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Photovoltaic Local Energy Communities—Design of New Energy Exchange Modalities—Case Study: Tolosa

Iraide López [1,*], Julen Gómez-Cornejo [1], Itxaso Aranzabal [1], Luis Emilio García [2] and Javier Mazón [1,*]

[1] Department of Electrical Engineering, University of the Basque Country (UPV/EHU), 48013 Bilbao, Spain
[2] Department of Power Grid Automation, Ingeteam Power Technology SA, 48170 Zamudio, Spain
* Correspondence: iraide.lopez@ehu.eus (I.L.); javier.mazon@ehu.eus (J.M.)

Abstract: Energy communities (ECs) can become a potential alternative to promote the fight against climate change. Technological progress and price reductions in recent years have made renewable energy-generation systems increasingly affordable and have generated economic benefits by reducing the value of electricity bills for community members, as well as reducing the growing environmental impact. In this context, the authors have taken Tolosa as a case study and conducted a technical and economic analysis of different possible structures of ECs (physical, virtual, with or without storage, participants with different types of consumption, etc.) by comparing them with each other. The generation capacity of the community and the optimal energy-management algorithms have been illustrated, from which the economic benefits for each member are extracted. A dynamic distribution factor is established as the basis of the algorithms, making the benefits fairer. The results obtained from this work, in addition to illustrating the economic benefits that each type of participant can receive, help to define the most appropriate community structure for each participant while highlighting the social and climate benefits that ECs can provide.

Keywords: energy community; solar energy; battery storage; energy-management strategy; energy aggregator

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Citation: López, I.; Gómez-Cornejo, J.; Aranzabal, I.; García, L.E.; Mazón, J. Photovoltaic Local Energy Communities—Design of New Energy Exchange Modalities—Case Study: Tolosa. *Energies* **2023**, *16*, 4000. https://doi.org/10.3390/en16104000

Academic Editors: Alessandro Ciocia and Antonio D'angola

Received: 4 April 2023
Revised: 24 April 2023
Accepted: 3 May 2023
Published: 9 May 2023

1. Introduction

Technological advances in recent years have made it possible to propose new forms of electricity production through renewable sources. The implementation of new resources aims to reduce the use of sources that produce high levels of pollution, promoting the fight against climate change. Local Energy Communities (LECs) are presented as an alternative for this energy transition. Communities have the opportunity to produce and consume their own energy, which allows for savings in electricity bills for users, improves energy efficiency due to the proximity of generation systems, and promotes new values of environmental awareness [1–3].

LECs may represent a new modality for energy exchange. Users can benefit from including new business models in the sector, generating new sources of employment, and promoting the well-being of the entire community [3,4].

The current trend is to produce energy through renewable sources, store a larger amount of energy, and meet energy needs. On the other hand, the transition from the pyramidal generation model to the distributed generation model opens up new fields of research, development, and investment, such as improving system flexibility through demand response [5–7], new business models [8,9], or optimal energy-exchange algorithms [10], among others. An extensive review [11] about the trajectories of the renewable energy communities has been presented. The energy market represents a beneficial source of business, and the inclusion of new projects makes it possible to reduce costs and analyze new-generation alternatives [12].

This document is structured as follows: first, the general context is described, indicating the reasons that have led to the development of ECs. Second, the different types of existing ECs are presented, as well as the different business models that can be derived from them. Third, the methodology carried out in this work is presented, which includes the case study, the analysis of alternatives, and the proposed optimal energy-management algorithms as a solution. Subsequently, the technical and economic results derived from the methodology are presented, and, finally, a brief discussion and conclusions are provided.

1.1. General Context

Energy transition is possible through the involvement of citizens, companies, and institutions. The main objective is to raise awareness among all the elements that make up the electrical system that the implementation of new small-scale energy projects, such as LECs, guarantees environmental and socioeconomic benefits today [4,12]. The use of renewable sources and electrical energy storage systems are highly potential alternatives that allow consumers to produce their own energy and store it to meet their needs, either locally, in physical communities, or remotely, in virtual communities (see Section 1.2).

Within the preambles of Directive 2018/2001 [13], it is stated that: "The term Local Energy Community (LEC) or Community Energy Community (CEC), except for its use in the proposal for a Directive on the internal electricity market that was part of the so-called Winter Energy Package, has not been taken up in the current European Directives, which choose to refer to the renewable energy community or citizen energy community".

The primary aim of Member States is to ensure that consumers, particularly domestic consumers, have the right to participate in renewable energy communities while fulfilling their obligations as end-users. In the case of private companies, participation should not constitute their main commercial or professional activity. The involvement of local authorities is not mandatory, but possible, since they are composed of citizens, despite the regulatory framework for energy activities or services posing difficulties. Moreover, participating companies are required to prioritize criteria other than economic profitability. Directive 2018/2001 encourages Member States to adopt provisions at the national, regional, and local levels to facilitate the establishment of renewable energy communities (art. 15.3). Directive 2019/944 [14] obliges them to implement a favorable legal framework, which necessitates an analysis of their legal nature and legal regime.

Directive 2018/2001 of the European Parliament and Council of the European Union, issued on 11 December 2018, promotes the use of energy from renewable sources and defines Renewable Energy Communities (REC). This entity has the freedom to participate in renewable energy projects in the vicinity of a locality, and its partners or members include natural persons, local authorities, and even municipalities. For environmental, economic, and social purposes, RECs are granted all the rights that the law allows [12].

On the other hand, Directive 2019/944 of the European Parliament and Council of the European Union, issued on 5 June 2019, establishes common rules for the internal electricity market and defines the Citizen Energy Community (CEC). The CEC is composed of partners or members, who can be individuals, local authorities, municipalities, or small businesses. The purpose of the CEC is to offer environmental, economic, and social benefits to the members, partners, or locality that participate in the project. The activities that a CEC can develop include generation from renewable sources or other sources, distribution, supply, consumption, aggregation, energy storage, provision of energy efficiency services, or provision of electric vehicle recharging services, among other energy services to partners or members of the community [12].

The two directives establish whether it is an REC or a CEC, and whether they have participation rights in energy production to achieve environmental and economic benefits, as well as contributing to society by generating employment. The two definitions proposed by the directives are referred to as LECs throughout the rest of the document, to generalize the types of entities.

1.2. Types of Local Energy Communities

The LECs can be differentiated based on how the electrical network is used and the management of accounting and billing for generated and consumed energy. Once these factors are known, they can be classified into two types [13,14]:

1. Physical communities: Those where there is a direct connection between generation and consumption, without the need to connect to the grid at high voltage levels. Instead, they connect to the low-voltage grid and are located close to the loads, allowing the LEC to generate relief to the general network. Within these types of communities there are:
    - Collective Self-Consumption Communities: These are consumers who are connected to a common node of the public distribution network and have a dedicated network for their consumption, for example, an apartment building or private residential development. The generated energy is consumed by the owners of the system and the surplus can be exchanged with the public network. In addition, the LEC may have a storage system and electric vehicle chargers.
    - Community Self-Consumption Communities: These are consumers who use the public distribution network to supply the energy generated by the LEC system. It is possible to supply energy to a greater number of loads because the participants are connected to a higher voltage level than the Collective Self-Consumption Communities.
2. Virtual communities are those where a direct connection between generation and loads cannot be guaranteed, and electricity may need to be acquired from outside the community. In these cases, optimized management is necessary in both the technological and administrative fields. Virtual communities can be classified into:
    - Regional Communities: Producers and consumers connect within a specific region. These types of communities do not have a physical relationship between generation and consumption, but it is necessary for the LEC to have fair-rate models that allow billing of the energy supplied and consumed.
    - Cloud Communities: These types of communities share the same characteristics as regional communities but are based on other aspects such as common technical requirements or the types of hardware used, including integrated storage systems in homes.

In Europe, in order to promote the social and solidarity economy through LECs, several projects, cooperatives, and studies have been developed based on renewable energy sources and energy management. Table 1 shows some projects and case studies of LECs that have been developed in various Member States of the European Union (EU) and the United Kingdom [15–18].

Table 1. Examples of LECs in Europe.

Project	Location	Year	Technology	Capacity	Storage	Surplus Sale	LEC Type
Brixton's energy	UK	2012	PV	133 kW	No	Yes	Self-Consumption Community
Freiburg EC	UK	2000	PV	445 kW	No	Yes	Self-Consumption Community
Jurassic	France	2016	PV	18 MW	No	Yes	Self-Consumption Community
Crevillent EC	Spain	2019	PV	5 MW	-	Yes	Self-Consumption Community
Esparza de Galar EC	Spain	2019	PV	18 kW	-	No	Self-Consumption Community
Urroz Villa EC	Spain	2020	PV	36 kW	-	Yes	Self-Consumption Community
Lasierra EC	Spain	2020	PV	30 kW	-	No	Self-Consumption Community

1.3. Business Models

The changes caused by new-generation sources that affect the traditional electrical network have an impact on various areas that comprise the electrical system. The decentralization of the electrical network, resulting from distributed generation, leads to complex changes in the system. Other affected factors include business models, where centralized generators offer the product and customers act as consumers. However, today's consumers can also be producers with distributed generation (DG) systems, changing the landscape of traditional business models.

Business models for distributed resources are scarce due to the recent integration of new systems at local or remote points. The classification of models depends on the type of service to be offered, the target audience, and the market segment in which they operate. They can be classified, among others, as follows [18,19]:

- Business models for DG: The evolution of local or distant systems is being promoted. The business models that can be found include the Rent-the-Space model, the supply of distributed generation systems, and Leasing or Power Purchase Agreement services. Other associated models include planning services or activities, installation, maintenance, etc.
- Demand management business models: These business models promote the optimal and rational use of electricity consumption through the use of devices with high energy efficiency and in hours of lower consumption (off-peak hours). The models they manage can be energy services, Smart home, demand response, and energy-management systems.
- Electrical or thermal storage business models: In order for the production through a photovoltaic solar system to be profitable, the application of electrical or thermal storage is necessary, which can be achieved through the use of batteries or energy accumulators. Some of the business models associated with energy storage include energy storage for network services, energy storage and optimization for users, energy storage for end-users, and cooptimization of the system, as well as cloud storage.
- Business models based on zonal aggregates: These models aim to control and optimize electricity production and consumption in virtual power plants and microgrids. These models often involve aggregating distributed energy resources, such as solar panels or wind turbines, to create a more reliable and resilient source of energy. They may also incorporate energy storage solutions to ensure consistent power delivery. Examples of business models in this category include peer-to-peer energy trading platforms, demand response programs, and virtual power plant operators.
- Business models for traditional utilities: These business models seek to involve these companies in energy transition, considering their accessibility to energy consumption. These models can be collective, providing services related to network operators, supplying distributed energy solutions, offering energy as a service, or simply functioning as a traditional utility, supplying electrical energy.
- Other business models are based on technology, consulting, and from a financing perspective.

It can be concluded that LECs fall under the classification of business models based on zonal aggregates, which focus on supply and demand services. The complexity of the model varies depending on factors that need to be controlled, such as production, consumption, storage, protection, infrastructure, maintenance, etc. Table 2 summarizes the detailed business models based on zonal aggregates that can be applied in the LEC alternatives that will be defined later.

Table 2. Potential business models based on zonal aggregates for LEC [18].

Model	Characteristics	Agents	LEC Type
Peer-to-peer electricity exchange	This type of model is based on online platforms for transactions between consumers and producers.	Producers, consumers, and prosumers	Preferably physical communities

Table 2. *Cont.*

Model	Characteristics	Agents	LEC Type
Virtual power plants (VPP)	Generation, storage, and consumption is managed by an aggregator, who is in charge of integrating the activities and participates in the purchase and sale of electricity.	Producers, consumers, prosumers, and energy aggregator	Physical and virtual communities
Microgrid	Distributed generation and consumption sources can operate connected to the grid or in isolation, depending on economic and security factors.	Producers and consumers	Physical communities
Community solar providers	Photovoltaic systems are installed in areas far from consumers and they can become part of the community through shares or by buying participation rights. The profits of the photovoltaic plants are distributed among the shareholders.	Shareholders	Virtual communities
Energy communities	This business model allows consumers in a community to participate in a renewable energy project to make use of the electricity produced and reduce their electricity bill. The system can be located in a single place close to the loads or distributed in homes.	Producers, consumers, and prosumers. Energy aggregator (optional)	Preferably physical communities Virtual communities

Regarding the business models described in Table 2, this work will apply those corresponding to community solar providers and energy communities. These models are the most probable alternatives for a physical and virtual LEC that will be implemented in this project.

2. Methodology

This work uses the MATLAB platform to study an LEC located in Tolosa, Spain. It proposes possible scenarios for the production and consumption of electrical energy among community participants, and through coordination algorithms among the different agents that make up the community, it determines the functions that an energy aggregator (EA) must fulfill. These functions range from knowing and combining the consumption, generation, and storage of customers to participating in the purchase, sale, and auction in energy markets, as well as studying business models and organized energy markets. This work aims to design a new modality of energy exchange between agents of an LEC, considering the energy and economic impacts for each of the scenarios.

2.1. Definition of the Study Cases

To obtain more reliable results that reflect real-world situations, it is crucial to understand the consumption patterns of customers who currently rely solely on the electrical distribution network and do not have an auxiliary energy production or storage system. The high cost and demand for energy are driving consumers in the area to seek alternative ways of producing electricity, particularly if the source is easily accessible, has high efficiency, and is renewable.

Among the consumption profiles to be analyzed are residential consumers with a contracted power of 5.7 kW, a commercial consumer in the form of an aesthetic center with a contracted power of 12 kW, and an industrial consumer in the form of a bakery with a contracted power of 41 kW. The TOLORGAI Distribution Company has provided all the necessary data for the consumers. As described later, this study examines three different

LECs. The first LEC will consist of five residential participants; the second LEC of five residential participants plus one commercial participant; and the third LEC of five residential participants, one commercial participant, and one industrial participant, with one of the objectives of this study being to analyze the benefits of including participants with very different consumption profiles. Thus, Figure 1 shows average monthly consumption profiles of these three types of consumers, as does Figure 2. where each color curve represents a month of the year (from July to May).

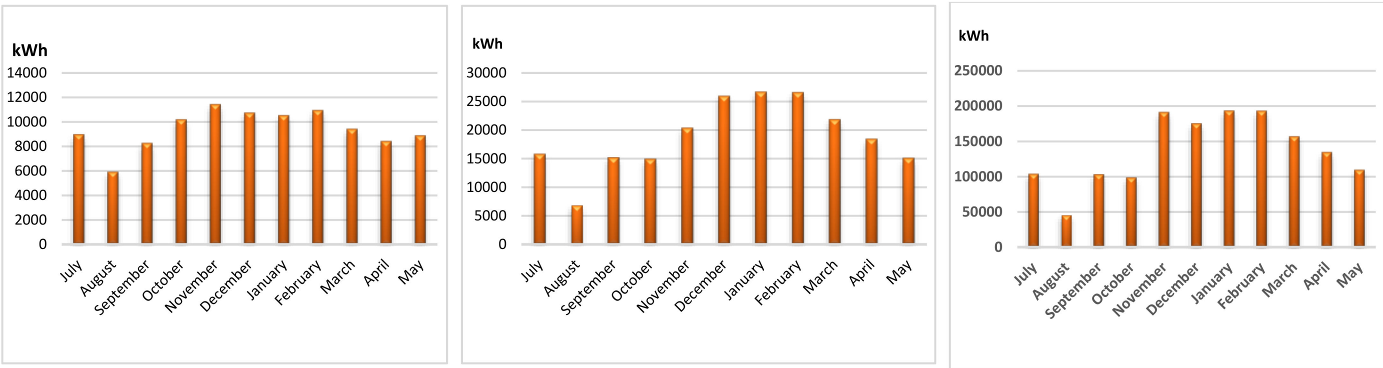


Figure 1. Average monthly consumption of a: (**a**) 5.7 kW consumer, (**b**) 12 kW consumer, and (**c**) 15 kW consumer.

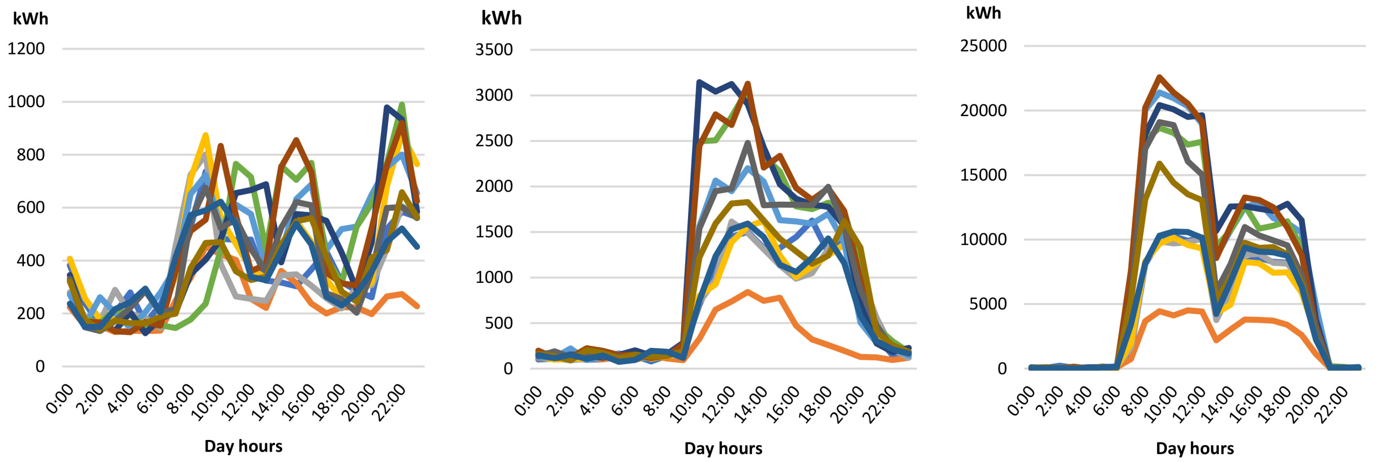


Figure 2. Average daily–monthly consumption profile of a: (**a**) residential consumer, (**b**) commercial consumer, and (**c**) industrial consumer.

Finally, Table 3 indicates the annual electricity consumption of each of the participants and the accumulated total of the members of the LEC. Likewise, it shows which electricity rate they are subject to, so that a correct economic calculation can later be made.

Table 3. Details of the total consumption of each LEC type by consumer.

Consumers	C1	C2	C3	C4	C5	C6	C7
kW/year	3422.14	3422.51	3421.96	3902.56	3417.17	6809.37	48,891.99
Tariff [20–22]	2.0 TD	2.0 TD	2.0 TD	2.0 TD	2.0 TD	2.0 TD	3.0 TD
Total LEC consumption (alternative 1—kWh/year)					17,586.33		

Table 3. *Cont.*

Consumers	C1	C2	C3	C4	C5	C6	C7
Total LEC consumption (alternative 2—kWh/year)						24,395.69	
Total LEC consumption (alternative 3—kWh/year)							73,287.68

2.2. Analysis of Alternatives

For the three case studies, it is necessary to propose three alternatives for LECs and analyze two possible scenarios for the application of each local community. In this way, it will be possible to differentiate the advantages and disadvantages of the business models that are applied in each case. The three LEC alternatives and the proposed business models for each are described in Table 4.

Table 4. Alternatives of LECs and their business models.

Alternative	Customer Type	Number of Customers	Scenario	Business Model
1	Residential	5	Physical community of collective self-consumption	Energy community
			Regional virtual community	Community solar providers
2	Residential + Commercial	5 + 1	Physical community of collective self-consumption	Energy community
			Regional virtual community	Community solar providers
3	Residential + Commercial + Industrial	5 + 1 + 1	Physical community of collective self-consumption	Energy community
			Regional virtual community	Community solar providers

As mentioned earlier, the first alternative integrates five residential clients in a building where they share their daily activities. For this reason, the first proposed scenario for this LEC corresponds to a physical community of collective self-consumption and an energy community business model, where the participation of the energy aggregator is taken into account to manage the production of electrical energy through a photovoltaic system, storage in lithium-ion batteries, and the efficient consumption of each client. In addition, the technical conditions of the installation classify this alternative within this scenario: the photovoltaic system is located near the loads, and they share the same common node of the distribution network. The building has an available roof area of 91.84 m^2, as can be seen in Figure 3, building A. For the same alternative, a second scenario is analyzed where the LEC treatment corresponds to a regional virtual community. The photovoltaic solar installation is located in an area far from the load, and the solar resource in the new area (Málaga, Spain) is much more abundant. Clients become shareholders within the LEC, and the participation of an energy aggregator is necessary for the management of energy produced and consumed. The applicable business model for this scenario would be community solar providers.

The second alternative integrates the five residential clients from alternative 1 with a commercial client located in an adjoining building. For this reason, the first scenario corresponds to a physical community for collective self-consumption, and the energy community business model is applied. Similarly, the participation of an EA is essential for managing the production of electricity through a photovoltaic system, storing energy in batteries, and consumption by each client. The available space for installation in both buildings is 155.43 m^2 (see Figure 3, buildings A and B) for the second scenario, the LEC is classified as a regional virtual community, and a community solar provider business model is applied. As in alternative 1, the solar installation is located in an area far from the loads (Málaga, Spain).

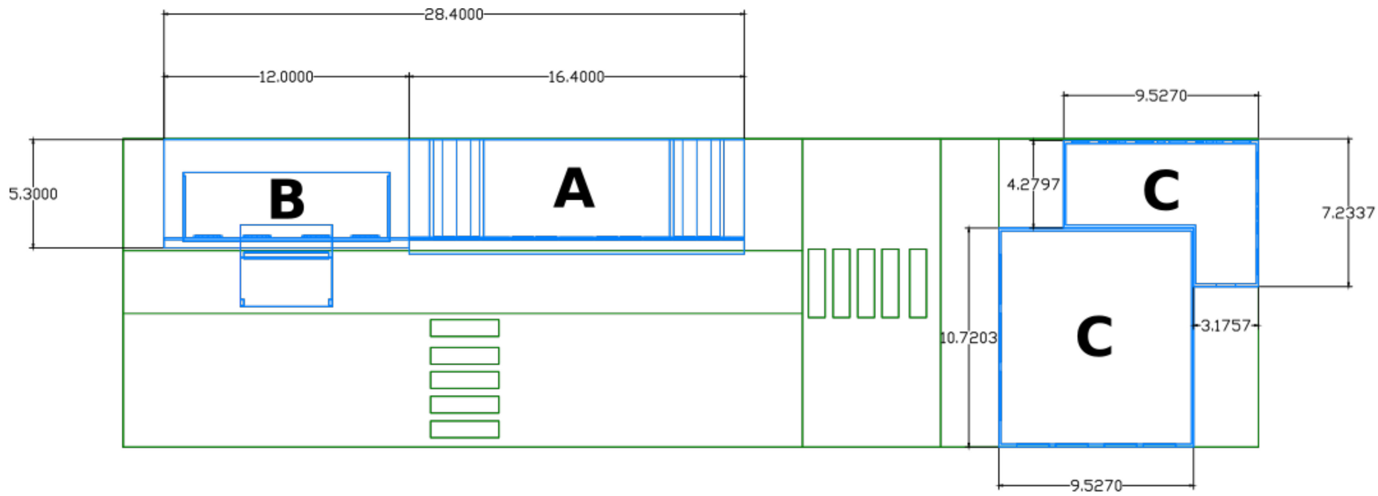


Figure 3. Floor plan of the buildings that make up the energy community. Building corresponds to each type of consumer (A, B, C) and the blue color serves to differentiate the study buildings from the rest of the elements such as the road and zebra crossings.

The third alternative integrates the customers from alternative 2 with an industrial customer, distributed among different households, commercial, and industrial premises in the same area. All consumers are connected to the same public distribution network at the same voltage level and, therefore, the LEC falls into the category of physical community self-consumption, with the energy community business model applied. The participation of an EA is necessary for managing production through a photovoltaic solar system, storage in batteries, and consumption of each client. The buildings have an available roof area of 345.93 m^2, as depicted in Figure 3, buildings A, B, and C. For the second scenario, the LEC falls into the category of a regional virtual community. Like the other alternatives, the LEC is made up of shareholders, and the photovoltaic system is located in a distant area (Málaga, Spain) from the loads.

2.3. Description of the Proposed Solution

The agent responsible for managing generation, demand, and storage is an EA. For each of the alternatives, a solution must be proposed from the point of view of this agent.

Figure 4 provides a general indication of the hourly management that the EA must perform in the physical LECs to understand the relationship between the systems and the clients. Afterward, the economic benefits of the LEC should be analyzed, taking into account whether or not it has a storage system. The participation of each client at the time of network consumption or storage must also be determined. The main objective is to reduce network consumption during peak times and maximize energy production by the generation system.

When managing energy, it is important to consider the value of energy consumed by clients, and whether implementing an LEC with a storage system will result in any reduction in their energy bill. Consumers typically contract the electrical service through a trading company based on their specific load needs. The price of energy consumed may vary depending on the type of tariff and the contracted power, and the benefits may fluctuate with regulated prices.

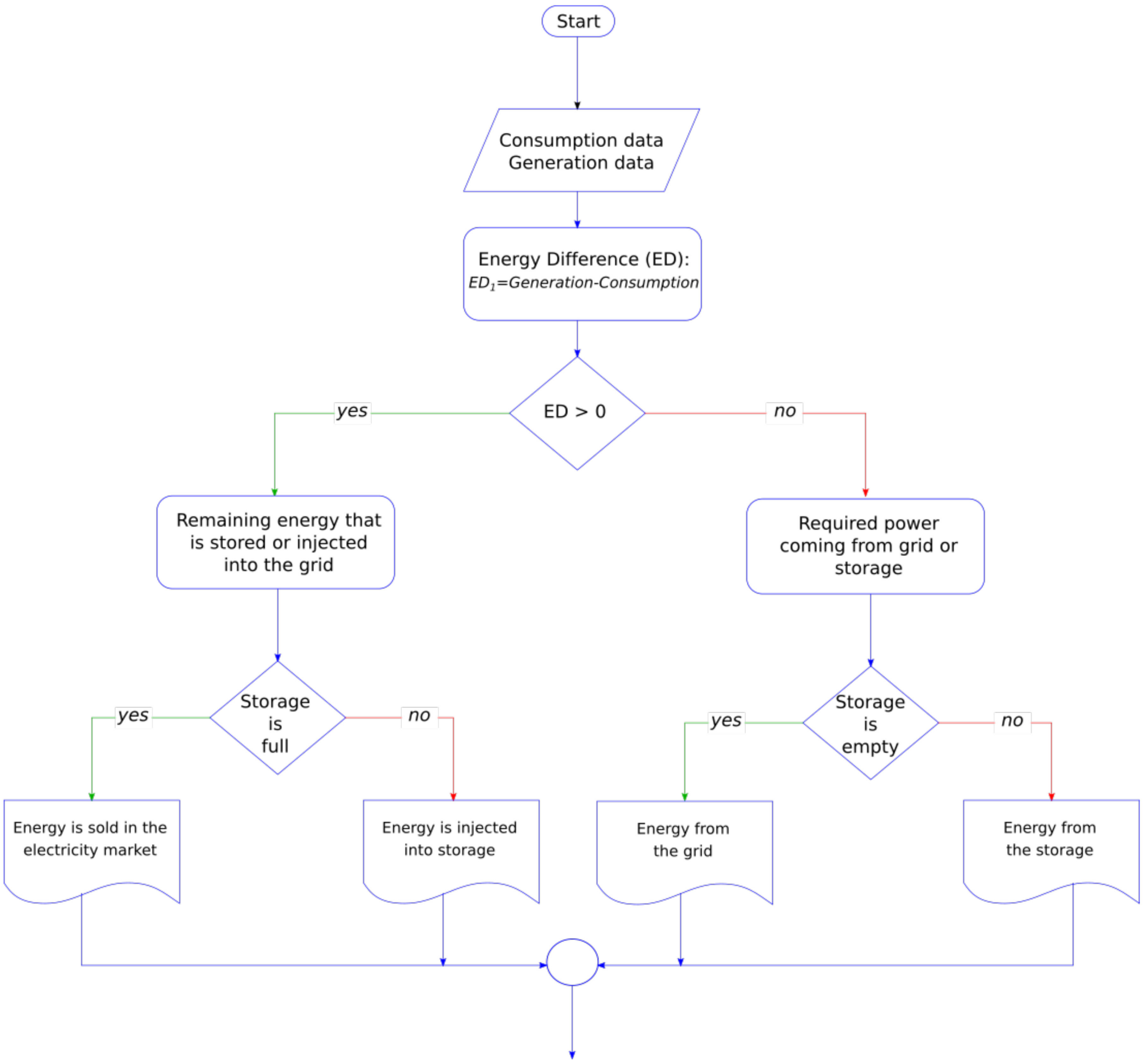


Figure 4. Flowchart for managing a physical LEC.

Secondly, managing a virtual LEC is quite different from a physical LEC. The photovoltaic system is located far from the load, which means that the EA must remotely control the energy produced and inject it entirely into the grid. The benefits for shareholders, who in this case are members of the virtual LEC, depend on the price of electricity generated that participates in the electricity market. The difference between the sale of energy generated by the photovoltaic system and the consumption by shareholders determines the reduction in the final bill. An hourly analysis is necessary to accurately determine the final results.

Next, we analyze the management of an EA over a virtual LEC using two flowcharts in Figure 5. Diagram number 1 represents the management that must be carried out in an LEC without considering energy storage, which is the most common situation in a virtual community. Diagram number 2 represents the management in an LEC with battery storage by the clients. For this project, we analyze the feasibility of installing a storage system close to the load while the generation system is distant.

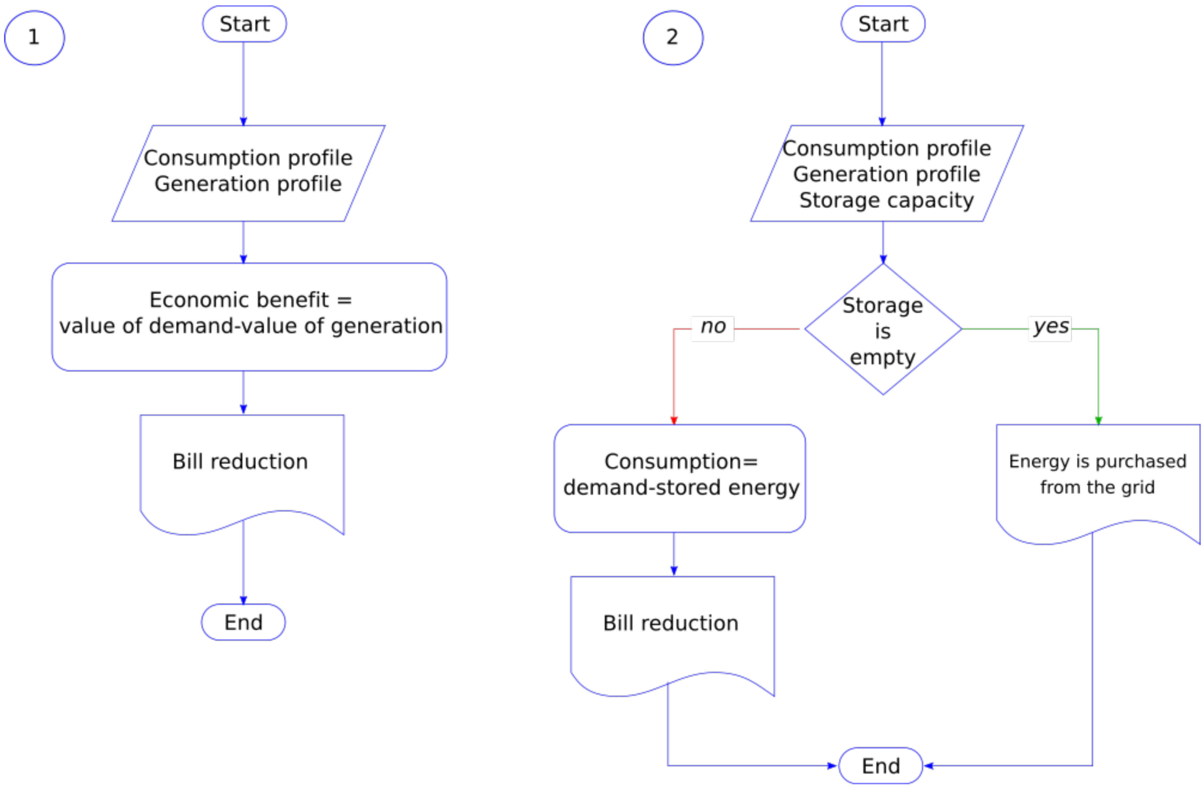


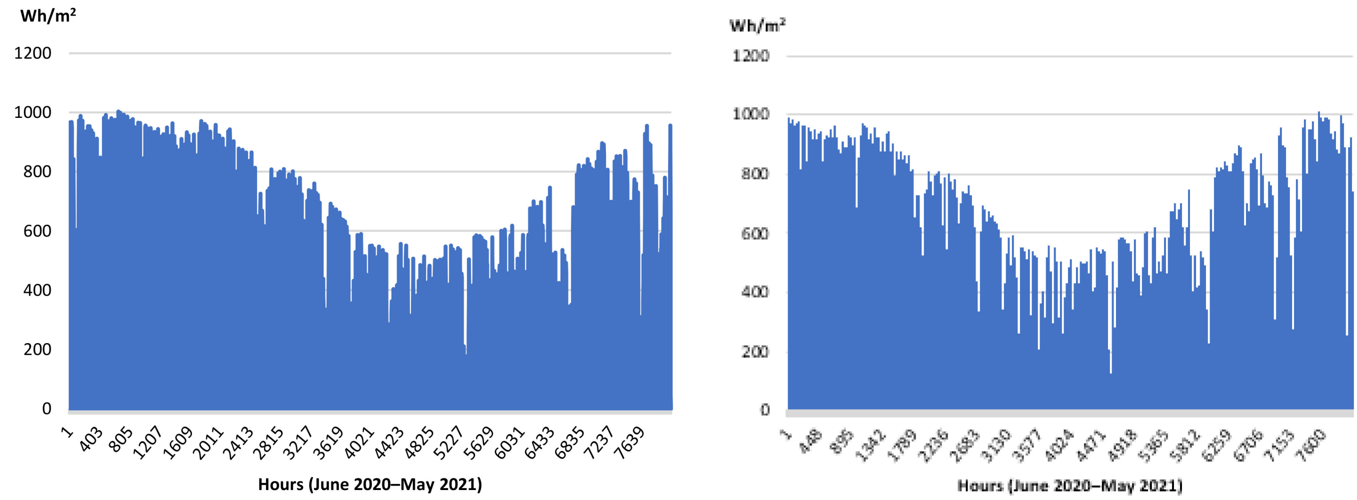
Figure 5. Flowcharts for managing a virtual LEC. (1) It is not considered to be a storage system. (2) It is considered to be a storage system.

In the same way, for a virtual LEC, the economic benefits must be analyzed taking into account the hourly rates for each alternative and verifying that the investment that shareholders must make generates benefits. Unlike a physical LEC, the business model to be applied is that of community solar providers.

2.4. Solar Resource and Photovoltaic System

To determine the solar energy potential of the two study locations, Photovoltaic Geographical Information System (PVGIS) and NASA-SEE databases have been consulted. The data extracted from the databases confirmed that the geographical location of Tolosa does not guarantee a constant solar resource due to the area's typical climatic conditions. The lack of irradiation could potentially reduce the performance of the photovoltaic system for generating electricity, and a slight oversizing may be necessary to achieve the desired results.

Figure 6 displays the irradiance data from 00:00 h on 1 June 2020 to 23:00 h on 31 May 2021. As can be seen in Figure 6a, irradiation during the summer is high, and in some cases reaches 900 Wh/m^2. However, during the winter season, irradiance is low and in the best cases, it only reaches 250 Wh/m^2. On an annual basis, it reaches irradiance values of approximately 1,374,215.4 Wh/m^2.



(**a**) (**b**)

Figure 6. Hourly Wh/m^2 irradiation for a year: (**a**) Tolosa and (**b**) Malaga.

Virtual LECs are characterized by the distance between the loads and the generation source. For this project, the possibility of implementing an LEC with the generation system located in Málaga is analyzed due to the area's climatic characteristics and high levels of irradiation, which make it feasible for the implementation of solar photovoltaic technology. Figure 6b shows the significant differences in irradiance levels between the two cities. In Malaga, the solar resource is much higher during the same time slot as Tolosa. Irradiance levels can reach up to 1000 Wh/m^2 during the summer and up to 600 Wh/m^2 in the best cases during the winter season. Similarly, the annual accumulated irradiance reaches 1,832,741.61 Wh/m^2.

The sizing of the photovoltaic system depends on the loads to be powered and the available solar resource. The knowledge acquired in the previous sections allows the establishing of the power of the generation source. The designed photovoltaic system is composed of solar panels, a DC/DC regulator, a storage system (if required based on the LEC's configuration), and a power electronic inverter (see Figure 7).

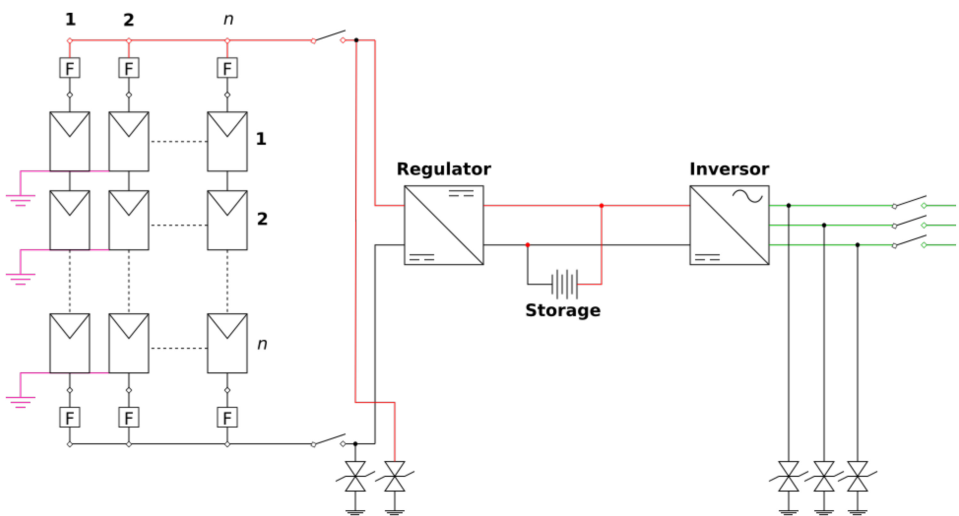


Figure 7. General electrical diagram of the photovoltaic installation.

The system is the same for both a virtual and a physical LEC, with the number of panels varying from one LEC to another; therefore, the capacity of the battery and power inverter, based on Equations (1) and (2), is [16]:

$$SC = \frac{CC \cdot AD \cdot CF}{DD}, \tag{1}$$

where SC represents the storage capacity in Ah; CC represents the client's consumption; AD represents the autonomy days, which are typically set to 0.5 as energy is also consumed at night; CF represents the correction factor (1.1); and DD represents the depth of discharge (0.8), as specified in the selected battery datasheet.

$$P = \frac{E}{PSH \cdot \eta} \tag{2}$$

where P represents the maximum installed power, E represents the energy of the system, PSH represents the peak solar hours (1374.22 for physical LECs and 1832.74 for virtual ones), and η represents the system efficiency, which depends on the installation conditions and the equipment losses that make up the system. It is fixed at 0.96 for physical LECs and 0.92 for virtual ones, as per the selected power electronic converter datasheet for each type of LEC. Finally, Table 5 summarizes the sizing calculations for the photovoltaic system for each alternative.

Table 5. Total yearly energy consumption/generation for each alternative.

		Physical LECs	Virtual LECs
Alternative 1	Demanded energy	17.59 MWh/year	17.58 MWh/year
	Installed PV power	13.6 kW	10.40 kW
	Inverter power	13.33 kW	10.43 kW
	Storage capacity	34.375 kWh/671.39 Ah	34.375 kWh/671.39 Ah
Alternative 2	Demanded energy	24.396 MWh/year	24.29 MWh/year
	Installed PV power	19.2 kW	14.40 kW
	Inverter power	18.49 kW	14.46 kW
	Storage capacity	34.375 kWh/671.39 Ah	34.375 kWh/671.39 Ah
Alternative 3	Demanded energy	73.28 MWh/year	73.28 MWh/year
	Installed PV power	56 kW	41.60 kW
	Inverter power	55.55 kW	43.46 kW
	Storage capacity	71.680 kWh/1400 Ah	71.68 kWh/1400 Ah

3. Technical Results

This section presents the results related to PV generation, consumption, storage, and purchase/sale of energy to the grid following the management strategy described in Figures 3 and 4. Once the generation and storage systems have been dimensioned, we proceed to estimate the energy production of the photovoltaic system and, later, the consumption of the LEC is quantified, considering the storage system.

By comparing the energy generated and consumed, the difference in energy can be analyzed on an hourly basis throughout the year of LEC operation. This allows for the calculation of the remaining energy from the generation system or the energy deficit needed to supply the system. The remaining energy from the generation system is the electricity that is not consumed during the day and can be used in two different ways. Firstly, excess energy can be sold to the grid to obtain an economic benefit. Secondly, if the LEC has a storage system, excess energy must be stored until the batteries reach maximum capacity and can be used during the night. If the batteries are fully charged, the excess power must be sold. If the storage system cannot meet the energy demand, additional energy must be obtained through the distribution network.

The summary of the LEC's operation for all the alternatives for a physical LEC is shown in Table 6, and the same information for virtual LEC alternatives is shown in Table 7.

Table 6. Physical LEC: total yearly energy consumption/generation for each alternative.

Type	Alternative 1 (MWh/Year)	Alternative 2 (MWh/Year)	Alternative 3 (MWh/Year)
Consumption	17.58	24.39	73.28
Generation	17.94	25.33	73.87
Generation breakdown			
Energy consumed directly from generation	6.67	10.50	35.68
Remaining energy from generation that is stored or poured into the grid	11.27	14.83	38.19
Remaining energy from generation that is stored	4.95	5.29	7.17
Remaining energy from generation that is poured into the grid	6.32	9.55	31.04
Grid or battery power feeding the load	10.92	13.89	37.60
Power coming purely from the batteries	4.95	5.29	7.17
Energy coming directly from the network	5.96	8.60	30.43

Table 7. Virtual LEC: total yearly energy consumption/generation for each alternative.

Type	Energy (Alternative 1) MWh/Year	Energy (Alternative 2) MWh/Year	Energy (Alternative 3) MWh/Year
Consumption	17.58	24.39	73.28
Generation	19.06	26.39	76.24
Generation breakdown			
Total energy provided by the grid	17.66	24.39	71.81
Energy stored in batteries	10.69	11.90	21.68
Energy consumed net from the grid	6.97	12.56	50.13

4. Economic Results

Small-scale storage PV systems can still be considered an expensive technology that requires several factors to obtain a payback in a short time. These factors depend directly on the prices of the equipment for installation, such as solar panels, inverters, batteries, wiring, and support structures, as well as the price of installation. Other factors that affect investment costs depend on the efficiency of the equipment and the installation location, which must guarantee lower losses in production and storage. Finally, there are external factors that can affect the initial investment, such as electricity prices in the market, average energy consumption, and subsidies and aid.

The prices of photovoltaic systems have been decreasing in recent years, making them more accessible for residential use. However, the costs are still significantly higher for commercial installations due to the larger scale of the facilities.

According to [23] and the IEA 2022 report [24], the average price for photovoltaic systems is established at 1 EUR/W in this work. In selecting the type of batteries, three factors were considered: efficiency, minimum cost, and a lifespan of 10 years, that is, given that the battery has to be changed every 10 years, reinvesting money in the purchase of a new one. Thus, the average price for the selected battery type is EUR 1650.00. To ensure proper operation of the LEC, regular maintenance is necessary to prevent potential issues, as stated in [25]. For commercial installations on roofs, the average price is 17.33 EUR/kW/year.

Likewise, Spain, and specifically the autonomous community of the Basque Country where Tolosa is located, offers aid programs and incentives for self-consumption and storage [26]. The chances of accessing these type of subsidies are very high, and it is considered that for this project, aid can cover up to 50% of the initial investment in the photovoltaic and storage systems.

Table 8 shows the costs for each of the scenarios related to physical LECs, based on the technical characteristics described in Section 2.4 and the previously indicated systems' costs.

Table 8. Investment cost for each of the physical LEC alternatives.

		Alternative 1 (5)	**Alternative 2 (5 + 1)**	**Alternative 3 (5 + 1 + 1)**
Without incentives	Total system cost with storage	EUR 13,600.00	EUR 19,200.00	EUR 56,000.00
	Total system cost without storage	EUR 25,150.00	EUR 30,750.00	EUR 79,100.00
With an incentive of 50%	Total system cost with storage	EUR 6800.00	EUR 9600.00	EUR 28,000.00
	Total system cost without storage	EUR 12,575.00	EUR 15,375.00	EUR 39,550.00

With the values obtained in the previous table, the initial investment cost to be divided among the clients can be calculated. For alternative 1, where the clients have similar consumption characteristics, the final cost will be divided equally among them.

Regarding alternative 2, since the participants have different consumption characteristics, the final value is divided based on the proportion of each client's energy consumption. For alternative 3, the same cost-sharing criteria as in alternative 2 applies.

On the other hand, Table 9 indicates the values corresponding to the initial investment cost of the generation and storage systems for the virtual LECs. In this case, no type of incentives has been considered since the generation system is located in Málaga. For the costs' distribution, the same criteria are applied as in the case of physical LECs.

Table 9. Investment cost for each of the virtual LEC alternatives.

		Alternative 1 (5)	**Alternative 2 (5 + 1)**	**Alternative 3 (5 + 1 + 1)**
Without incentives	Total system cost with storage	EUR 10,400.00	EUR 14,400.00	EUR 41,600.00
	Total system cost without storage	EUR 21,950.00	EUR 25,950.00	EUR 64,700.00
With an incentive of 50%	Total system cost with storage	-	-	-
	Total system cost without storage	EUR 16,175.00	EUR 20,175.00	EUR 53,150.00

4.1. Profitability Analysis

It is necessary to establish the economic valuation of the cost of the generation and storage system, which includes expenses throughout the useful life of the project. The valuation allows a comparison of production costs with other sources of generation and the determination of a minimum price of commercialization of the energy, with which all the expenses of the project are covered [27].

Equation (3) allows the determination of the minimum cost of the energy produced, taking into account the useful life of the generation system, potential expenses, and energy production.

$$LCOE = \frac{\sum_{j=0}^{n} \frac{(Discharge)_j}{(1+1)^j}}{\sum_{j=0}^{n} \frac{(Production)_j}{(1+1)^j}} \quad (3)$$

where i is the discount rate, j is the year, and n is the number of years of useful life of the system.

The discount rate is used to evaluate investment projects and is an indicator of the present value of money that will be generated in the future. In Spain, the interest rate was 2% in 2022 [28]; therefore, the discount rate is approximately 0.66%.

4.1.1. Profitability Analysis for Physical LECs

The applied business model for physical LECs corresponds to the energy communities' model. The EA manages the energy production and consumption of all participants in such a way that the value of the bill is reduced and benefits are generated for them. In order to calculate the economic benefits for each participant, it is necessary to determine the generation LCOE, the cost of the storage system located in Tolosa, establish a minimum price for the energy (in this work, a price of 0.05 EUR/kWh has been estimated based on [22]), and the purchase price of energy from the grid according to each participant's tariff (see Table 3).

Taking all of the above into account, Table 10 presents the LCOE values and energy savings for each of the alternatives, both in physical and virtual communities.

Table 10. LCOE value and energy savings for each physical community alternative.

		LCOE	Consumed Energy Value in One Year without LEC	Consumed Energy Value in One Year with LEC	Consumed Energy Saving of the Energy with LEC in One Year	Savings during the 25 Years of Useful Life
Alternative 1 (5)	No batteries and no incentives	EUR 0.05	EUR 4947.30	EUR 2500.90	EUR 2446.40	EUR 49,602.16
	With batteries and without incentives	EUR 0.14	EUR 4947.30	EUR 1352.40	EUR 3594.90	EUR 47,389.48
	Without batteries and with incentives	EUR 0.03	EUR 4947.30	EUR 2500.90	EUR 2446.40	EUR 56,402.16
	With batteries and with incentives	EUR 0.08	EUR 4947.30	EUR 1352.40	EUR 3594.90	EUR 71,514.48
Alternative 2 (5 + 1)	No batteries and no incentives	EUR 0.05	EUR 7137.90	EUR 3308.70	EUR 3829.20	EUR 80,630.61
	With batteries and without incentives	EUR 0.11	EUR 7137.90	EUR 2033.20	EUR 5104.70	EUR 82,004.81
	Without batteries and with incentives	EUR 0.03	EUR 7137.90	EUR 3308.70	EUR 3829.20	EUR 90,230.61
	With batteries and with incentives	EUR 0.06	EUR 7137.90	EUR 2033.20	EUR 5104.70	EUR 108,929.81
Alternative 3 (5 + 1 + 1)	No batteries and no incentives	EUR 0.05	EUR 23,922.00	EUR 10,461.00	EUR 13,461.00	EUR 299,919.71
	With batteries and without incentives	EUR 0.09	EUR 23,922.00	EUR 8691.60	EUR 15,230.40	EUR 280,593.23
	Without batteries and with incentives	EUR 0.03	EUR 23,922.00	EUR 10,461.00	EUR 13,461.00	EUR 327,919.71
	With batteries and with incentives	EUR 0.05	EUR 23,922.00	EUR 8691.60	EUR 15,230.40	EUR 343,243.23

As can be seen in Table 10, the lowest LCOE cost value corresponds to the system without batteries and with incentives for the initial investment, reaching EUR 0.03 for each alternative. However, the greatest savings are obtained with an LEC with batteries and incentives, reaching EUR 71,514.48 in savings in alternative 1 at year 25, EUR 108,929.81 in alternative 2, and EUR 343,243.23 in alternative 3.

If it is not possible to obtain any type of incentive, the best option would be an LEC without batteries in all three cases (LCOE for alternative 1 is EUR 0.05, for alternative 2 it is EUR 0.11, and for alternative 3 it is EUR 0.05), obtaining savings of EUR 49,602.16 in the 25-year useful life in alternative 1, EUR 82,004.81 for the second alternative, and EUR 299,919.71 for the third one.

For a proper distribution of the benefits obtained from participating in a CLE, it is necessary to calculate a sharing coefficient for each participant. While this coefficient can be fixed, this work proposes a dynamic calculation with an hourly periodicity. In other words, this factor is recalculated every hour. The introduction of dynamic sharing coefficients allows for adjustments to different consumption scenarios. This will be particularly beneficial, for example, in cases where a participant is not at home during a certain period of time or to adapt to different daily consumption habits of participants in shared self-consumption (it is not the same for a residential property as it is for a commercial property or an office building).

In this work, a sharing factor is proposed based on the energy consumed by each participant relative to the total consumption in the LEC, as indicated in Equation (4), and it will be recalculated on an hourly basis.

$$Dynamic\ sharing\ factor\ (\%) = \frac{Wh_i}{Wh_{LEC}} \cdot 100, \tag{4}$$

with i being each community participant.

Likewise, each participant must contribute a certain capital for the initial investment. As previously mentioned, depending on the consumption characteristics of each participant, the percentage of participation will be defined. Thus, this participation percentage, which will define how much each member should contribute to the initial investment, is calculated by the ratio of the energy consumption of each participant during previous years to the total energy consumption of all participants. These consumption data are prior to the establishment of the LEC itself (Equation (5)):

$$Participation\ \% = \frac{MWh/year_i}{MWh/year_{LEC}} \cdot 100, \tag{5}$$

with i being each community participant. Thus, through this participation factor, the benefits obtained by the community will be distributed among the participants in an equitable manner.

Table 11 presents the economic data, participation, and benefits of each shareholder for each case study.

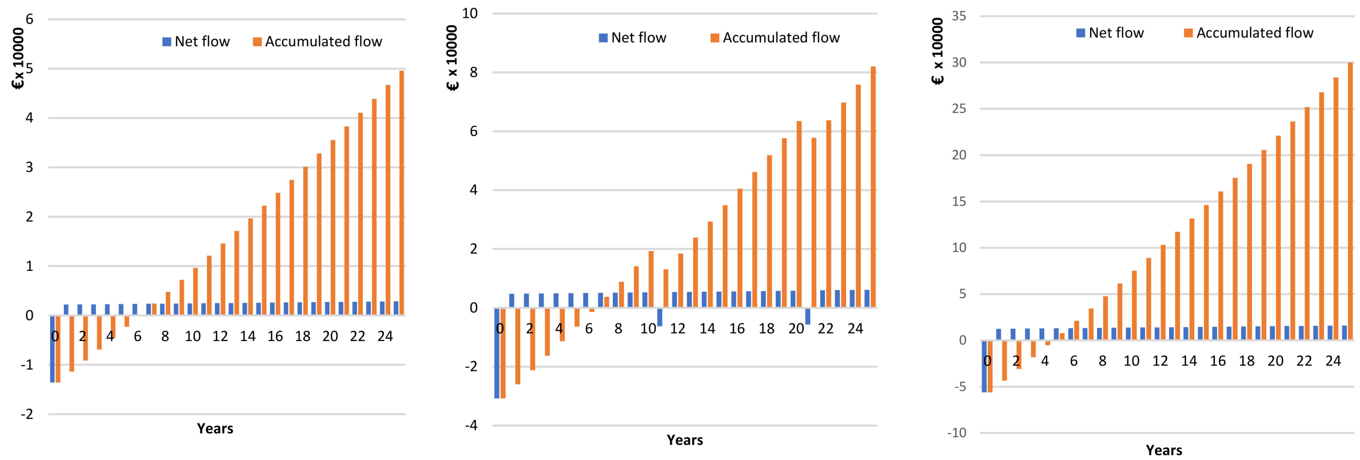
Table 11. Participation and benefits for each participant for physical communities.

		Participant 1	**Participant 2**	**Participant 3**	**Participant 4**	**Participant 5**	**Participant 6**	**Participant 7**
Alternative 1 (5)	% Participation	19.45%	19.46%	19.45%	22.19%	19.43%	-	-
	Initial investment for the LEC without batteries and without incentives	EUR 2645.20	EUR 2646.56	EUR 2645.20	EUR 3017.48	EUR 2642.48	-	-
	Initial investment for the LEC with batteries and with incentives	EUR 2.445.83	EUR 2447.09	EUR 2445.83	EUR 2790.39	EUR 2443.32	-	-
	Value of energy consumed without LEC	EUR 962.94	EUR 963.03	EUR 962.88	EUR 1096.80	EUR 961.56	-	-
	Value of energy consumed with LEC without batteries	EUR 485.07	EUR 485.14	EUR 485.08	EUR 562.98	EUR 482.65	-	-
	Value of energy consumed with LEC with batteries	EUR 264.29	EUR 264.31	EUR 264.31	EUR 300.48	EUR 258.98	-	-
EUR Alternative 2 (5 + 1)	Participation%	14.02%	14.02%	14.02%	15.99%	14.00%	27.91%	-
	Initial investment for the LEC without batteries and without incentives	EUR 4311.15	EUR 4311.15	EUR 4311.15	EUR 4916.93	EUR 4305.00	EUR 8582.32	-
	Initial investment for the LEC with batteries and with incentives	EUR 2156.74	EUR 2156.98	EUR 2156.63	EUR 2459.52	EUR 2153.62	EUR 4291.49	-
	Value of energy consumed without LEC	EUR 994.59	EUR 994.69	EUR 994.53	EUR 1.132.90	EUR 993.17	EUR 2028.00	-
	Value of energy consumed with LEC without batteries	EUR 478.91	EUR 478.96	EUR 478.92	EUR 559.82	EUR 476.03	EUR 836.03	-
	Value of energy consumed with LEC with batteries	EUR 259.76	EUR 259.73	EUR 259.78	EUR 300.15	EUR 253.62	EUR 700.16	-

Table 11. *Cont.*

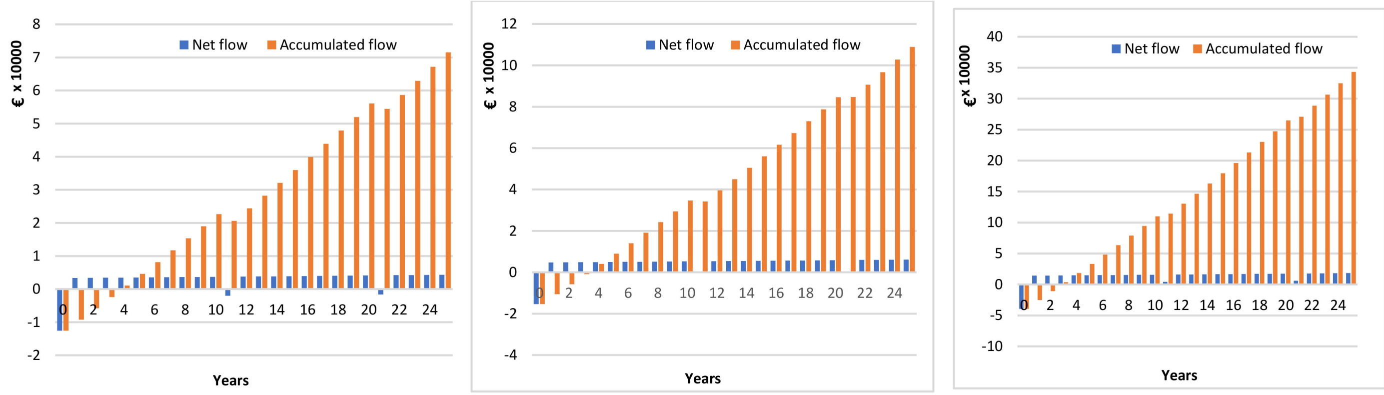
		Participant 1	Participant 2	Participant 3	Participant 4	Participant 5	Participant 6	Participant 7
Alternative 3 (5 + 1 + 1)	Participation%	4.66%	4.66%	4.66%	5.32%	4.66%	9.29%	66.71%
	Initial investment for the LEC without batteries and without incentives	EUR 2614.89	EUR 2615.18	EUR 2614.75	EUR 2981.99	EUR 2611.10	EUR 5203.11	EUR 37,358.95
	Initial investment for the LEC with batteries and with incentives	EUR 1846.76	EUR 1846.97	EUR 1846.67	EUR 2106.03	EUR 1844.08	EUR 3674.70	EUR 26,384.76
	Value of energy consumed without LEC	EUR 1071.70	EUR 1071.80	EUR 1071.60	EUR 1215.20	EUR 1069.20	EUR 2242.40	EUR 16,180.00
	Value of energy consumed with LEC without batteries	EUR 363.18	EUR 363.18	EUR 363.20	EUR 447.93	EUR 359.12	EUR 886.29	EUR 7678.49
	Value of energy consumed with LEC with batteries	EUR 139.67	EUR 139.60	EUR 139.71	EUR 183.98	EUR 134.07	EUR 762.02	EUR 7192.57

Attending to the results presented in Table 11, there is a significant reduction in the energy costs for participants in all three alternatives, with the community with batteries showing the greatest savings, but in the case of accessing an incentive, the benefits will be even greater. In addition, it is considered that the surplus energy is fed into the grid at a price of EUR 0.05. Figures 8 and 9 illustrate the cash flow of the two best options for each alternative. For alternatives 1 and 3, the best two options are an LEC without batteries and without incentives (Figure 8a,c) and an LEC with batteries and incentives (Figure 9a,c). However, for alternative 2, the best two options are an LEC with batteries and without incentives (Figure 8b) and an LEC with batteries and incentives (Figure 9b). In the scenario of an LEC without batteries and incentives, the payback time for alternatives 1 and 2 is approximately 7 years. However, in alternative 3, the return time can be reduced to 5 years.



(**a**) (**b**) (**c**)

Figure 8. Cash flow for a physical LEC: (**a**) alternative 1, with no batteries and no incentives, (**b**) alternative 2, with batteries and no incentives, and (**c**) alternative 3, with no batteries and no incentives.



(**a**) (**b**) (**c**)

Figure 9. Cash flow for a physical LEC with batteries and with incentives: (**a**) alternative 1, (**b**) alternative 2, and (**c**) alternative 3.

In the scenario of an LEC with batteries and incentives which, as we have seen, achieves greater savings, the payback time for alternative 1 is approximately 5 years, for alternative 2 it is 4 years, and for alternative 3 it is 3 years. Therefore, the third alternative is the best scenario among them.

4.1.2. Profitability Analysis for Virtual LECs

The business model applied in this alternative corresponds to that of community solar providers. The EA remotely manages the energy production and consumption of all shareholders, reducing the value of the invoice and generating benefits for them. It is necessary to determine the LCOE of the generation system in Málaga and storage in Tolosa, establish a minimum price for energy to calculate the economic benefits of selling in the market at an approximate price of 0.12 EUR/kWh [29], and, finally, determine the purchase price of energy from the grid according to each participant's tariff (see Table 3). It should be indicated that the 0.12 EUR/kWh is an estimated price for the virtual LEC to be competitive, and it depends greatly on the energy distribution company to which the energy will be sold. This value has been determined based on several simulations in MATLAB and by considering the LCOE.

Table 12 summarizes the obtained economic results. As can be seen, the lowest LCOE value corresponds to the system without batteries and without a subsidy for the initial investment, reaching EUR 0.04 and generating the greatest savings in the three alternatives. If it is not possible to obtain any help, the best option would be an LEC without batteries and without a subsidy, with savings of EUR 37,949.92 in the 25-year useful life for alternative 1, EUR 52,562.46 for alternative 2, and EUR 92,734.07 for alternative 3.

Table 12. LCOE value and energy savings for each virtual community alternative.

		LCOE	Consumed Energy Value in One Year without LEC	Consumed Energy Value in One Year with LEC	Consumed Energy Saving of the Energy with LEC in One Year	Savings during the 25 Years of Useful Life
Alternative 1 (5)	No batteries and no incentives	EUR 0.04	EUR 4947.30	EUR 2287.30	EUR 2660.00	EUR 37,949.92
	With batteries and without incentives	EUR 0.12	EUR 4947.30	EUR 2525.30	EUR 2422.00	EUR 10,021.80
	With batteries and with incentives	EUR 0.08	EUR 4947.30	EUR 2525.30	EUR 2422.00	EUR 27,346.80

Table 12. *Cont.*

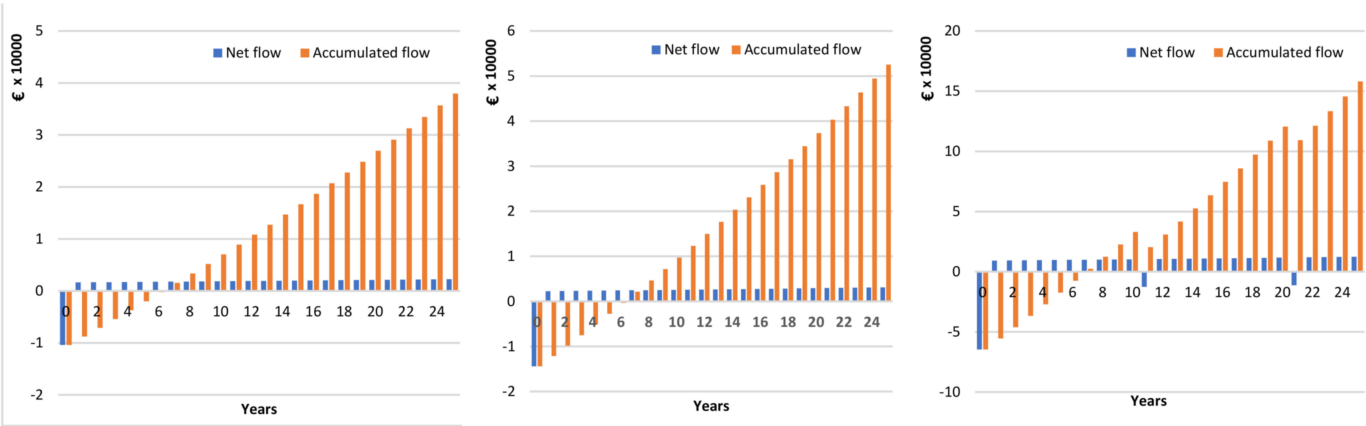
		LCOE	Consumed Energy Value in One Year without LEC	Consumed Energy Value in One Year with LEC	Consumed Energy Saving of the Energy with LEC in One Year	Savings during the 25 Years of Useful Life
Alternative 2 (5 + 1)	No batteries and no incentives	EUR 0.04	EUR 7137.90	EUR 3167.00	EUR 3970.90	EUR 52,562.46
	With batteries and without incentives	EUR 0.09	EUR 7137.90	EUR 3167.00	EUR 3674.00	EUR 26,297.87
	With batteries and with incentives	EUR 0.06	EUR 7137.90	EUR 3167.00	EUR 3674.00	EUR 43,622.87
Alternative 3 (5 + 1 + 1)	No batteries and no incentives	EUR 0.04	EUR 23,992.00	EUR 9219.00	EUR 14,773.00	EUR 153,725.81
	With batteries and without incentives	EUR 0.08	EUR 23,992.00	EUR 9219.00	EUR 12,165.00	EUR 158,084.07
	With batteries and with incentives	EUR 0.06	EUR 23,992.00	EUR 9219.00	EUR 11,827.00	EUR 192,734.07

As in the previous case of the physical LEC, each participant must contribute a certain amount of capital for the initial investment. The percentage of participation and the benefits obtained will be defined based on the consumption characteristics of each participant. Table 13 presents the economic data, participation, and benefits of each shareholder. It can be observed that there is a considerable reduction in the value of the energy consumed by the shareholders who are part of the LEC.

Table 13. Participation and benefits for each participant in virtual communities.

		Participant 1	Participant 2	Participant 3	Participant 4	Participant 5	Participant 6	Participant 7
Alternative 1 (5)	Participation%	19.45%	19.46%	19.45%	22.19%	19.43%	-	-
	Initial investment for the LEC with batteries and with incentives	EUR 2023.74	EUR 2023.96	EUR 2023.63	EUR 2307.84	EUR 2020.80	-	-
	Value of energy consumed without LEC	EUR 962.94	EUR 963.03	EUR 962.88	EUR 1096.80	EUR 961.56	-	-
	Value of energy poured into the network	EUR 445.08	EUR 445.13	EUR 445.06	EUR 507.57	EUR 444.44	-	-
	Savings from the sale of energy	EUR 517.85	EUR 517.89	EUR 517.81	EUR 589.22	EUR 517.11	-	-
Alternative 2 (5 + 1)	Participation%	14.02%	14.02%	14.02%	15.99%	14.00%	27.91%	-
	Initial investment for the LEC with batteries and with incentives	EUR 2019.97	EUR 2020.19	EUR 2019.87	EUR 2303.55	EUR 2017.04	EUR 4019.35	-
	Value of energy consumed without LEC	EUR 994.59	EUR 994.69	EUR 994.53	EUR 1132.90	EUR 993.17	EUR 2028.00	-
	Value of energy poured into the network	EUR 444.25	EUR 444.30	EUR 444.23	EUR 506.62	EUR 443.61	EUR 883.97	-
	Savings from the sale of energy	EUR 550.33	EUR 550.38	EUR 550.29	EUR 626.27	EUR 549.55	EUR 1144.02	-
Alternative 3 (5 + 1 + 1)	Participation%	4.66%	4.66%	4.66%	5.32%	4.66%	9.29%	66.71%
	Initial investment for the LEC with batteries and with incentives	EUR 2481.81	EUR 2482.08	EUR 2481.68	EUR 2830.22	EUR 2478.21	EUR 4938.31	EUR 35,457.65
	Value of energy consumed without LEC	EUR 1071.70	EUR 1071.80	EUR 1071.60	EUR 1215.20	EUR 1069.20	EUR 2242.40	EUR 16,180.00
	Value of energy poured into the network	EUR 430.47	EUR 430.52	EUR 430.45	EUR 490.91	EUR 429.85	EUR 856.56	EUR 6150.21
	Savings from the sale of energy	EUR 641.22	EUR 641.27	EUR 641.14	EUR 724.28	EUR 639.34	EUR 1385.83	EUR 10,029.78

Likewise, Figure 10 illustrates the cash flow of the best option for each alternative. For alternatives 1 and 2 (Figure 10a,b), the best option is the case of an LEC without batteries and without incentives, with paybacks of approximately 9 years for alternative 1 and 7 for alternative 2. However, the best option for alternative 3 is the case of LEC with batteries and incentives, with a return rate of approximately 6 years. In the absence of incentives, the best option is the case of an LEC with batteries, where the return rate is approximately 7 years (see Figure 10c).



(**a**) (**b**) (**c**)

Figure 10. Cash flow for a: (**a**) alternative 1, with virtual LEC without batteries and without incentives, (**b**) alternative 2, with virtual LEC without batteries and without incentives, and (**c**) alternative 3, with virtual LEC with batteries and without incentives.

Table 14 shows a summary comparison of all the alternatives in terms of bill reduction for each LEC over the course of one year. It is important to note that the calculation of the benefit value takes into account the hour-by-hour participation percentage (see Equation (4)), which ensures a more equitable distribution of consumption.

Table 14. Invoice reduction summary for each alternative.

LEC Type	Participant 1	Participant 2	Participant 3	Participant 4	Participant 5	Participant 6	Participant 7
Physical LEC 1 WITHOUT batteries	EUR 485.07	EUR 485.14	EUR 485.08	EUR 562.98	EUR 482.65	-	-
Physical LEC 1 WITH batteries	EUR 264.29	EUR 264.31	EUR 264.31	EUR 300.48	EUR 258.98	-	-
Physical LEC 2 WITHOUT batteries	EUR 478.91	EUR 478.96	EUR 478.92	EUR 559.82	EUR 476.03	EUR 836.03	-
Physical LEC 2 WITH batteries	EUR 259.76	EUR 259.73	EUR 259.78	EUR 300.15	EUR 253.62	EUR 700.16	-
Physical LEC 3 WITHOUT batteries	EUR 363.18	EUR 363.18	EUR 363.20	EUR 447.93	EUR 359.12	EUR 886.29	EUR 7678.49
Physical LEC 3 WITH batteries	EUR 139.67	EUR 139.60	EUR 139.71	EUR 183.98	EUR 134.07	EUR 762.02	EUR 7192.57
Virtual LEC 1 WITHOUT batteries (default)	EUR 517.85	EUR 517.89	EUR 517.81	EUR 589.22	EUR 517.11	-	-
Virtual LEC 2 WITH batteries (default)	EUR 550,33	EUR 550.38	EUR 550.29	EUR 626.27	EUR 549.55	EUR 1144.02	-
Virtual LEC 3 WITH batteries (default)	EUR 641.22	EUR 641.27	EUR 641.14	EUR 724.28	EUR 639.34	EUR 1385.83	EUR 10,029.78

5. Discussion

The studied alternatives have different characteristics and depend on the number of partners, each of whom has consumption profiles that vary according to their activities. When sizing photovoltaic systems with storage for different locations (Tolosa, physical LEC, and virtual LEC Málaga), it has been observed that the installed power of a photovoltaic system is much higher in Tolosa than in Málaga due to differences in irradiance levels between the two areas. The main challenge in sizing the systems for each alternative is the availability of space for installing solar panels, as more surface area is required for installation as the installed power of the system increases.

The analysis of the economic aspects has confirmed a reduction in the value of electricity consumption of the network by more than 50% in some cases. The goal of implementing an LEC is to reduce the electric bill as much as possible. However, reaching a consumption value equal to zero requires a greater investment, larger location areas, higher operation and maintenance expenses, and, in virtual LECs, an increase in land rental expenses. While a more powerful system can further reduce the value of the invoice, the aforementioned factors may represent obstacles to taking such an action. For the physical LEC of alternative 1, savings of up to EUR 71,514.48 can be generated in the best-case scenario during the

25-year useful life. In the physical LEC of alternative 2, savings of up to EUR 108,929.81 can be generated in the best-case scenario. In the physical LEC of alternative 3, savings of up to EUR 343,243.23 can be generated. On the other hand, for the virtual LECs of alternatives 1, 2, and 3, savings of up to EUR 37,949.92, EUR 52,562.46, and EUR 192,734.07 can be generated, respectively.

There are greater savings in physical LECs than in virtual ones, and this is due to several factors. For virtual LECs, it is necessary to pay the rent for a plot of land in Malaga for the installation, and the price is proportional to the required size. Additionally, if an agreement that benefits both the inhabitants of Málaga and the members of the LECs in Tolosa is not reached, the energy must be fully transferred to the network and participate in the market for the sale of energy, which in some cases can be marketed at relatively low prices.

The current regulations are a major obstacle to the implementation of this type of project. The absence of some regulations tends to create problems between the members of the LEC or with the different components of the Spanish electrical system. In recent years, greater attention has been paid to this type of alternative, as energy transition is a goal that can be achieved through the development of these systems.

The application of LECs can generate environmental benefits. For alternative 1, approximately 5.82 tons of CO_2 emissions can be avoided annually. For alternative 2, approximately 8.07 tons of CO_2 emissions can be avoided annually. For alternative 3, approximately 24.25 tons of CO_2 emissions can be avoided annually.

6. Conclusions

The study carried out in this project presents different types of energy communities and proposes an optimal energy-management algorithm applying a dynamic distribution factor. The results obtained from this study conclude that being a member of an energy community always provides an economic benefit, which will vary to a greater or lesser extent depending mainly on two factors: the available surface area for the installation of the photovoltaic generation system and the type of consumer.

Based on the results, it seems clear that in the case of setting up a physical LEC, including batteries is not an option, since the economic benefit obtained by participants, regardless of their type (residential, commercial, or small industry), is significantly higher without them. Additionally, it is concluded that the benefit for residential consumers decreases as more participants with much higher consumption (commercial and industrial) are added to the community. This is because the majority of residential consumers lower their consumption levels during the peak hours of the day, when commercial and industrial consumers usually maintain high levels of consumption. In other words, photovoltaic generation during the peak hours of the day mainly supplies commercial and industrial participants. However, the participation of commercial and industrial consumers in a community energy project does increase their benefits (see Table 14).

Regarding virtual LECs, it is concluded that the greatest savings on the electricity bill are obtained by including energy storage systems (with the exception of LECs consisting solely of residential participants). However, when comparing physical and virtual LECs, it is observed that physical ones appear to be the better option at present.

Author Contributions: Conceptualization, I.L.; methodology, I.L. and L.E.G.; software, L.E.G. and J.G.-C.; validation, I.L. and I.A.; formal analysis, J.M.; investigation, I.L., L.E.G., J.G.-C. and I.A.; resources, I.L.; writing—original draft preparation, I.L.; writing—review and editing, J.G.-C., I.A. and J.M. All authors have read and agreed to the published version of the manuscript.

Funding: This work is financially supported by the Basque Government under Grant IT1647-22 (ELEKTRIKER research group), and by the Ministerio de Ciencia e Innovación, the Agencia Estatal de Investigación. and the European Union under Grant TED2021-129930A-I00 funded by MCIN/AEI/10.13039/501100011033 and by the "European Union NextGenerationEU/PRTR".

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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