak reductions.
- The penetration of EVs will allow consumer to actively participate in the energy market, supporting the network in system management and regulatory activities.
- Electric vehicles may be useful to store surplus generation for renewables through various charging topologies. They can also provide power in generation shortages and contribute to achieve a more balanced supply and demand curve through V2G. [15].

If not managed efficiently, the integration of EVs into the grid and dumb charging can have severe consequences on grid stability and security of supply. The impact of EVs on the distribution network is significant. Peak demand is increased, especially in periods where most EVs are connected to the grid and charging. The load increase that EVs entail has direct impact on the voltage levels, producing variations that can exceed the safety limits, restricting the capacity of the lines. Further studies suggest that the increase in load demand could also affect the thermal capacity of transformers in distribution networks, as they have primarily been designed without considering EV load [16]. To minimize the impact of such effects, smart charging is necessary, whether its unidirectional or bidirectional.

As previously mentioned, optimized smart charging must be deployed to avoid the inefficiencies in grid operations, through unidirectional or bidirectional charging. Both have advantages, allowing the reduction of the load of the grid, which may be caused by the increasing demand of electric vehicles at certain times. However, the technology of Vehicle-to-Grid (V2G) would bring potential benefits due to the electricity flow between the vehicles and the grid in both directions, creating synergies. In the following section, the vehicle-to-grid is explored more in depth.

2.1.1. Vehicle-to-Grid (V2G)

The introduction of electric vehicles and its connection to the grid may be challenging and may cause some grid operational issues leading to grid constraints violations. The consolidation of EVs implies a substantial demand for electricity, that can be located in relatively small areas, which may affect frequency, voltage or reactive power, leading to shortages having a considerable impact on security of supply. These effects become even more relevant during peak hours when EVs are connected and charging all at the same time. To solve these grid security problems, ancillary power generators are needed to reduce these fluctuations without incurring into more losses or damage on the grid. To address these challenges, concepts such as vehicle-to grid (V2G), vehicle-to-building (V2B), vehicle-to-vehicle (V2V) are emerging [17]. However, in this thesis the main focus is on Vehicle-to-Grid technologies.

Vehicle-to-Grid technology refers to the ability of EVs to exchange energy with the grid in a bidirectional flow. This system is represented as an incentive to encourage EV owners to participate as active users on energy practices, so that during low periods of demand when there is surplus energy, EV owners can charge their vehicles with lower tariffs. On the contrary, in periods of high demand, when the need for electricity is bigger, batteries may discharge their excess energy at higher rates, allowing EV owners to make a profit. This energy exchange can be simplified in Figure 3: the bidirectional flow enables energy flows not only from the grid or the household's DERs to the EV but also vice versa. Likewise, the household has also bidirectional flow due to imports from the grid and exports from the distributed energy resources.

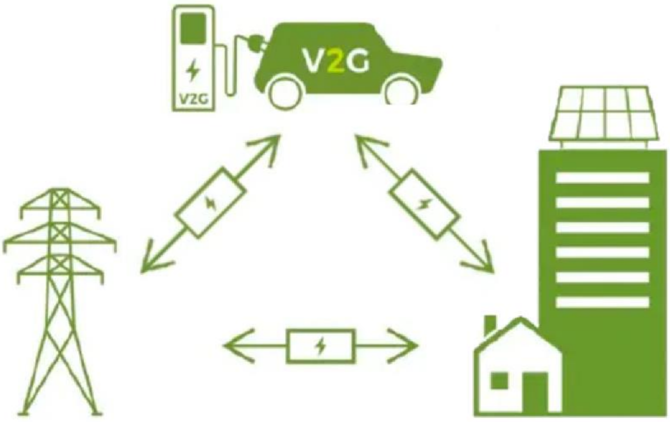

Figure 3 Vehicle-to-Grid diagram [18]

The integration of V2G technology entails several advantages in technical, economic and environmental aspects:

- Independence and self-sufficiency as the battery allows the consumer to store the excess energy to use it when prices rise or production decreases.
- Cost reduction as less power is imported from the grid and at lower prices. Furthermore, customers can have an income from energy sold at peak hours.
- CO2 emissions reductions by the integration of EVs in the market while enhancing the reliability of Variable Energy Resources.
- Referring to EVs as mobile energy storage units, they can provide flexibility services at numerous locations of the network [19].

However, there are some barriers that limit and slow down the consolidation of electric vehicles as one of the main alternatives for transportation but also grid support.

- Battery degradation due to cyclic charging and discharging reduces the useful life of the electric vehicle. This effect is further exacerbated by the use of external charging devices [19].
- Energy losses due to charging and discharging are inevitable. Depending on the conditions on the EV, the charging point and the environmental conditions, the charging efficiency may vary between the 70% and the 90% [20].
- Regulation uncertainty towards bidirectional charging and the integration of V2G technology in European markets. Regulation regarding this topic is necessary to achieve widespread support. Due to the wide variety of stakeholders involved in the installing V2G services, it is very hard to reach agreements [19].

2.2.Community Energy Trading

Recently, there has been a severe increase of energy prices and inflation in Europe. As a result, European authorities such as the European Commission and local governments started to encourage citizens to actively engage in energy-related affairs, such as consumption and load reduction, energy savings and cost minimization. The energy sector is going through serious changes that involve the participation of individuals and communities in energy projects. This implementation would lead to the achievement of the Net-Zero Objective proposed by the European Union for 2050, where more than the 80% of households would actively contribute to these goals by lowering their energy consumption, changing to 100% renewable energy providers, participating in energy generation and storage with renewables or participating in demand response mechanisms [21]. Thus, citizens change their roles in the energy sector, from being strictly consumers to prosumers, who have the ability to produce and sell their energy likewise.

Consequently, energy communities arise as a new way for customers to participate actively in energy efficiency mechanisms through distributed energy resources. Renewable energy sources, especially PV for self-consumption, are already integrated in the network, sharing the benefits among neighbors, such in collective self-consumption facilities. The use of PV and ESS may contribute to the efficient allocation of energy among consumers, but the future incorporation of electric vehicles as a load is the main challenge for grid operation. Thus, the optimization of EV charging and vehicle-to-grid integration become relevant.

Energy communities are defined as legally recognized organizations that enables members to generate, manage and share the locally generated energy. Communities can be made up of different participants, including generators, distributors and consumers, which can be houses, businesses or even authorities. By being independent and controlling the assets, communities may benefit from clear information and cheaper energy, allowing them to improve their energy efficiency, monitor their costs and guarantee their investments' profitability [22].

Community Energy Trading, also known as Peer-to-Peer Energy Trading, allows prosumers to share their energy surplus from distributed energy resources, such as photovoltaic generation (PV) or storage (BESS), with peers with energy deficit within the community [23]. The local allocation of energy among members of the community entails advantages for both producers and consumers. Producers have the option to sell excess energy to neighbors at a premium compared to selling it to the retailer. Likewise, consumers have the opportunity to purchase this energy at a discounted rate compared to buying it directly from the retailer. This model also promotes competition between electricity retailers and distributed energy resources

[3]. Some of the benefits that community energy trading may entail are the promotion of competition between electricity retailers and distributed generation resources and the establishment of an equilibrium between supply and demand in the community. It can also boost the consumption from local distributed generation, diminish the reliance on the main grid and optimize the costs for both prosumers and consumers, resulting in more favorable prices within the community compared to the retailer [3].

2.3. Regulatory Framework for Energy Communities

Energy communities are strongly emerging worldwide, reshaping energy policies towards cleaner and more decentralized power systems. Institutions such as the European Union and the United Nations have included energy communities in the Clean Energy for All Europeans package and the Sustainable Development Goals respectively as crucial elements for sustainable energy transition. Citizens join these communities looking for financial benefits, independence and environmental concerns [24].

However, the term “energy community” still does not have a universal definition, leading to different interpretations. There are those who interpret it as local project with shared benefits, while other define it as groups of producers and consumers joining resources for billing purposes. Despite the regulatory frameworks within the EU, clear definitions and guidelines are still to be developed [24].

This section explores the European regulations for energy communities and its incorporation into legislation, taking into account the difficulties of the implementation and different approaches of every Member State.

2.3.1. EU's Regulatory Framework on Energy Communities

This thesis is particularly relevant within the European Union, where policymakers are encouraging the establishment of energy communities that deploy distributed energy resources and engage in local energy trading. Several entities are being established, but they have not still been fully implemented in Spain, but their introduction is anticipated in the near future.

The aim of the thesis is to optimize the energy allocation among members of energy communities by minimizing their costs. However, it would not make sense to develop this project without considering how the European regulation understands energy communities right now and what the future may look like for energy communities.

Over the last few years, the European Union has adopted a number of policies focused on changing the energy landscape towards a more sustainable, distributed and renewable model through three key packages: Clean Energy for all Europeans, European Green Deal and Fit for 55 [24]. These initiatives served as the foundation for establishing the concept of energy communities and defining the regulatory framework.

There are currently five legal figures that could be classified as energy communities within the EU legislation:

- Jointly-acting renewable self-consumers (JARSC).
- Renewable energy community (REC).
- Jointly-acting active consumer (JAAC).
- Citizen Energy Community (CEC).
- Closed distribution system [24].

The definition and standards set for these five legal figures are different from each other, but the are some common dimensions identified in all of them, such as access to energy markets, activities of the participants, cross-border participation, obligations of the Member States and operation of the grid, among others. A detailed of the energy communities' legal figures is available in the report "Regulatory framework for fostering flexibility deployment: roles, responsibility of agents & flexibility mechanism design" [24].

However, there are still some gaps and obstacles on the EU regulation for energy communities. Some of the terms utilized on European directives are not defined in on these directives nor in any other European regulation. Furthermore, some of these legal figures are very similar between each other, so it would be beneficial to simplify and standardize, to prevent from overlaps and contradictions.

3. Optimization Data and Modelling

3.1. Methodology

To evaluate the objectives of the Master's Thesis, the model formulated on the research article "Impacts of Community Energy Trading on Low Voltage Distribution Networks" is taken as reference for the following analysis [3]. This model is used, modified and adapted to perform the different simulations of the scenarios considered.

The goal of Community Energy Trading is to minimize costs while maximizing the profits of selling the energy surplus back to the retailer, and consequently, reduce the energy imports from the retailer. This objective is accomplished by promoting energy trading from distributed energy resources among community members, leveraging the flexibility offered by Battery Storage Energy Systems (BESS) and electric vehicles (EVs).

The model explained in the aforementioned article involves two sequential stages: an optimization problem and a power flow analysis. The first stage consists of an optimization based on community energy trading, generating the optimal dispatch for market participants. The model is based on MATLAB and takes photovoltaic generation profiles, load profiles, import and export prices and the features of distributed energy resources as inputs for the optimization. The resulting output of the market model includes the dispatch for the prosumers' DERs and the demand profile for second step [3]. Thus, this model enables us to study the impact of the different DERs on grid consumption, grid exports and the costs implied.

In the subsequent stage, a power flow analysis is executed to assess the physical effects on the grid of the optimization problem solved in the first stage. The results from the first stage optimization are used as inputs for this power flow analysis to evaluate the voltage unbalances at the connection nodes of the loads, component loading and the voltage levels of the three phases [3]. However, this second stage is out of the scope of this thesis but would be very relevant to examine the behavior of the network regarding voltages, frequency and losses.

3.2. Design of the LVDN, Data and Constraints

The simulations are going to be made considering an energy community in which the members of the community can import and export energy from their own DER's to their neighbors or to the grid. The community is represented by a low voltage distribution network that includes 55 members, as represented in Figure 4. Each of the numbers represents a single-phase resident and member of the community. They are connected to the network at distinct connection points. The members are distributed in three phases differentiated by colors (phase A in blue, phase B in green and phase C in orange), so that the system is more balanced, and to avoid overloads and guarantee quality of supply. The distribution of consumers is unbalanced: 21 residents are connected to each phase A and B and 19 to phase C. The consumer profiles, obtained from real measurements in Madrid, have been anonymized by i-DE, a Spanish Distribution System Operator under the Iberdrola group [3]. Each consumer has a unique consumption profile, randomly appointed from recorded historical data of consumers in Madrid. They are sampled at hourly intervals. This model only involves active power trade between members but does not incorporate reactive power simulations. Consequently, a constant power factor of 0.95 pu is considered for all the loads. This network was originally conformed by the IEEE and is commonly utilized in research for Distributed Energy Resources' integration. The configuration of the network is radial, a prevalent layout in European LVDNs. To connect to the main grid, the LVDN employs a MV (11kVA) / LV (416V) transformer rated at 800 kVA with delta/grounded star grounded winding connections. The windings' resistance is 0.4% and reactance is 4% [3].

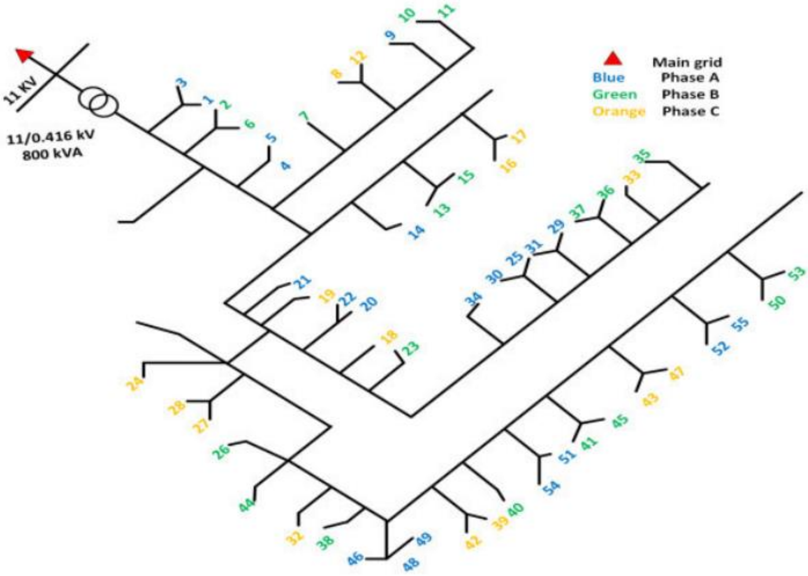

Figure 4 Single-line diagram for an unbalanced low voltage distribution network [3]

Each of the customers in the LVDN has different DERs installed, which have been assigned randomly. In the network represented in Figure 4, 33 customers rely on PV for generation, 22 customers include BESS and 18 customers have EVs. The allocation of DERs among customers is represented on Table 2:

Cust.	PV	BESS	EV	Cust.	PV	BESS	EV	Cust.	PV	BESS	EV	Cust.	PV	BESS	EV
1	Yes	Yes	No	**15**	Yes	Yes	No	**29**	No	No	No	**43**	Yes	No	No
2	Yes	Yes	Yes	**16**	Yes	No	Yes	**30**	Yes	Yes	No	**44**	No	No	No
3	Yes	Yes	No	**17**	No	No	No	**31**	No	No	Yes	**45**	Yes	Yes	No
4	No	No	No	**18**	Yes	Yes	No	**32**	Yes	No	No	**46**	No	No	Yes
5	Yes	Yes	No	**19**	No	No	No	**33**	Yes	Yes	No	**47**	No	No	No
6	No	No	No	**20**	Yes	Yes	Yes	**34**	Yes	No	No	**48**	Yes	Yes	No
7	Yes	No	Yes	**21**	No	No	No	**35**	No	No	Yes	**49**	Yes	No	Yes
8	Yes	No	No	**22**	No	No	No	**36**	No	No	No	**50**	Yes	Yes	Yes
9	Yes	Yes	Yes	**23**	Yes	Yes	No	**37**	Yes	Yes	No	**51**	No	No	No
10	No	No	No	**24**	Yes	No	No	**38**	No	No	No	**52**	Yes	Yes	No
11	No	No	No	**25**	Yes	No	Yes	**39**	Yes	No	Yes	**53**	Yes	Yes	Yes
12	Yes	Yes	Yes	**26**	No	No	No	**40**	Yes	Yes	No	**54**	Yes	Yes	Yes
13	No	No	No	**27**	Yes	Yes	No	**41**	Yes	No	Yes	**55**	Yes	Yes	Yes
14	No	No	No	**28**	No	No	Yes	**42**	No	No	No				

Table 2 Allocation of DERs among consumers [3]

The simulation is conducted with data from the month of July, which implies bigger penetration of solar PV, more surplus energy and more energy trading within the community.

In addition, the parameters regarding the PV production and the limits and efficiency of the BESS and the EVs must be defined. The PV production is rated at 5 kWp. The nominal power rating of the BESS is 5 kW/13.5 kWh. The charging and discharging efficiency is equal to 95%. Concerning the EVs, the nominal power rating of the batteries is 24 kWh with a charger rating of 3.6 kW. The charging and discharging efficiency is equal to 96% [3]. Depending on the scenario considered, the EV chargers allow unidirectional or bidirectional charging (V2G).

The input data that are used in the optimization model include maximum and minimum levels of the state of charge of the ESS, as well as of the EVs. In both, the state of charge must remain between the 20% and 100% of the nominal power. Additionally, the state of charge of EV batteries should be, at least, at 75% of its total capacity by 8 a.m., so that customers may use their EVs without limitations. Regarding EVs scenarios, EVs are connected to the LVDN from 6 p.m. to 8 a.m., except in an exceptional case that is mentioned in Case Studies afterwards.

Other parameters that are essential to guarantee the effective results of the optimization model proposed is the electricity prices. These prices are taken from Red Eléctrica, the Spanish transmission operator, also for the month of July [3]. In Figure 5, the price for imports and exports follows a characteristic pattern:

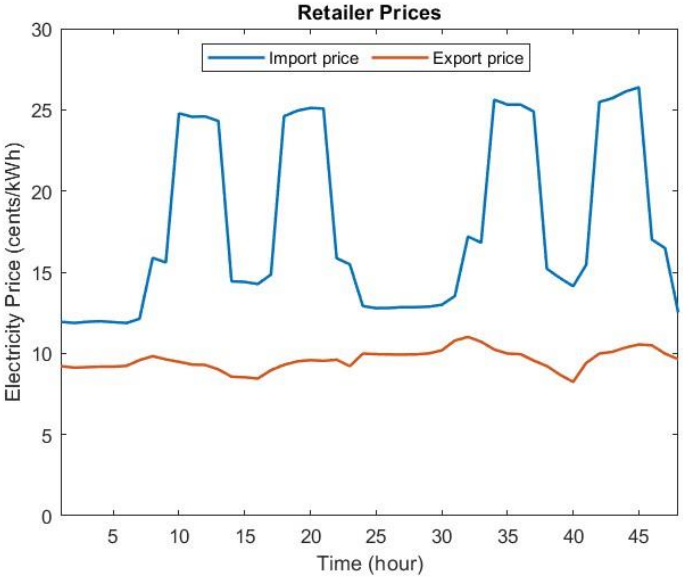

Figure 5 Retailer's import and export electricity prices [3]

The import prices from the grid show more instability than export prices, exposing higher prices during the morning, between 10 am and 2 pm, and afternoon, between 5 pm and 10 pm, which normally corresponds to the periods when consumption is usually higher. The fluctuations vary from 12 cents/kWh to 25 cents/kWh approximately. On the other side, prices for electricity exports remain mainly constant around 10 cents/kWh.

3.3. Optimization Problem Formulation

In this section, the optimization problem is going to be developed, along with the constraints and restrictions. To establish a distinction between the variables of the problem and the parameters and the scalars, the variables are written in upper case letters, while parameters and scalars are written in lower case letters [3].

Variables	
$G^{(t,h)}$	Energy consumption from the grid of home *h* at instant *t*
$I^{(t,h)}$	Imports from peers in the community to home *h* at instant *t*
$E^{(t,h)}$	Energy stored at ESS of home *h* at instant *t*
$D^{(t,h)}$	ESS discharge power at home *h* at instant *t*
$D_{EV}^{(t,h)}$	EV discharge power at home *h* at instant *t*
$X^{(t,h)}$	Exports to peers in the community from home *h* at instant *t*
$E_{EV}^{(t,h)}$	Energy stored at EV of home *h* at instant *t*
$F^{(t,h)}$	Energy supply to the main grid from home *h* at instant *t*
$C^{(t,h)}$	ESS charge power at home *h* at instant *t*
$C_{EV}^{(t,h)}$	EV charge power at home *h* at instant *t*
$I_p^{(t,h \leftarrow p)}$	Energy imported to home *h* from its peer *p* at instant *t*
$X_p^{(t,h \rightarrow p)}$	Energy exported from home *h* to its peer *p* at instant *t*
Parameters, scalars and sets	
$dem^{(t,h)}$	Demand of home *h* at instant *t*
$pv^{(t,h)}$	PV generation of home *h* at instant *t*
$p_G^{(t)}$	Import price at instant *t*
$p_F^{(t)}$	Export price at instant *t*
η^c	ESS charging efficiency
η^d	ESS dicharging efficiency
$P_d^{(t,h)}$	Net power demand of home *h* at instant *t*
η^c_{EV}	EV charging efficiency
η^d_{EV}	EV discharging efficiency
$\bar{C}$ and $\bar{D}$	Upper limits of charging and discharging powers of ESS
$\bar{C}_{EV}$ and $\bar{D}_{EV}$	Upper limits of charging and discharging powers of EV
$\bar{E}$ and $\underline{E}$	Upper and lower limits of ESS storage level
$\bar{E}_{EV}$ and $\underline{E}_{EV}$	Upper and lower limits of EV storage level
$b^{(t)}$	Binary parameter to define if the EV is connected to the LVDN
Δt	Trading period duration
ψ^{P2P}	P2P trade loss factor
$t \in T$	Time instant *t* in time horizon *T*
$h, p \in H$	Home *h* and peers *p* in a community of *H* homes

Table 3 Variables, scalars, parameters and sets of the CET model [3]

The optimization problem is made up of the objective function and the different constraints that consider the restrictions of the variables of the problem. The objective function represents the goal of the optimization problem, which is to minimize the cost of the electricity for the end-user. This implies the minimization of the costs from the electricity imports from the grid and the maximization of profits from the electricity exports to the grid for all the connection points (houses and buildings) for all the periods of time t. Consequently, the objective function is represented as:

$$min \sum_t \sum_h (p_G^{(t)} \cdot G^{(t,h)} - p_F^{(t)} \cdot F^{(t,h)}) \Delta t \tag{1}$$

Where $p_G^{(t)}$ is the price of the energy imported from the retailer, $G^{(t,h)}$ is the energy quantity imported from the retailer, $p_F^{(t)}$ is the price of the energy exported to the retailer and $F^{(t,h)}$ is the energy quantity exported to the retailer at time period *t* for home *h* [3]. This objective function is followed by a series of equations that represent the constraints and restrictions of the model and its variables.

At every consumption node, the energy supply must be equal to the energy consumption for every time period *t*. This equation establishes the energy balance by considering all the DERs of the loads, including photovoltaic production, storage and electric vehicles. It is modified for the consumption loads that do not include all the DERs, eliminating the corresponding terms from the equation. In the most general form of the equation, the sum of the consumption from the grid, the imports from other members of the community, the production from solar panels, the discharge from the batteries and from electric vehicles, must be bigger than energy demand, the exports to other members of the community, the exports to the grid and the charge of the batteries and electric vehicles:

$$G^{(t,h)} + I^{(t,h)} + \mathrm{pv}^{(t,h)} + D^{(t,h)} + D_{EV}^{(t,h)} \geq X^{(t,h)} + \mathrm{dem}^{(t,h)} + F^{(t,h)} + C^{(t,h)} + C_{EV}^{(t,h)} \quad \forall t \in T, \forall h \in H \tag{2}$$

For safety and stability reasons and to increase the lifespan of the devices, the batteries and the EVs should operate between certain limits. The lower limit for the charging and discharging of the batteries is null, meaning that the battery has no energy stored left. The upper limit for the charging and discharging of the batteries is restricted by the maximum capacity of the power converter that transforms DC to AC. Moreover, the state of charge of the batteries should always remain within certain limits to maintain the health and longevity of the batteries [3]. These conditions are represented by the following equations:

$$0 \leqslant C^{(t,h)} \leqslant \bar{C} \qquad \forall t \in T, \forall h \in H \tag{3}$$

$$0 \leqslant D^{(t,h)} \leqslant \bar{D} \qquad \forall t \in T, \forall h \in H \tag{4}$$

$$\underline{E} \leqslant E^{(t,h)} \leqslant \bar{E} \qquad \forall t \in T, \forall h \in H \tag{5}$$

The energy stored in a battery at a certain period *t* is calculated based on the state of charge of the battery on the previous period *t-1* and the charge and discharge of the battery on the current period, taking into account the charging and discharging efficiency of the battery, following this expression:

$$E^{(t,h)} = E^{(t-1,h)} + \eta^{c} \cdot C^{(t,h)}\Delta t - \left(\frac{1}{\eta^{d}}\right) \cdot D^{(t,h)}\Delta t \qquad \forall t \in T, \forall h \in H \tag{6}$$

The same structure is followed for the definition of the constraints of the EVs. The lower limit for the charging and discharging of the EVs is null, meaning that the EVs' cannot provide any energy to the network. The upper limit for the charging and discharging of the EVs is restricted by the maximum capacity of the power converter of the charging point of the EV. Moreover, the state of charge of the EVs should always remain within certain limits to maintain the health and longevity of the batteries of the EVs [3].

$$0 \leqslant C_{EV}^{(t,h)} \leqslant \bar{C}_{EV} \, . \, b^{(t)} \qquad \forall t \in T, \forall h \in H \tag{7}$$

$$0 \leqslant D_{EV}^{(t,h)} \leqslant \bar{D}_{EV} \, . \, b^{(t)} \qquad \forall t \in T, \forall h \in H \tag{8}$$

$$\underline{E}_{EV} \leqslant E_{EV}^{(t,h)} \leqslant \bar{E}_{EV} \qquad \forall t \in T, \forall h \in H \tag{9}$$

To determine whether the EV is connected the network, a binary parameter *b* is defined for a given time period *t*. The parameter takes value 1 when the EV is connected to the network and value 0 when the EV is disconnected from the network.

$$b^{(t)} = \begin{cases} 1, if\ the\ EV\ is\ connected\ to\ the\ LVDN\ at\ time\ instant\ t \\ 0, otherwise \end{cases} \tag{10}$$

The energy stored in at each EV at a certain period *t* is calculated based on the state of charge of the EV on the previous period *t-1* and the charge and discharge of the EV on the current period *t*, taking into account the charging and discharging efficiency of the EV, following this expression:

$$E_{EV}^{(t,h)} = E_{EV}^{(t-1,h)} + \eta_{EV}^{c} \cdot C_{EV}^{(t,h)}\Delta t - \left(\frac{1}{\eta_{EV}^{d}}\right) \cdot D_{EV}^{(t,h)}\Delta t \qquad \forall t \in T, \forall h \in H \tag{11}$$

Regarding the Peer-to-Peer exchange of energy, the energy imported of prosumer *h* from peer *p* is the same as the energy exported of peer *p* to prosumer *h*, considering the efficiency of the energy exchange, that represents the losses on the network due to energy transmission [3].

$$I_{p}^{(t,h\leftarrow p)} = \psi^{P2P} \cdot X_{p}^{(t,p\rightarrow h)} \qquad \forall p \neq h \tag{12}$$

Considering the houses with DERs, the total energy exported to other members of the community must be the same as sum of the energy imported from that certain house in period *t*.

$$X^{(t,h)} = \sum_{p\neq h} X_{p}^{(t,h\rightarrow p)} \qquad \forall t \in T, \forall h \in H \tag{13}$$

The opposite consideration is expressed in equation 14. The total energy imported for a defined house in period *t* must be the same as the sum of the energy imported from other members of the community.

$$I^{(t,h)} = \sum_{p \neq h} I^{(t,h \leftarrow p)} \qquad \forall t \in T, \forall h \in H \tag{14}$$

To establish the balance of the peer-to-peer trade among members of the community, the exports of all houses must be equal to all the imports considering the loss factor in the network [3].

$$\sum_h \psi^{P2P} \cdot X^{(t,h)} = \sum_h I^{(t,h)} \qquad \forall t \in T \tag{15}$$

As previously mentioned, these 15 equations reflect the most general variation of the optimization model. Some of them are neglected or included depending on the case study examined and the number of DERs involved in each simulation.

4. Case Studies

To fulfil the objectives of the thesis, several cases are going to be formulated to conduct the simulations on MATLAB regarding different scenarios for distributed energy resources. The model considers the installation of DERs randomly in some of the customers, as stated in Table 2. The DERs considered are PV, ESS and EVs. From the obtained results, conclusions are drawn regarding the impact of electric vehicles as demand response mechanisms on the grid. In Table 4, there is a summary of DERs included in each one of the simulations.

DERs	PV	ESS	EV Charging	EV Discharging	% EVs
Case 1: No DERs	No	No	No	No	0%
Case 2: PV	Yes	No	No	No	0%
Case 3: PV & ESS	Yes	Yes	No	No	0%
Case 4: PV, ESS & EV charging	Yes	Yes	Yes	No	33%
Case 5: PV, ESS & EV Charging and Discharging	Yes	Yes	Yes	Yes	33%
Case 6: PV, ESS & EV Charging and Discharging - More Connection Time	Yes	Yes	Yes	Yes	33%
Case 7: PV, ESS & EV Charging and Discharging - 100% EV Penetration	Yes	Yes	Yes	Yes	100%

Table 4 Case studies

4.1. Case 1: No DERs

This is the initial case of the simulations. Thus, this case study acts as a reference and base case for the following case studies. No DERs are included in this simulation. Consequently, the only possible way to meet the demand is to import energy from the bulk power system. Therefore, the resulting effects and benefits of the integration of distributed energy resources on the network may be analyzed.

4.2. Case 2: DERs - PV

The second case study included in the master's thesis includes only PV in the customers specified previously in Table 2. The energy produced by the PV installed may be used to cover the demand at that same moment, exported to help other peers meet their demand or exported to the grid and sold to the retailer to obtain a profit if demand is covered and there is no need for more electricity. The impact of PV in energy communities is examined using the case study.

4.3. Case 3: DERs - PV & ESS

This case study includes the same distribution of PV resources among customers, as well as battery energy storage systems in customers also specified in Table 2. Storage systems allow customers to storage surplus energy and use it in periods when prices are higher and renewable generation decreases. The combined benefits of PV and ESS are analyzed in this case study, to quantify the minimization of costs compared to other case studies.

4.4. Case 4: DERs - PV, ESS & EV charging

These resources are allocated among consumers as stated in Table 2, including PV, ESS and EVs. The simulation of electric vehicles only contemplates the possibility of charging the EVs efficiently. In this case, EVs cannot discharge to provide efficiency services to the grid. This case is used to study the benefits of DERs and quantify the energy savings. It is also used to analyze the Vehicle-to-Grid integration on the LVDN.

4.5. Case 5: DERs - PV, ESS & EV charging and discharging

For this case, the model considers the exact same distribution of DERs among consumers specified in Table 2. PV and ESS are modelled in the same way as in previous cases. However, in this case, EVs may charge their batteries when the prices are low and act as demand response mechanisms, with the possibility of providing energy from their batteries to cover the demand of their own needs or export the electricity to other consumers or the grid. EVs are connected to the grid from 6 p.m. to 8 a.m.

4.6. Case 6: DERs – PV, ESS & EV charging and discharging – More Connection Time

This case is similar to case 5. It includes DERs and the electric vehicles' batteries can be charged and discharged depending on the needs of consumers. However, the time that EVs are connected to the network and can provide grid services has been increased in 4 hours, from 2 p.m. to 8 a.m. Comparing this case with Case 5, the efficiency of having more energy capacity available is examined.

4.7. Case 7: DERs – PV, ESS and EV Charging and Discharging – 100% EV

Finally, in the last case study, the distribution of PV and ESS among customers is the same as in the previous scenarios, shown in Table 2. However, every single customer has an EV that allows them to store energy. This scenario is supposed to simulate the future that energy communities may hold, as EVs tend to be more present in our households. The EV can also be charged and discharged. The hours that EVs remain connected to the grid is the from 6 p.m. to 8 a.m.

5. Results and Discussion

This section presents and analyses the results obtained in the simulations performed. Although the optimization problem is performed for a whole month, only the results for the first 48 hours are going to be displayed, so that clearer and more detailed analysis can be made, as the simulations show similar behaviour and results for the remaining days of the simulations, not affecting the validity of this analysis. Moreover, to verify that the simulations are carried out correctly, the optimization problem has been solved in an incremental way, from the simplest scenario with no distributed energy resources to the most complex scenario, which includes PV, ESS and EVs. As stated above, the order of the simulations starts considering no distributed energy resources, followed by the simulation including PV. In case 3, storage systems complement PV production. In case 4, EV charging is introduced and in cases 5 to 7, all DERs are incorporated, considering both EV charging and discharging.

Since the results depend on the location of the customer and the DERs installed in each of the houses, the most complete scenario is going to be presented, which corresponds to customer 53 in the LVDN. Customer 53 includes PV, ESS and EV. The demand profile of customer 53 is shown in the Figure 6.

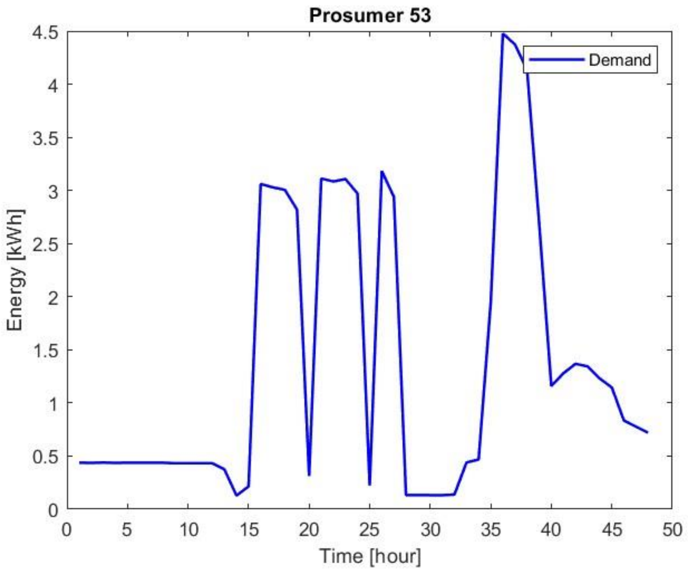

Figure 6 Demand profile of customer 53

The demand profile of customer 53 shows a constant demand of 0.5 kW during the first 15 hours. Then, there are three peaks of demand of 3 kW approximately, with a duration between two and three hours, each of them separated by an hour with a low demand of 0.5 kW. After these peaks, the demand decreases below 0.5 kW around hour 30, followed by a sudden increase of the demand to its highest peak in hours 36 and 37, almost reaching 4.5 kW. Finally, it decreases to values around 1 kW from hour 40 onwards.

In the following sections, the results for the presented cases are represented.

5.1. Case 1, 2, 3 and 4: No DERs, PV, PV& ESS and PV, ESS & EV charging

The analysis of the results and the comparison between case 1 without any resources and cases 2,3 and 4 including DERs is going to be performed in this segment. As previously stated, the simulations have been executed incrementally from the simplest to the most complex case. The chosen customer for the analysis is customer 53, with photovoltaic, battery energy storage systems and an electric vehicle.

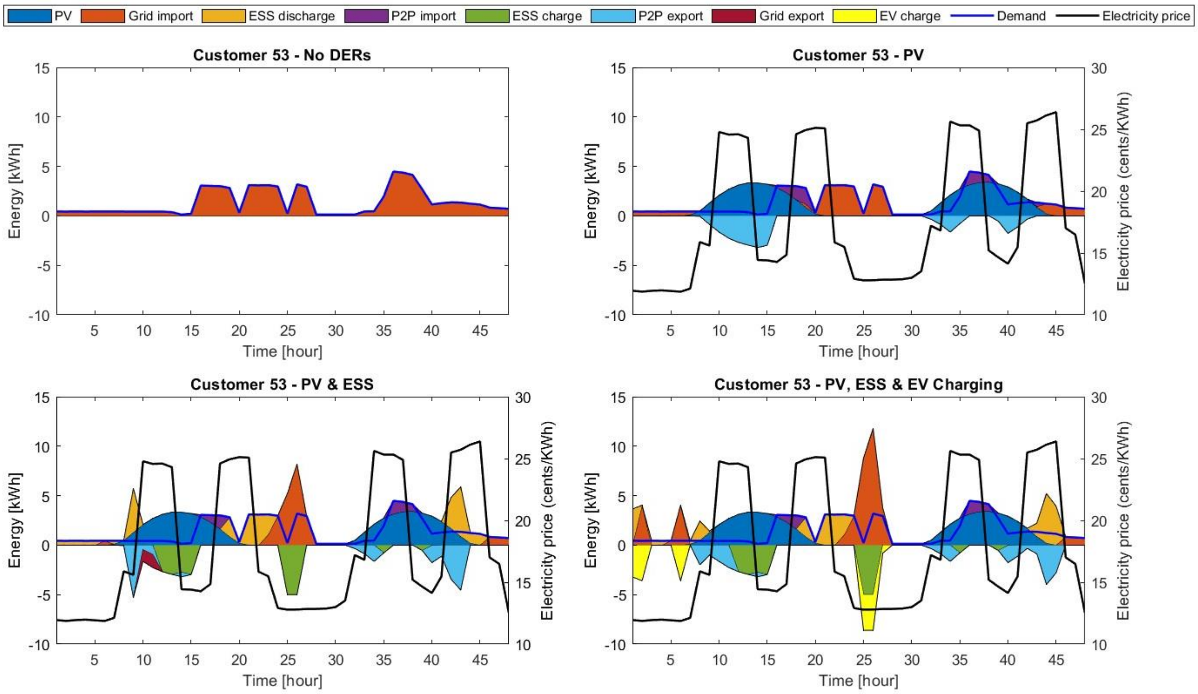

Figure 7 Results of customer 53 for scenarios a) No DERs b) PV c) PV & ESS and d) PV, ESS and EV Charging

The first hypothesis considered for this study is the simulation of the LVDN without any DERs, as if the energy community does not exist. Taking into account that there are no other resources that generate energy, the only option is to import the energy from the bulk power system.

As shown on the top left graph, the demand of consumer 53 is fully covered by the energy imported from the grid.

The top right graph represents the second simulation that considers only PV as distributed energy generation from the installation of solar panels on the rooftop of consumer 53. The PV production is represented in dark blue, following a standard solar profile for the city of Madrid. Naturally, the photovoltaics only produce during the day, between 9 am and 8 pm approximately, considering that the simulation has been performed for July. In the hours when there is still no sunlight, and consequently, no production from the solar panels, the demand is completely covered by the energy imported from the grid.

However, during the day hours there are two possibilities: if the demand is lower than the PV production, the demand is fully covered by the PV production and the surplus energy is exported. If the demand is higher than the PV production, part of the demand is covered by the PV production and the remainder is covered by imported energy. Considering the description of the model, the surplus energy is preferably exported to other members of the community, since producers can sell it at a higher price than they would sell it to the retailer and consumers buy it cheaper than they would do it from the bulk power system. Consequently, as shown in the graph, the excess of energy is mainly exported to other customers. On the other hand, when there is lack of energy, the customer imports from peers when there is surplus energy during the daytime. If there is no energy available, the energy is imported from the bulk power system.

On the bottom left side, the results for the third simulation are shown. This scenario contemplates the installation of PV as well as batteries, so that the energy that is not consumed at the moment can be stored for future usage, whether for their own consumption or to export it to other members of the community when prices are higher. To examine the proper allocation of the energy, the electricity price has been represented in black on the secondary axis on the right of the graph. The initial battery state of charge for customer 53 is 10 kWh. Since the state of charge of the battery is initially charged in more than a 75%, this energy is used to cover most of the demand of customer 53 for the first hours of analysis until hour 8, since the demand is really low. Between hours 5 and 6, the demand is covered by energy imported from the grid because the electricity prices are low, below 15 cents/kWh. It is more efficient to save the energy available in the battery to use when the prices tend to increase. Consequently, in hour 9 there is a peak in peer-to-peer exports as electricity prices start to rise above 15 cents/kWh. After this hour, the solar generation starts to increase and covers the demand. The surplus energy is mainly stored in the battery (shown in green), while the remaining energy is exported to other peers or to the grid and sold to the retailer.

From hour 15 onwards, the demand of customer 53 starts to increase at the same time that the solar profile is decreasing. As the graph depicts, from hour 16 to hour 19, the demand is supplied by the solar generation and imports from other peers (shown in purple). When electricity prices rise, instead of importing energy from peers, the battery supplies the demand with their needs. When the electricity prices decrease after hour 22, the customer benefits from the low prices and imports energy from the bulk power system to meet the demand and charge the battery for future more expensive periods.

The second day of the simulation is similar to the first one. Most of the demand is covered by the solar production. Since the battery has been previously charged during the previous night with low prices, most of the excess energy is exported to other peers (shown in light blue). Between hours 36 and 38, the demand is higher than the PV production, so energy is imported from other members of the community since there are customers that cannot rely on batteries, and these are the hours of the highest solar production. Finally, from hour 40 up to hour 48, the batteries are used to meet the demand and supply energy to other customers when the electricity prices are high.

Finally, the bottom right graph shows the most efficient energy allocation for the PV, ESS and EV charging scenario. As stated before, in this case the EV can only be charged and cannot act as a demand response mechanism. The initial battery state of charge of customer 53 is 10 kWh, same as in the previous scenario. The initial EV battery state of charge of customer 53 is 8 kWh. Considering that EVs battery capacity is 24 kWh, the constraints express that the EV must be, at least, at a 75% of their total capacity (18 kWh) by 8 a.m., with the lower limit of state of charge of the EV's battery being 4,8 kWh to guarantee the durability and functionality of the battery. The EV has some energy stored from the starting point of the simulation to provide support for the customer itself or other customers. However, given the circumstances of this case, the EV can only be charged so it cannot discharge as the ESS.

As seen in bottom right graph, during the first 8 hours of the simulation when the energy prices are low and the demand of most customers, including customer 53, is low, the EV is charged using energy from the BESS but mainly imported from the grid. From hour 8 onwards, the electricity prices increase. Also on hour 8, the PV starts to generate electricity. During the first hours of PV when production is still low but prices are high, the batteries export energy so that other community members can meet their needs. When the PV production is already high, customer 53 can cover its demand, store the surplus energy in the BESS and later export it to other community members.

From hour 15 onwards, demand starts to rise as the PV production starts to diminish. Consequently, while the prices are still high, the demand is covered by energy imported from other members of the grid who are not using it and by the energy stored in the batteries of consumer 53. After hour 24, when electricity prices are low, below 15 pence/kWh, the demand is met by energy imported from the grid. Furthermore, consumer 53 takes advantage of the low electricity prices to charge the EV and the BESS.

On the second day of the simulation, the results are very similar. The excess of energy from PV production that the consumer does not need to meet its demand is exported to other customers or stored in batteries. If the demand is higher than the energy obtained from the solar panels, electricity is imported from peers with surplus. Finally, when PV production decreases there are two possibilities. If electricity prices are high, the demand is covered with energy from BESS and the excess is exported to other peers. If electricity prices are low, the customer imports energy from the bulk power system to meet its demand.

5.2. Case 4: DERs - PV, ESS & EV charging and Case 5: DERs - PV, ESS & EV charging and discharging

This scenario is studied to analyze and compare the impact of the EVs as active resources that can provide grid services using Vehicle-to-Grid technology. This way, not only can EVs adapt their charging to the hours where there is high renewable energy penetration or low prices, but also can act as if they were BESS, storing energy when there is surplus or prices are low and providing it to consumers when prices and demand are higher. Consequently, the nature of this hypothesis is similar to the integration of ESS as EVs incorporate batteries. This simulation also includes constraints regarding the state of charge of the battery. The battery must be, at least, at a 75% of their total capacity (18 kWh) by 8 a.m. so that customers can use their EV in the morning. Additionally, the lower limit of state of charge of the EV's battery is limited to 4,8 kWh to guarantee the durability and functionality of the battery. However, during the time that EVs are connected to the grid, they may charge and discharge to efficiently allocate energy while minimizing the costs for the end-users.

The optimal results obtained in the simulations for customer 53 are shown in Figure 8.

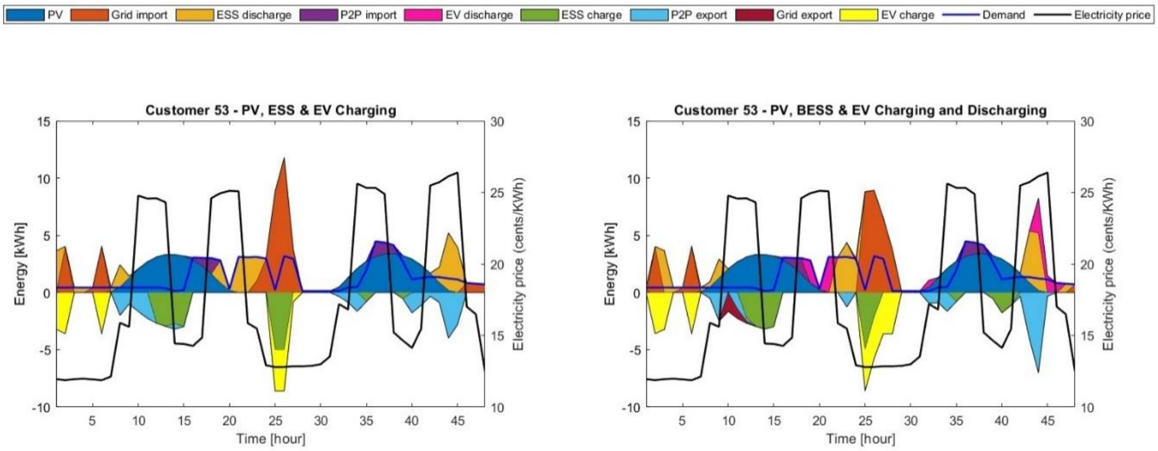

Figure 8 Results of customer 53 for scenarios a) PV, ESS and EV Charging and b) PV, ESS and EV Charging and Discharging

The graph represented on the left side shows the results of the energy allocation and management of customer 53 including PV, BESS and EV charging. The results are the same presented as in section 5.1.

As mentioned previously, in this scenario, the electric vehicle (EV) can only be charged and cannot serve as a demand response mechanism. Customer 53 begins with a battery state of charge of 10 kWh, consistent with the previous scenario, while the EV starts with an 8 kWh battery state of charge. Considering that the EV's battery capacity is 24 kWh, it must reach at least 75% of its total capacity (18 kWh) by 8 a.m. so that customers can use it, with a minimum state of charge of 4.8 kWh to ensure battery durability and functionality.

During the initial 8 hours of the simulation, when energy prices are low and demand is minimal, the EV primarily charges using energy from the bulk power system but also ESS. From the 8th hour onward, electricity prices rise, and solar panel (PV) production begins. Initially, when PV production is low but prices are high, batteries export energy to support other community members. As PV production increases, Customer 53 can meet its demand and store excess energy in the ESS.

Starting from the 15th hour, as demand rises and PV production declines, high-priced electricity is sourced from grid peers with surplus energy and from Customer 53's battery storage. After the 24th hour, when electricity prices drop below 15 cents/kWh, energy demand is met by importing from the grid, and Customer 53 utilizes the low prices to charge both the EV and the BESS.

On the second day of the simulation, similar patterns emerge. Excess PV energy not needed by Customer 53 is either exported to other customers or stored in batteries. If demand exceeds solar panel production, electricity is imported from peers with surplus. As PV production decreases, two scenarios unfold: during high electricity prices, energy is sourced from the BESS with surplus exported, while during low prices, grid energy is imported to meet demand.

On the right side there is the graph showing the results of the simulation allowing EVs to charge and discharge to provide additional services and minimize the cost for the energy community. As it is verified in the following explanation, the EV is charged in periods with low prices or surplus energy and is discharged when prices are high, managing the DERs production more efficiently within the energy community.

The initial hypothesis is the same as in the previous scenario. The initial state of charge of the ESS of customer 53 is 10 kWh and the initial EV battery state of charge of customer 53 is 8 kWh, meaning that at the starting point of the simulation there is some stored energy available to avoid grid imports.

During the first 8 hours of the simulation, prices are low, so the demand is met by electricity imports from the bulk power system and by the initial energy stored in the BESS. As a result of the low prices, the EV is charged to reach the minimal state of charge of 18 kWh at 8 a.m. When the solar production starts to increase from the 8th hour onwards, the energy distribution is similar to the left scenario. The demand is covered by the PV production, and the excess energy is either stored in the BESS or shared with peers in the community. However, since in this simulation there is more storage capacity because of the EVs being able to discharge during certain periods of the day, more customers have this flexibility to use it in their favor. Consequently, as ESS contribution may be smaller and less energy is shared among customers, there are some grid exports.

At hour 15, the demand rises to 4 kWh approximately as the PV production starts to slow down and prices increase. The demand is met by imports from other members and by discharging the EV batteries instead of the ESS. Therefore, this customer can now use the energy from the ESS system in the following hours, between hour 21 and 25, reducing the amount of energy imported from the bulk power system and reducing costs. From hour 24 onwards, the prices are low, and the EV and the ESS recover the energy used in previous hours with electricity from the bulk power system.

During the second day of the simulation, the energy allocation is similar to the first day. The energy for the solar panels is used to meet the demand, with the surplus being exported to other peers or stored for future use. Between the 36th and the 38th hours, the demand exceeds the PV production. To cover the demand during this period, energy is imported from other peers who do not have resources to store the surplus as the energy prices are high. These results are similar to the previous simulation.

When the solar production decreases, between hours 42 and 45, electricity prices reach their peaks, so customer 53 covers its own demand with the energy stored in its EV and BESS. Since these distributed energy resources have charged their batteries during the night, they export energy to other members of the community during these expensive hours of electricity, minimizing the cost for the entire energy community. The energy exports during these final hours are higher than in the left scenario, which mean that other members are benefiting from these exports at lower prices instead of importing from the bulk power system, reducing the overall costs.

In these simulations, it is possible to use the energy stored in the ESS or the EVs. The ESS may be used all the time, but the EVs may be used only when they are connected at their charging point. When both resources are available, there may be some questions on which one is better to use. Based on their availability, the ESS are better since they do not have any restrictions on their state of charge at any certain time, contrary to EVs which must be at their 75% of their maximum capacity by 8 a.m. Given that the efficiency of EVs and ESS is the same, the decision is mainly based on the availability.

5.3. Case 5: DERs - PV, ESS & EV charging and discharging and Case 6: DERs – PV, ESS & EV charging and discharging - More Connection Time

In this scenario, two different scenarios are studied to analyze the impact of the EVs charging schedule in the low voltage distribution network. The EVs are able to charge and discharge their batteries in both scenarios. The first scenario is the same that was presented in the previous section. The charging schedule for EVs in this scenario is from 6 p.m. to 8 a.m, which approximately corresponds to eight working hours and commuting time from home to the workplace. In the second scenario, the charging schedule is extended. The EVs are connected to the grid from 2 p.m. to 8 a.m. of the following day, so it is possible to manage the energy more efficiently since more storage capacity is available for more time.

This simulation incorporates restrictions concerning the battery's state of charge. The battery needs to reach a minimum of 75% of its total capacity (18 kWh) by 8 a.m., enabling customers to utilize their electric vehicles in the morning. Furthermore, the EV's battery state of charge must not fall below 4.8 kWh to ensure the battery's longevity and operational effectiveness.

The optimal results obtained in the simulations for customer 53 are shown in Figure 9.

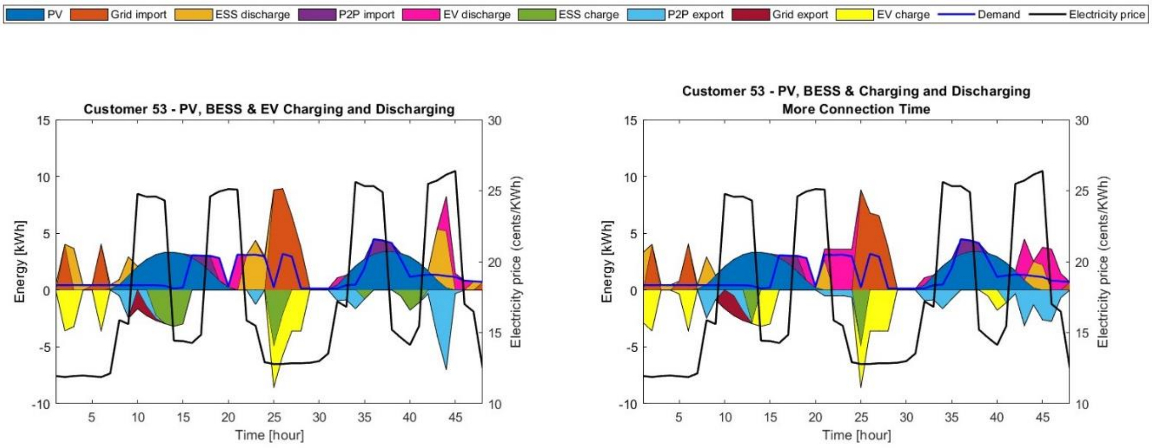

Figure 9 Results of customers 53 for scenarios a) PV, ESS and EV Charging and Discharging and b) PV, ESS and EV Charging and Discharging - More Connection Time

Firstly, in the left graph the results for the initial charging schedule (from 6 p.m. to 8 p.m.) are represented. During the initial 8-hour phase of the simulation, when prices are low, demand is satisfied through electricity imports from the bulk power system and the initial energy reserves stored in the Energy Storage System (ESS). This low-price period allows the electric vehicle (EV) to be charged sufficiently to attain a minimum state of charge of 18 kWh by 8 a.m. As solar production increases from the 8th hour onward, a distribution pattern similar to the previous scenario emerges: PV production covers demand, with surplus energy either stored in the BESS or shared among community peers. However, in this simulation, the additional storage capacity provided by EVs enables more customers to retain surplus energy for later use, resulting in increased energy storage and reduced inter-customer sharing, leading to some grid exports as less energy from ESS is used.

At around the 15th hour, demand increases to approximately 4 kWh as PV production slows down and prices rise. This demand is met by imports from other community members and by discharging the EV batteries rather than the ESS. Consequently, the energy stored in the ESS becomes available for use in subsequent hours (between hour 21 and 25), reducing grid imports and costs. From the 24th hour onward, prices drop, allowing the EV and BESS to recover the energy utilized in previous hours using grid electricity.

On the second day of the simulation, energy distribution mirrors that of the first day: solar panel energy meets demand, with surplus either exported or stored. Between the 36th and 38th hours, demand exceeds PV production, needing energy imports from peers without surplus resources due to high energy prices.

As solar production decreases between hours 42 and 45, electricity prices peak. During this period, Customer 53 meets its demand using energy stored in its EV and BESS. Since these distributed energy resources charged their batteries overnight, they export surplus energy to other community members during these costly electricity hours, thereby minimizing costs for the entire energy community.

In the second simulation represented on the left graph, the energy allocation problem is solved. In this scenario, customers with EVs are connected longer to the grid so they have more capacity to store energy when there is surplus or prices are low. In the first 8 hours, electricity is imported from the bulk power system, since prices are at their minimum. Moreover, the EV is charged so that end-users can use it in the morning, taking advantage of the low prices.

Between the 8th and the 15th, the solar panels are producing enough electricity to cover the demand of customer 53. The surplus is shared with other customers with less resources or higher demands, stored in the ESS or the EV or exported to the grid. Taking into account that in the first hours of the simulation less energy from the ESS is used than in the preceding simulation, there is less capacity available to store the surplus from the PV panels. Therefore, more energy is exported to the grid than in the previous case. Nevertheless, since the EV is connected to the grid from the 14th hour onwards, the EV is charged using that excess energy from the solar production during the afternoon.

When the demand rises in the 15th hour and prices are still high, the demand is mainly covered by the EV, as it has just been recharged and is has no battery limitations until the following day. This effect was not as pronounced in the other scenario because the EV had not been charged during the day, so the ESS effect was more significant. As the prices decrease in hour 24, the ESS and EV are charged with the grid imports.

On the second day of the simulation, the energy allocation follows a similar pattern to the first day: solar panel energy fulfils demand, and any excess is either exported or stored. However, between the 36th and 38th hours, demand surpasses the production capacity of the solar panels. This requires importing energy from peers who lack surplus resources due to elevated energy prices.

In the final hours of the simulation, when the PV profile decreases, energy is exported to other peers using the ESS but mainly the EV batteries. The most noticeable difference between these two scenarios is that EVs usage as distributed energy resources has increased as they are longer connected to the grid. Furthermore, since all the customers have more capability to store energy longer, the peaks caused by peer-to-peer trading during the expensive hours have been reduced, as it is appreciated in the 44th hour. Energy imports peaks are stable.

5.4. Case 6: DERs – PV, ESS & EV charging and discharging and Case 7: DERs – PV, ESS & EV charging and discharging - 100% EV Penetration

Taking into account the European effort to achieve net zero emissions by 2050, the transportation sector is leading towards the electrification and electric vehicles are becoming more and more common among everyday users. Therefore, it seems relevant to study and compare the energy allocation situation that may arise in the future. In this section, two scenarios are going to be compared: the first scenario that includes the DERs specified in Table 2 with the EVs being able to charge and discharge. In the second scenario, EVs have also charging and discharging capabilities, but they are integrated in every consumer's resources, replicating a 100% EV integration in all the households.

The optimal results obtained in the simulations for customer 53 are shown in Figure 10.

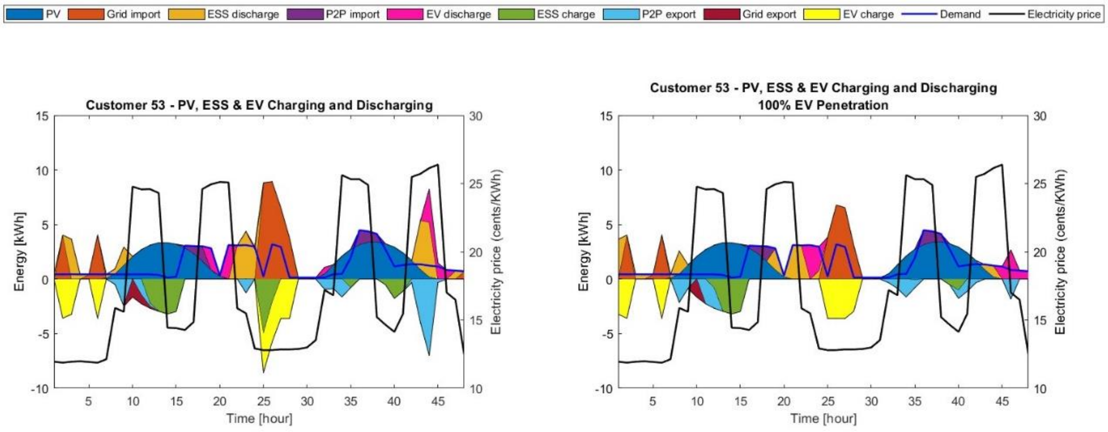

Figure 10 Results of customers 53 for scenarios a) PV, ESS and EV Charging and Discharging and b) PV, ESS and EV Charging and Discharging with 100% EV Penetration.

Initially, the left graph depicts the outcomes of the initial DERs' distribution defined in Table 2. During the initial 8-hour phase of the simulation, characterized by low prices, demand is met through electricity imports from the grid and the existing energy reserves stored in the storage system. This period of low prices facilitates the sufficient charging of electric vehicles to achieve a minimum state of charge of 18 kWh by 8 a.m. As solar production increases beyond the 8th hour, a distribution pattern similar to the previous scenario emerges: photovoltaic production meets demand, with any surplus energy either stored in the ESS or shared among community members. However, this simulation's additional storage capacity provided by EVs enables more customers to retain surplus energy for future use, resulting in increased energy storage, lower use of ESS and reduced inter-customer sharing, leading to some grid exports.

Around the 15th hour, demand rises to approximately 4 kWh as PV production slows and prices escalate. This increased demand is satisfied through imports from other community members and discharging the EV batteries rather than relying on the ESS. Consequently, the energy stored in the ESS becomes accessible for subsequent use (between hour 21 and 25), reducing grid imports and costs. Beyond the 24th hour, prices decrease, enabling the EV and ESS to replenish the energy utilized in prior hours using grid electricity.

On the second day of the simulation, the energy distribution pattern mirrors that of the first day: solar panel energy fulfills demand, with any surplus either exported or stored. However, between the 36th and 38th hours, demand surpasses PV production, needing energy imports from peers lacking surplus resources due to high energy prices.

As solar production declines between hours 42 and 45, electricity prices peak. During this period, Customer 53 meets its demand using energy stored in its EV and BESS. Since these distributed energy resources charged their batteries overnight, they export surplus energy to other community members during these costly electricity hours, thereby minimizing costs for the entire energy community.

On the other side are depicted the results for the simulation considering 100% EV penetration, including electric vehicles in every consumption point. The energy usage and distribution of customer 53 is almost identical to the preceding analyzed scenario, During the initial 8 hours of the simulation the minimal demand is covered, and the EV is charged by using the ESS but mainly the imports from the grid, as electricity prices are at their lowest level, below 15 cents/kWh.

The solar PV profile starts to increase from the 8th hour. During this period between the 8th and the 15th hour, the surplus energy left over from meeting the demand is exported to other peers, stored in batteries or exported to the grid if it is not needed. The ideal is to store as much energy as possible from renewable production to minimize the imports from the bulk power system, and use energy reserves during expensive electricity periods. As the demand of customer

53 increases at hour 16, it is covered using the same resources as in the previous simulation, but the allocation is different. Firstly, there are two hours with energy imports from other peers while the solar production is still significant. However, on the first simulation demand is covered using the energy from the EV followed by the battery, but on the second simulation the order changes, starting with the battery and followed by the EV. As previously stated, the efficiency of both ESS and EVs are similar, so it does not really have an impact on which is more appropriate to use.

The main difference that arises from the comparison of these two models is the decrease in energy imported from the grid and energy traded between members of the energy community. Considering that in the second scenario all the customers rely on an EV and have the ability to store, at least during some periods, and use the energy more efficiently regarding the energy prices and the optimal management, there is less need for grid imports (as customer 53 already had an EV in previous simulations). However, in customers that did not incorporate EVs in the other scenarios, the imports from the bulk power system are naturally higher.

Furthermore, members that previously did not have any distributed energy resources have gained independence from the grid as well as from other customers. They still depend on the energy from the bulk power system to charge the EV when prices are low, but the impact on the costs is much lower.

As an example, the results for Customer 10 are represented in Figure 11. On the left side, the graph shows the energy usage along 48 hours including solar PV, ESS and EV charging and discharging as DERs. As stated in Table 2, Customer 10 does not incorporate PV, BESS or the EV in this scenario, but in the second simulation every customer relies on the EV as a DER.

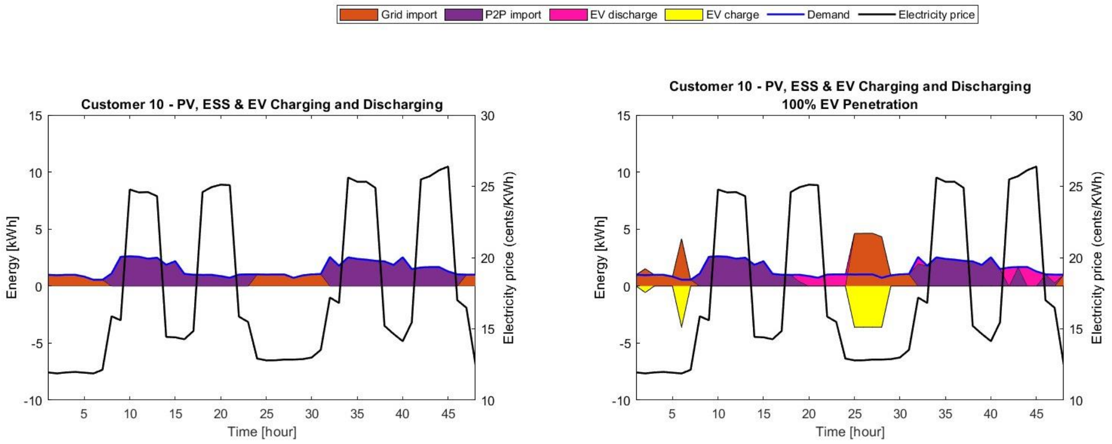

Figure 11 Results of customer 10 for scenarios a) PV, ESS and EV Charging and Discharging and b) PV, ESS and EV Charging and Discharging with 100% EV Penetration.

The two graphs shown regarding Customer 10 are considerably less complex to the ones of Customer 53, given the lack of DERs for Customer 10. As a consequence, the energy can only be imported from the bulk power system or from other members of the community. Taking into consideration the electricity prices, during the night when the energy is cheaper, electricity is imported from the bulk power system. During the day, given that the PV production is high and some consumers have surplus energy, electricity is imported from other members as peer-to-peer trade.

Alternatively, in the second simulation the energy allocation is quite different as the customer can charge and discharge the EV and use it in its favor. As a result, grid imports increase during the nights, since the EV has to be charged up to at least the 75% of its charging capacity by the morning. Nevertheless, the presence of the EV allows the customer to have more flexibility regarding the use of the energy. Hence, customer 10 can meet the demand for some hours by using the EV battery, reducing the dependence on the grid or other customers. Furthermore, the energy imports take place when electricity prices are at their lowest.

5.5.Energy allocation and cost analysis

Based on the previous exposition of the energy allocation along the different scenarios studied for this Master's Thesis in section 5, it can be seen that the greater the use of distributed energy resources, less are the costs for consumers in the energy community. In this segment, the evolution of grid consumption, grid production, traded energy and the costs incurred by customers is going to be examined to determine whether the proposed cases led to an effective cost minimization. The results are separated in two sections: the integration of distributed energy resources into the model following the cases' order, from no DERs, PV, PV & ESS and PV, ESS & EV charging in the first section, and the electric vehicles' scenarios in the second section.

Distributed Energy Resources' Integration

In Figure 12, the consumption from the grid is represented for the first 48 hours of the simulation with the electricity prices in the secondary axis on the right.

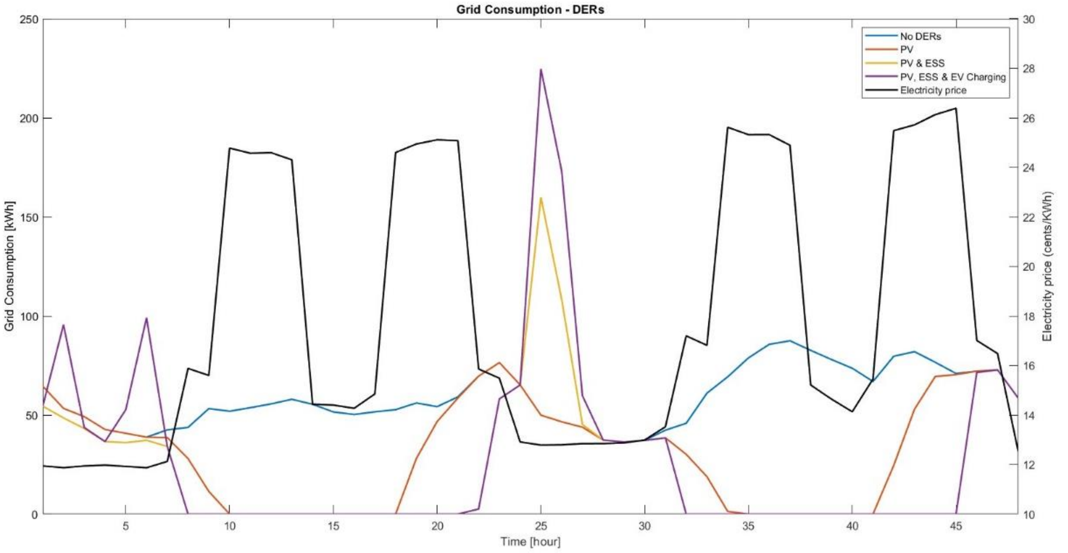

Figure 12 Grid Consumption - DERs Scenarios

Represented in blue is the base scenario where no distributed energy resources are included in the model. This base case shows the grid consumption needed to cover the entire demand for the energy community, equally represented by the aggregated demand curve of the 55 customers belonging to the low voltage distribution network.

Adding exclusively the photovoltaic resources to the simulations, the grid consumption exhibits a substantial reduction during the daytime (represented in orange), managing to cover all the demand of the energy community in these hours. However, when the solar resource disappears during the night, the grid consumption is exactly the same as in the base scenario with no DERs, as energy cannot be stored.

The third scenario showcasing grid consumption including PV and ESS is presented in yellow. Storage makes it possible to storage the energy and further decrease energy consumption more than in previous scenarios. The main changes in grid consumption are the increase in hours where electricity is not imported from the bulk power system, covering from 7 a.m. to 10 p.m. in the first day of the simulation. Precisely, this time is also when the electricity prices are higher, decreasing the overall costs for customers. Furthermore, peaks in grid consumption are seen during night hours when electricity from the grid has low costs and enable battery charging for future usage.

Finally, considering only EV changing and comparing the results to previous scenarios, a huge increase in energy consumption can be appreciated at nights. This effect is caused not only by the charging of batteries, but also from EVs, which must be, at least, at the 75% of their maximum capacity by 8 a.m. This increase in demand due to EV's integration implies that results cannot be compared to previous scenarios, but they imply similar benefits to the integration of ESS. Consequently, EVs are analyzed in the next section.

In Figure 13, the production of the low voltage distribution network towards the bulk power system is represented, that is to say, the energy exports.

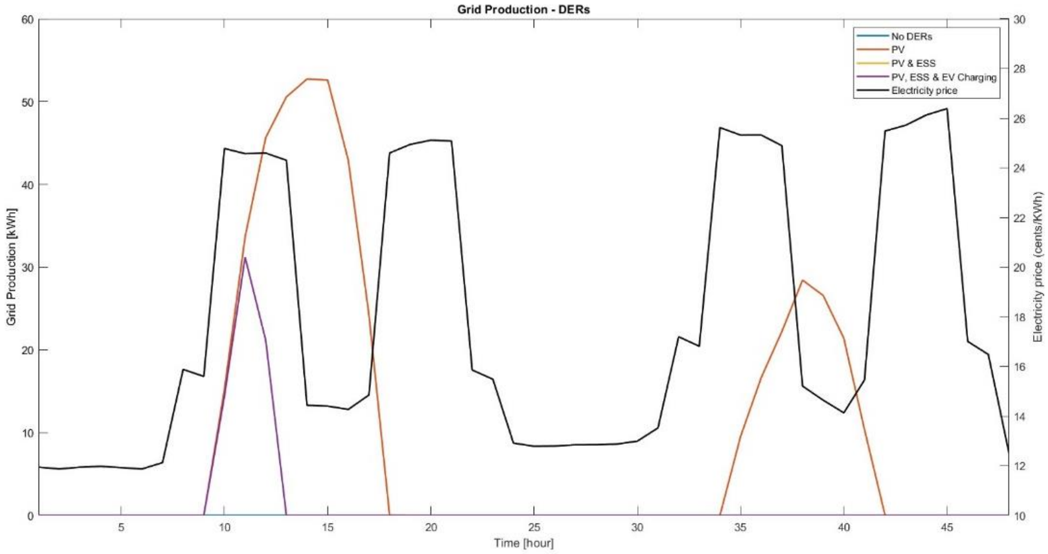

Figure 13 Grid Production - DERs Scenarios

For the base scenario represented in blue, where no distributed energy sources are considered, the energy exports are null, as there is no production means within the energy community. All the energy is imported from the grid.

The grid production shown in orange are the results integrating PV production in the model. This scenario showcases the biggest grid exports, reaching peaks higher than 50 kWh, since there are no storage facilities where the energy surplus can be stored. Consequently, the remaining energy not consumed must be sold to the retailer. Naturally, the periods where the energy exports take place are during the day, when the solar production is maximized.

The results of grid production for the third and fourth scenarios are identical. This is because EVs during these hours are not connected to the LVDN, so they cannot benefit from the solar production taking place. Moreover, EVs are only available for charging, but not for discharging, so they cannot act as batteries neither provide services to the grid. The energy exports peaks are reduced around a 40% from the preceding scenario, reaching around 30 kWh during the first day of the simulation. However, in the second day the storage capacity is not fully covered, as there are no energy exports to the grid.

The traded energy between peers within the energy community during the first 48 hours of the simulation is exhibited in Figure 14.

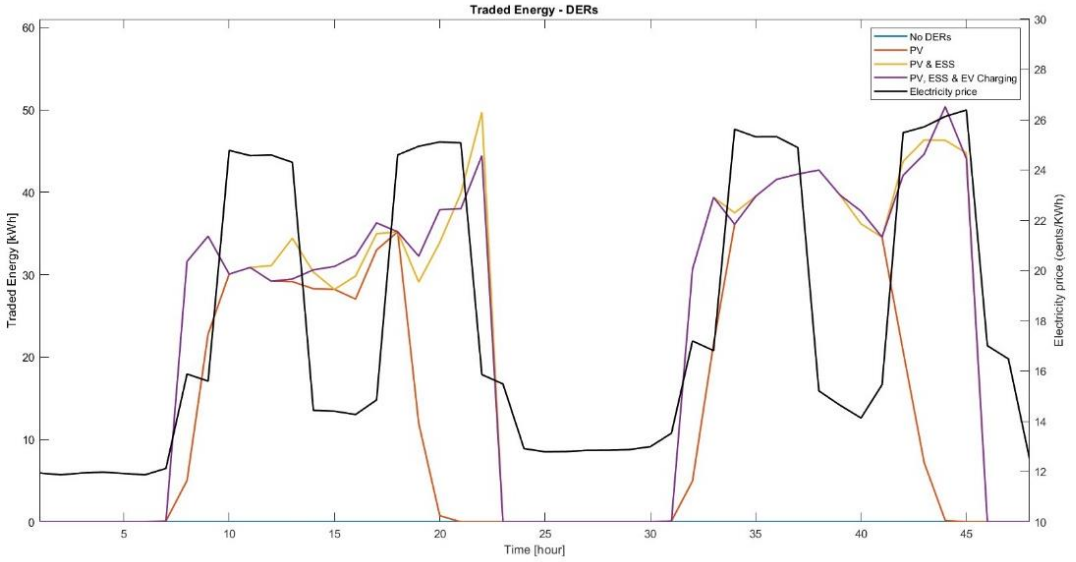

Figure 14 Traded Energy - DERs Scenarios

The previous graph is very important to evaluate the efficiency of the sharing mechanism of peer-to-peer trading. As in other figures, traded energy in the base case is impossible, because there are no resources for energy production in the community.

Secondly, represented in orange is the traded energy concerning PV integration in the low voltage distribution network. The energy trading is limited by the number of hours that the solar PV is producing. As seen before in Figure 12 and Figure 13, if the solar production is capable of providing all the electricity for the demand for the energy community, energy trading is maximized to avoid consumption from the grid, and the surplus is exported to the grid.

The third simulation refers to PV and ESS implementation in the energy community, whose results are depicted in yellow. The integration of batteries in the system makes it possible to store the excess energy to use it at different times. Thus, not only is energy traded when the PV systems are producing but also later in the evening and sooner in the morning. Moreover, energy is mainly traded when electricity prices tend to be higher, minimizing the cost for end-consumers. Despite the consumption levels, since electricity prices are really low during the night, it is not profitable to trade energy but rather import it from the grid anyways.

Finally, when considering EV charging along with PV and ESS, the results show a similar behavior of traded energy to the ones without EVs. During the hours that energy trading takes place, the EVs are not connected to the LVDN, so the differences are not significant. A very small part may be used to charge the EVs, but the majority of them are charged during the night taking advantage of the low electricity prices instead of traded energy. Notice that EVs use additional electricity and therefore the cost is higher in comparison when they are not considered.

To finalize the comparison between the DERs simulations, the quantitative results are featured in Table 5.

Results	No DERs	PV	PV & ESS	PV, ESS & EV Charging
Grid Imports (kWh)	47.229,00	24.567,00	21.874,00	26.323,00
Grid Exports (kWh)	0,00	4.580,00	851,91	851,91
Total Trade (kWh)	0,00	11.112,00	15.688,00	15.678,00
Peak Grid Consumption (kWh)	105,91	88,36	164,16	228,96
Grid Supply Percentage (%)	100,00	52,02	46,31	55,73
DERs Supply Percentage (%)	0,00	47,98	53,69	44,27
Total Cost (€)	7.622,40	3.324,75	2.592,35	3.106,35
Grid Import Cost (€)	7.622,40	3.741,70	2.672,90	3.186,90
Grid Export Revenue (€)	0,00	416,95	80,55	80,55

Table 5 Results of DERs integration

Taking the first case with no DERs as a reference, it is remarkable to examine the huge impact that installing PV systems in energy communities with peer-to-peer trading may have for the members of the community. Solar production is able to cover almost the 50% of the total demand of the energy community, reducing the grid imports by 48%, leading to a 56,38% reduction of total costs. Furthermore, grid exports are substantial considering that there is no storage capacity available in this simulation, Thus, additional revenues of 416,95 € are obtained from the grid exports sold to the retailer.

However, when introducing the ESS into the low voltage distribution network, the energy allocation is optimized, resulting in lower grid imports and exports, but higher energy traded. Grid imports are reduced on a 11% as a result of a 41% increase in energy traded due to the storage capabilities. Exports are substantially reduced on an 81,40% compared to the only PV case. Therefore, DERs are capable of supplying the 53,69% of the total demand of the energy community while also decreasing the total cost for customers an additional 22%.

The results for the last scenario including EV charging show similar results to the previous one in terms of grid exports and traded energy. However, the integration of EVs implies a higher demand as EVs act as a load. As a consequence, grid imports, as well as costs, increase approximately 20%. In depth analysis of EV integration is executed in the following section.

The evolution of peak grid consumption must be also revised, since it increases almost the 50% from the second to the third scenario and an additional 40% in the fourth scenario. This effect may be clearly seen in Figure 12, and is produced by the energy consumed at night to charge ESS and EVs. It is relevant to evaluate the impacts that these demand peaks may cause in the optimal operation of the low voltage distribution network.

To clearly see the effect of the integration of electric vehicles in the network, analyze and compare the impact on the behavior and costs, the following section is presented.

Electric Vehicles' Integration

In Figure 15, the consumption from the grid is represented for the first 48 hours of the simulation. In this segment, apart from the different EV charging and discharging assumptions, all the scenarios consider PV and ESS.

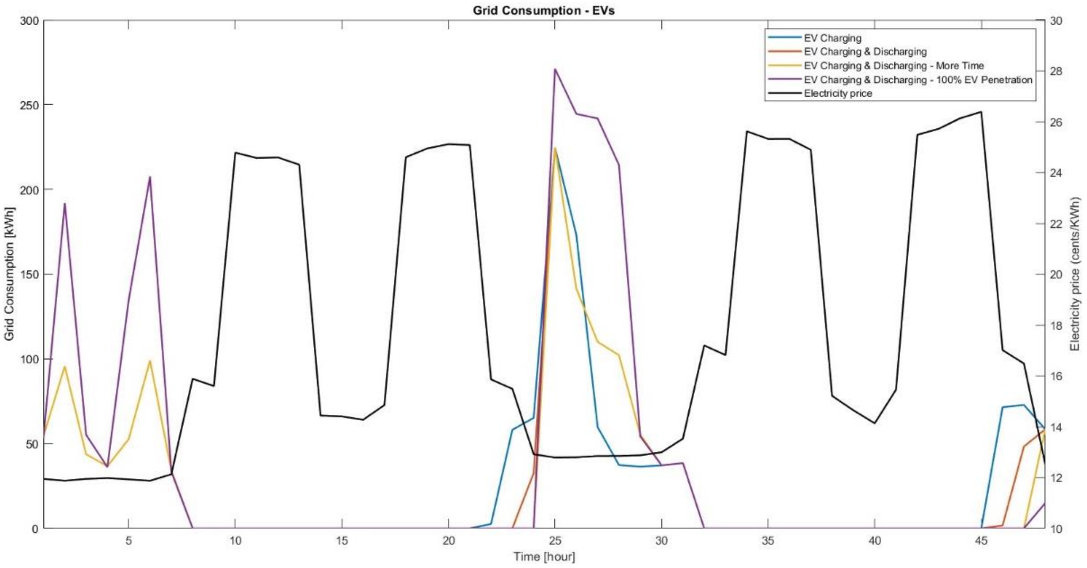

Figure 15 Grid Consumption - EVs Scenarios

The first scenario presented in blue only considers EV charging, without EVs being able to store energy for later use. There is no grid consumption during the periods of solar production, but there is high demand during nighttime to charge EVs batteries, taking advantage of low electricity prices.

In orange, EV discharging is also possible. The ability of discharging makes it possible to even store energy similarly to storage systems, but only when the EVs are connected to the LVDN. Therefore, imports in this scenario are a little bit higher than considering only EV charging, as they must recover the energy discharged from the EV batteries. These imports take place during the night as electricity prices continue to be low.

On the third scenario shown in yellow, where EVs are connected to the grid 4 hours more than in the previous case, the grid consumption patterns are very similar. The effect over the grid consumption is a minimal decrease in consumption from the grid, as the remaining energy of EVs when the connect to the network can be used for consumption or trading, but they are not going to be charged during this first hours of connection as energy prices are higher.

Finally, on the last case assuming a 100% EV penetration, the grid consumption is significantly higher due to EV charging demand. The outcome of the demand increase results in peak imports, especially at night. For a quantitative analysis, Table 6 is presented at the end of the section.

In Figure 16, the production of the low voltage distribution network towards the grid is represented, that is to say, the energy exports.

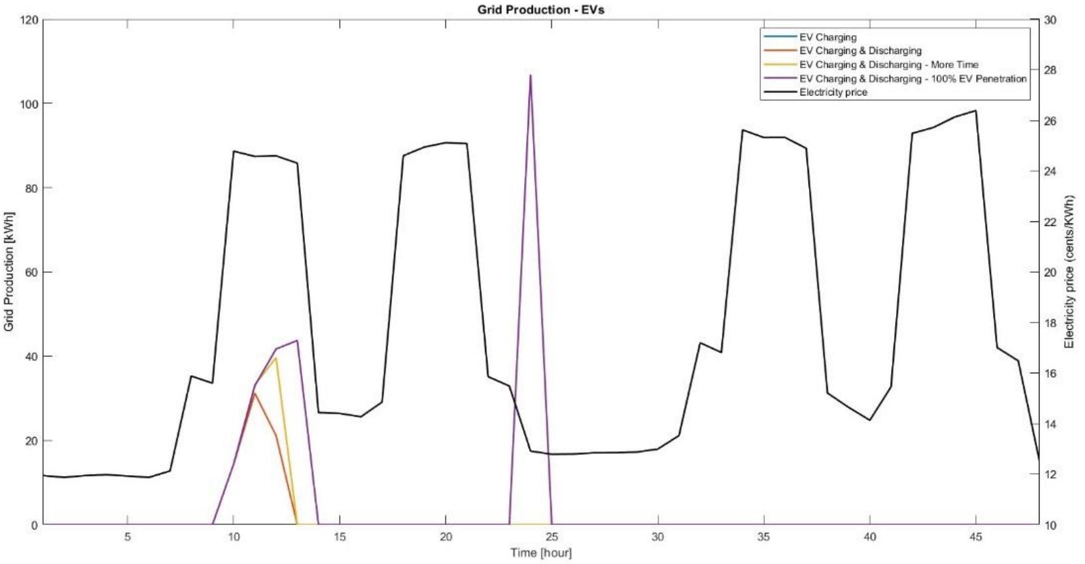

Figure 16 Grid Production - EVs Scenarios

Looking at the first two scenarios, regarding only EV charging and both EV charging and discharging, the grid exports are identical in the first hours of the simulation, and are mainly linked to the surplus energy of solar production. During the daytime, when PV production is maximized, the demand is covered exclusively by solar energy. Furthermore, during the day hours, the EVs are not considered to be connected to the grid, so the surplus energy cannot be used for EV charging. Thus, energy is exported.

When the EV connection time to the grid is increased in four hours, the results do not present much variation from previous scenarios. The energy exported slightly increases during the central hours of the day. Since EVs connection time is longer, they can provide energy for consumers with the remaining energy after their use, so less energy is needed, increasing the energy exports as it cannot be stored as ESS are full and EVs are not connected.

On the final scenario representing the total integration of electric vehicles in every customer, the energy exports keep increasing during the daytime of the first day of the simulation because there is more storage capacity since all households rely on EVs. However, there is also a spike in energy exports at the 24th hour, when the demand is lower at night. Despite the huge storage capacity that ESS and EVs hold, EVs only remain connected to the LVDN from 6 p.m. to 8 a.m. Depending on the DERs of each customer, there may be cases where it is more cost-effective to export energy and sell it to the retailer than trade energy stored from one customer to another storage facility of other peer, taking into account the efficiency of DERs.

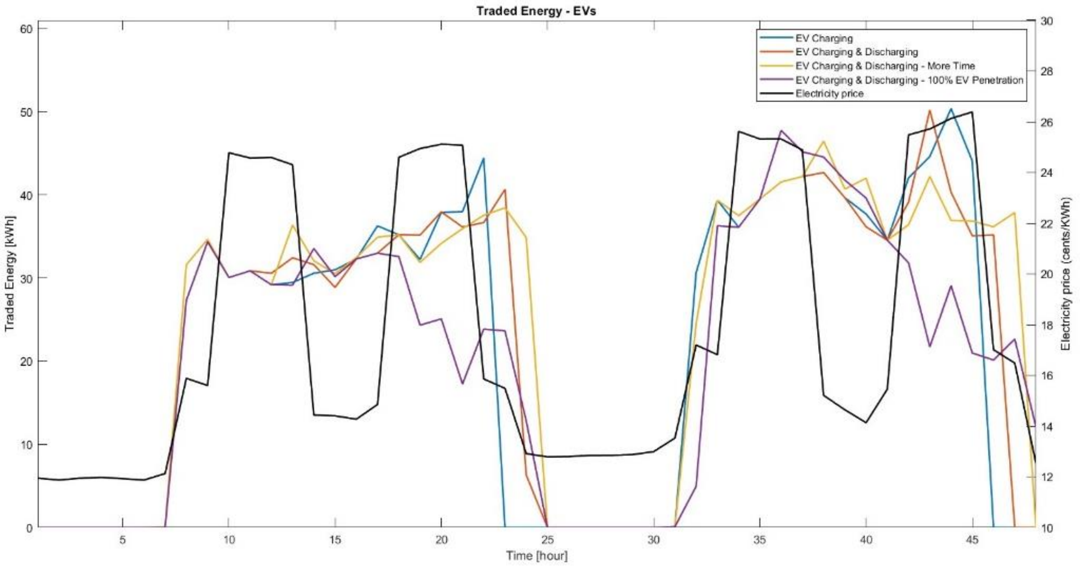

Figure 17 Traded Energy - EVs Scenarios

To finalize the comparison between the EVs simulations, the quantitative results are featured in Table 6 Results of EV integration, including the simulations for EV charging and discharging.

Results	EV Charging	EV Charging & Discharging	EV Charging & Discharging - More Time	EV Charging & Discharging - 100% EV Integration
Grid Imports (kWh)	26.323,00	26.621,00	25.522,00	37.919,00
Grid Exports (kWh)	851,91	927,17	1.342,50	3.091,20
Total Trade (kWh)	15.678,00	16.796,00	17.356,00	15.380,00
Peak Grid Consumption (kWh)	228,96	228,96	228,96	362,16
Grid Supply Percentage (%)	55,73	56,37	54,04	80,29
DERs Supply Percentage (%)	44,27	43,63	45,96	19,71
Total Cost (€)	3.106,35	3.007,28	2.767,72	4.057,81
Grid Import Cost (€)	3.186,90	3.095,70	2.896,20	4.359,90
Grid Export Revenue (€)	80,55	88,42	128,48	302,09

Table 6 Results of EV integration

The first column is going to be taken as reference for the comparison. The fourth scenario regarding the 100% EV integration is treated independently at the end of this section as it implies a considerably higher demand.

The results for the whole energy community show that grid imports slightly fluctuate from 25.500 kWh to 27.000 kWh. As might be first expected, the lower the grid imports are, the lower the total cost for the network customers. However, the relevant issue is not how much energy is imported from the grid, but when the energy is imported and consequently, which the cost of the energy is. Despite consuming more energy from the grid in the second simulation, the grid imports cost and the total costs are lower than in the first simulation, decreasing a 2,86% and 3,19% respectively.

Additionally, another critical factor must be considered to compute and examine these results. That is traded energy. Traded energy allows to minimize the costs because it maximizes the utilization of DERs. The implementation of Vehicle-to-Grid technology, allowing charging and discharging and introducing electric vehicles as active participants that can inject, consume and store power, increases energy trading in a 7,13% from the first to the second scenario. Moreover, since the EVs remain more time connected to the network, it enables more storage capacity and more energy traded. Therefore, peer-to-peer trading is even higher between scenarios 2 and 3, increasing an additional 3,33%.

The total cost for the low voltage distribution network not only depends on the energy imported from the grid and its costs, but also depends on the exports and the revenues obtained in exchange. As illustrated in Figure 5, the prices of the exports remain around 9 cents/kWh approximately, so the revenues mainly rely on the volume of energy exported. The energy exports are directly linked to the storage capacity of the DERs installed in the network. Similarly to the traded energy analysis, as more energy can be stored, more energy that is not needed nor can it be stored or used at certain times, is sold to the retailer. The energy exports increase in a range of 500 kWh from the first scenario to the third. As a result, in the first scenario, the revenues obtained from grid imports are 80,55€. This number is increased in a 9,78%, reaching an 88,42€ when EVs are able to discharge in the second simulation and an additional 45,61% at 128,48€ when EVs spend more time connected to the network.

Although it may seem that having EVs may enable a bigger coverage of the demand by using DERs, it does not necessarily have to follow this pattern, as the objective of the optimization model is to minimize the cost for the customers by importing at low prices, sharing the energy among peers and exporting at high prices. As an example, in the second case, the percentage of the demand that is met by using DERs is lower than in the first case, but the overall costs are lower.

Finally, the total cost to provide energy to all the members in the energy community is mainly determined by the cost of the grid imports. The cost of the grid exports is also considered important, but it has a small influence on the overall cost. Therefore, the scenario that minimizes the costs for customers is scenario 3, which includes PV, ESS, and EV charging and discharging for the longest time, resulting in a total cost of 2.896,20€. The costs for scenarios 2 and 1 increase an 8,66% and 12,33% respectively.

The last column of Table 6 displays the results of the fourth scenario included in the scope of this project. This scenario aims to simulate the energy optimization as if every customer had an electric vehicle. This integration results in a huge increase in the energy demand of the energy community, hence the results cannot be compared to the previous scenarios, although several conclusions may be made from them. The grid imports are obviously higher than in previous cases, as well as the exports. Regardless of these increases in imports and exports, traded energy decreases in comparison to the other scenarios, because in this simulation every customer relies, at least, on EVs to manage effectively their energy consumption, while in previous scenarios there were customers without DERs whose electricity must come from trading or imports. Now, every customer has the possibility to store energy during some hours of the day. Another effect on this scenario is the increase of a 58,18% in peak demand consumption, probably as a consequence of the huge energy consumption that takes place at night when all the electric vehicles are charging at the same time, benefitting from the low electricity prices. Eventually, the overall cost in this case is 4.057,87€, around a 37,4% more than in the other simulations.

6. Conclusion

There is no doubt that the integration of distributed energy resources is bringing numerous changes and challenges to power systems. There are many approaches towards the efficient operation of the distribution network including DERs. Different views can be held arguing which is the best scenario to introduce DERs into the grid, such as minimal costs for consumers, maximum traded energy, etc. but, generally, DERs bring benefits for end-consumers in terms of economic savings and energy efficiency when forming energy communities. Therefore, DERs should be a valuable option to take advantage of at a distribution level, not only photovoltaics or batteries, but especially electric vehicles.

The approach of community energy trading (CET) has arisen as a valuable option for the coordinated management of DERs, which still needs further investigation. Consequently, this thesis studies seven different scenarios that review different DERs integration schemes, based on a realistic LVDN in Madrid.

The analysis conducted has revealed the optimal energy allocation with the objective of reducing the total costs for the energy community, by minimizing energy imports from the grid, importing when the electricity prices are low and maximizing the utilization of storage systems and EV batteries for energy trading between members of the community.

Evaluating the scenarios without electric vehicles, the results show a reduction in total costs of more than a 50%, exhibiting the huge impact that only the introduction of PV can make in an energy community. These total costs reflect the grid import cost minus the revenues obtained from grid exports. Combined with ESS, the reduction in costs is further improved and additional 22%, obtaining the best results of all the simulations. It is important to highlight that these total costs do not include CAPEX investments and are calculated only in terms of the operation of DERs and the LVDN setting up the energy community. The current investment costs of storage systems may reduce the benefits of the case studies performed.

As a matter of course, the costs in the scenarios including electric vehicles are higher due to the increase in the demand that it entails. The minimal cost scenario is the one incorporating PV, ESS and EV charging and discharging with the higher availability to the low voltage distribution network, as the storage capacity of the electric vehicles can be used for providing grid services, improving flexibility.

On the last scenario regarding 100% EV integration, the minimal cost is also procured. Since all network customers own an electric vehicle, the total cost is evidently higher than in precedent cases. Despite this constraint and the increase in demand that also involves, the costs are minimized on a 47% respect to the initial simulation without DERs and considerably lower demand to cover, exhibiting optimal results for customers.

Therefore, the objectives of the thesis have been achieved. Community energy trading has been proven to be a profitable solution for energy communities to minimize their costs. It has also been demonstrated that the greater the availability of EVs combined with PV and ESS, the lower the costs for the energy community, as exhibited in the results of case 6.

7. Future Work

The work carried out in this thesis has been focused on the optimization of the energy allocation problem towards achieving the minimal costs for the members of an energy community, supporting the integration of distributed energy resources. However, the technical constraints and the repercussions of the energy allocation solution obtained for each of the simulations have not been examined in depth.

The model used to perform the simulations for the studied cases takes the demand profiles, the photovoltaic generation profile, import and export prices, and the attributes of each distributed energy resource as an input. The results of the optimization model are the customer's DERs dispatch individually and the net profiles of demand, imports, exports and traded energy, along with the costs. These outputs combined with the distribution and connection of customers on the LVDN may be used to perform a 3-phase power flow to evaluate the load stability parameters in the network, such as voltage unbalance at the connection point of every household, components loadings, and the voltage magnitude at the 3 phases.

After the performance of the power flow, the capacity of the lines would also be a relevant case for further study. Seen in Figure 12 and Figure 15, in some hours there are huge variations in energy imports, exports or traded energy among peers within the energy community. The results for peak grid consumption show spikes up to 362 kWh of energy imported from the grid at night, when all the EVs are connected to the grid and charging. It would also be of interest to study the distribution network lines to evaluate the congestion management that may arise due to the introduction of EVs into the grid and the load increase that it entails.

The case studies do not consider investment costs, which are crucial to compare the profitability of DERs. Furthermore, opportunities to participate with DERs in different electricity markets should be further explored.

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ANNEX A: Sustainable Development Goals

ALIGNMENT WITH THE SUSTAINABLE DEVELOPMENT GOALS

This Master's Thesis is intended to make an impact and face the challenges that will be relevant in the coming years in the energy sector. Consequently, it aligns with some of the Sustainable Development Goals established by the United Nations to promote and work on peace and prosperity for everyone from now into the future:

- Goal 7: Affordable and Clean Energy

This goal aims to guarantee the access of affordable, sustainable and modern energy for everyone and increase energy efficiency [25]. Due to the increasing prices of electricity prices in recent years, it is necessary to look for solutions that will enable to enhance the effects of energy efficiency and reduce prices so that energy becomes more affordable. Moreover, the base of this thesis is a higher renewable energy penetration in the market, specifically DERs along the distribution network. The objective of this Master's Thesis is to minimize the overall costs of electricity for customers belonging to an energy community, maximizing the benefits from renewable production such as PV by using ESS and EVs to make the most of the solar production and avoid curtailment, while also optimizing grid consumption. This involves obtaining preferably clean energy at more affordable prices.

- Goal 9: Industry, Innovation and Infrastructure

This goal aims to build resilient infrastructure and promote a sustainable industrialization [26]. The integration of DERs promotes the consumption of renewable energy, creating sustainable industries. Additionally, the creation of energy communities is still not widely developed and it is considered an innovative solution to contribute to the optimization of energy resources, for example, by using community energy trading. By evaluating the impacts of EVs on the different scenarios described above, a more efficient EV charging distribution could be developed, contributing to build a stronger and environmentally friendly industry.

- Goal 11: Sustainable Cities and Communities

This goal aims to turn cities and community into safer, more resilient, inclusive and sustainable places [27]. Considering a future bigger creation of energy communities and implementation of community energy trading mechanisms, cities and communities will become more sustainable because of a better use and optimization of energy resources and the integration of renewable energy sources that decarbonize the system and reduces CO2 emissions. The integration of EVs also promotes cleaner and more sustainable environments in cities and communities.

- Goal 12: Responsible Consumption and Production

This goal aims to promote and achieve a more sustainable and efficient management of resources and improve the patterns of consumption [28]. Through this Master’s Thesis, different scenarios are studied to find the best allocation of energy resources that promote a responsible consumption while also minimizing costs. Furthermore, renewable energy usage is maximized by the flexibility that DERs provide, reducing curtailment and energy spillage.

ANNEX B: Simulations' Input Data

Initial Charge of ESS and EVs

In Table 7, the initial charge of the battery energy storage systems and the electric vehicles for cases 4, 5 and 6 is featured.

Customer	ESS	Initial Charge (kWh)	EV	Initial Charge (kWh)	Customer	ESS	Initial Charge (kWh)	EV	Initial Charge (kWh)
1	Yes	10	No	0	**29**	No	0	No	0
2	Yes	5	Yes	5	**30**	Yes	8	No	0
3	Yes	10	No	0	**31**	No	0	Yes	14
4	No	0	No	0	**32**	No	0	No	0
5	Yes	7	No	0	**33**	Yes	4	No	0
6	No	0	No	0	**34**	No	0	No	0
7	No	0	Yes	12	**35**	No	0	Yes	15
8	No	0	No	0	**36**	No	0	No	0
9	Yes	2,7	Yes	11	**37**	Yes	4	No	0
10	No	0	No	0	**38**	No	0	No	0
11	No	0	No	0	**39**	No	0	Yes	12
12	Yes	3	Yes	12	**40**	Yes	8	No	0
13	No	0	No	0	**41**	No	0	Yes	13
14	No	0	No	0	**42**	No	0	No	0
15	Yes	9	No	0	**43**	No	0	No	0
16	No	0	Yes	8	**44**	No	0	No	0
17	No	0	No	0	**45**	Yes	6	No	0
18	Yes	5	No	0	**46**	No	0	Yes	18
19	No	0	No	0	**47**	No	0	No	0
20	Yes	6	Yes	7	**48**	Yes	6	No	0
21	No	0	No	0	**49**	No	0	Yes	12
22	No	0	No	0	**50**	Yes	5	Yes	15
23	Yes	6	No	0	**51**	No	0	No	0
24	No	0	No	0	**52**	Yes	3	No	0
25	No	0	Yes	12	**53**	Yes	10	Yes	8
26	No	0	No	0	**54**	Yes	10	Yes	6
27	Yes	8	No	0	**55**	Yes	7	Yes	10
28	No	0	Yes	13					

Table 7 Initial charge of ESS and EVs for cases 4, 5 and 6

In Table 8, the initial charge of the battery energy storage systems and the electric vehicles for case 7, where all the customers have EVs, is featured.

Customer	ESS	Initial Charge (kWh)	EV	Initial Charge (kWh)	Customer	ESS3	Initial Charge (kWh)	EV	Initial Charge (kWh)
1	Yes	10	Yes	5	**29**	No	0	No	21
2	Yes	5	Yes	5	**30**	Yes	8	No	17
3	Yes	10	Yes	8	**31**	No	0	Yes	14
4	No	0	Yes	5	**32**	No	0	No	7
5	Yes	7	Yes	10	**33**	Yes	4	No	8
6	No	0	Yes	8	**34**	No	0	No	23
7	No	0	Yes	12	**35**	No	0	Yes	15
8	No	0	Yes	7	**36**	No	0	No	9
9	Yes	2,7	Yes	11	**37**	Yes	4	No	7
10	No	0	Yes	14	**38**	No	0	No	8
11	No	0	Yes	6	**39**	No	0	Yes	12
12	Yes	3	Yes	12	**40**	Yes	8	No	9
13	No	0	Yes	20	**41**	No	0	Yes	13
14	No	0	Yes	18	**42**	No	0	No	15
15	Yes	9	Yes	7	**43**	No	0	No	13
16	No	0	Yes	8	**44**	No	0	No	9
17	No	0	Yes	6	**45**	Yes	6	No	6
18	Yes	5	Yes	19	**46**	No	0	Yes	18
19	No	0	Yes	22	**47**	No	0	No	8
20	Yes	6	Yes	7	**48**	Yes	6	No	7
21	No	0	Yes	8	**49**	No	0	Yes	12
22	No	0	Yes	14	**50**	Yes	5	Yes	15
23	Yes	6	Yes	6	**51**	No	0	No	6
24	No	0	Yes	5	**52**	Yes	3	No	7
25	No	0	Yes	12	**53**	Yes	10	Yes	8
26	No	0	Yes	8	**54**	Yes	10	Yes	6
27	Yes	8	Yes	7	**55**	Yes	7	Yes	10
28	No	0	Yes	13					

Table 8 Initial charge of ESS and EVs for case 7