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Community energy solutions for addressing energy poverty: A local case study in Spain

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ABSTRACT

Advancements in renewable energy technologies, a growing awareness of the need for sustainable energy solutions, and the emergence of new business models in the energy sector, have contributed to the growth of Energy Communities. Public entities can find in energy communities today an opportunity to tackle energy poverty, to increase the cooperation among citizens and to empower them to be a more active player within the energy sector. This paper analyzes energy communities in Europe and focuses specifically on Spain; considering the three beneficial aspects previously mentioned. It aims to obtain ground truth about the applications of these new citizens' arrangements. A citizen-led initiative at the city of Getafe (Madrid, Spain) is included and discussed in detail. This case study focused on reducing energy poverty of its participants. An energy community was designed and implemented as a collective PV solar self-consumption infrastructure. The roofs of various public buildings in the two case study neighborhoods were selected for locating the PV installations. Real metered data were used to evaluate the solution. A public building was selected for the energy community, considering generation on roof and dwellings proximity. The results provided that out of the 77% PV generations could be used to contribute to the demand of 100 residences; while the resulting 23% would provide approximately 60% of the energy demand of the public building. The setting up of the Energy Community not only had the technical part but also included workshops seminars and information sessions, to ensure that people prone to benefit and maximize its impact.

1. Introduction

Energy transition in the European Union involves establishing a new energy model with lower emissions and respect for the environment. Moreover, the COVID-19 pandemic has caused unusual global energy demands and an increase energy prices [1]. The recent Ukrainian crisis has aggravated the situation, clearly influencing how power is generated, distributed, managed, and consumed. In this scenario, the decarbonization movement towards a cleaner and decentralized energy model has encouraged renewable energy integration into current power networks. This is similar to other sectors, such as electrical conditioning or the electrical mobility sector, which are still highly dependent on fossil fuel and have substantial carbon footprints. In recent decades, technologies to foster renewable energy sources (RESs) have experienced a steady growth, resulting in high penetration levels within the power grid. However, the fluctuations inherent to these energy sources have had an impact on the grid [2]. The integration of electric mobility in the transportation sector presents a similar scenario, imposing an additional burden on European energy systems [3]. In addition to the increasing demand on most power systems, system operators also face other challenges. In fact, they face the major challenge of ensuring adequate management and balancing of power demand, as renewable technologies which yield cannot be adjusted, become more numerous into power systems. Establishing a new market and ensuring that power standards are not compromised, is key for ensuring a secure supply and power availability in this new situation. As renewable technologies continue to grow and evolve, it is imperative to implement appropriate measures to maintain the reliability and stability of power systems [4].

One of the opportunities that brings local generation is self-consumption. The definitions, conditions and characteristics of

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individual and collective self-consumption activities, are defined in the European legislation of the Renewable Energy Directive (RED II), which is part of the Clean Energy for all Europeans Package (CEP) [5]. The so called collective self-consumption is usually based on individual energy producers that are controlled, operated, and their production distributed as a single collective. Photovoltaic (PV) technology is the most common way of renewable energy generation for collective local production or for small distributed renewable units, which are typically installed on rooftops or near locations where electric power is required. Recent initiatives and policies promote the adoption of renewable energy by the public, and it stimulate the neighborhood to generate electric power via these collective self-consumption installations [6]. A self-consumption installation allows end users to first cover their demands and sell their surplus, according to their load demand profiles within the legal frameworks and conditions of the country. This usually offers end customers remarkable storage and energy flexibility [7,8]. Over the past few years, Renewable Energy Cooperatives (RE Co-ops) have emerged, aiming to generate and distribute RES production among their members while reducing national and international energy dependency [9. In addition, other solutions such as Local Energy Markets (LEM), have also encouraged end-user to exchange energy and to equilibrate the power system balance between the demand and supply sides in a competitive market [10]. In this context, energy-efficient homes, including zero-energy buildings (ZEB), are primarily concerned with energy savings, energy efficiency, and sustainability. If these buildings are associated to facilitate collective self-consumption, those savings could be even more noticeable. Moreover, citizens are becoming more conscious of their energy consumption behaviour, thereby assuming a more active role in the energy sector. Energy Community projects were recognized under European legislation (the previously CEP directive). Currently, both Renewable Energy Communities (RECs) and Citizen Energy Communities (CECs) are within the energy communities (ECs) and are considered non-commercial market actors [11].

The European Commission in the Renewable Energy Directive states that each member state must develop a legal framework to enable the development and implementation of Ecs [12]. With respect to the previously mentioned self-consumption, system management in an energy community to achieve it requires legal definitions. An example of that is defining how energy management should be developed or how contractual energy management should be carried out among community participants [13]). In the south of France, a real case study of an Energy Community (EC) involved seven households. The focus of this case study was on the management aspect. Each household has a photovoltaic setup, with four 3.2 kW plants, except for one household that has a 6.12 kW plant. Two households, however, do not have any photovoltaic installations, but yet they benefited from it. The results when the households are organized as an energy community to exploit collective self-consumption show a potential bill reduction of 11.7% [13]. In Italy, an EC of two office users in southern Italy have a 9 kW and 14.25 kW peak power of PV plant in their respective roofs. The community when undertaking self-consumption covered 75% of their demand with the energy generated on site. This means, that the community would be able to reduce dependency on external sources [14]. Another relevant study was found that comprised ten single-family houses, with five of them equipped with photovoltaic (PV) plants installed on their roofs. Through the sharing of PV electricity within the community, the self-consumption of PV was enough to cover consumption from 23% and 32%, resulting in enhanced energy independence [15]. Also in this study, they focused on assessing the impact of different self-consumption management methods and costs within the community, without falling into situations of energy vulnerability. Note that approximately 8% of all EU households were not able to adequately heat their homes in 2020 [16], and this scenario is expected to worsen because of the uncertain global energy supply situation and rising energy prices. Energy poverty is commonly associated with low-income households that cannot afford heating [17]. From the perspective of the community, energy solvency can be achieved, and energy vulnerability situations reduced by EC implementation, which signals positive resilience [12,18]. The empowerment of citizens through Ecs promotes sustainable, social, and environmentally friendly models of living at different levels. Various studies indicate that the interest of citizens in participating in renewable initiatives exceeds 70% [19], which is clearly beneficial for the continued development of Ecs, with citizens at the forefront. In most cases examined, large public programs of energy efficiency in European homes are not primarily or specifically aimed at improving the housing conditions of the energy-poor [20]. Unquestionably, one of the main elements with greater potential for improving policy design is directing cost-effective programs, both energy efficiency and renewable energy, to vulnerable populations; for instance, impacting elders affected by energy poverty not only in the short term as a measure of income but also in the medium and long-term considering their living conditions. The contribution of this study to existing research dealing with energy communities and their use to alleviate energy poverty, emphasizes the opportunities offered by Ecs to promote energy efficiency at the household level and highlights Ecs as mechanisms to combat energy poverty by reducing consumption in the presence of less expensive supply prices, in accordance with Directive (EU) 2018/2001 [7].

Under this framework of EC potential, this study includes a state-of-the-art analysis of Ecs and a practical case study of a real Spanish EC created considering the data consumed by their participants. The case study illustrated a proposed citizen-led initiative that aims to tackle energy poverty through energy communities (Ecs), and involves collaborative partnerships between public entities and citizens. Within the framework of this study, the EC consisted of a public building as well as vulnerable and non-vulnerable households (with their respective occupants), with the latter constituting energy-poor households. The public building used with a PV installation for collective self-consumption was the energy producer. The costs of solar PV installation was considered to be shared between the public buildings and the non-vulnerable participants. The energy generated was shared among all participants (the public building, vulnerable households, and non-vulnerable households). Vulnerable participants were exempt from paying the designated fee to pay back the initial installation investment. They benefited from energy-cost savings, similar to the other participants. This initiative focused on the reduction of energy poverty and the promotion of Ecs from a global benefit perspective for all participants.

The remainder of this paper is organized as it follows: Section 2 discusses the literature concerning Ecs, energy poverty, and collective self-consumption as applied to the Spanish case study. Section 3 describes the technicalities of the creation of the energy community. Section 4 presents the technical and economic results. Section 5 discusses the results and the potential future applications and dissemination information regarding Ecs from a global perspective. Section 6 summarises the conclusions and Section 7 and 8 are the acknowledgment and references respectively.

2. Literature review

2.1. *Energy communities and energy poverty*

Renewable Energy Communities (REC) are entities that generate renewable energy locally [21]. RECs are allowed to participate in all segments of the energy supply chain and are not required to meet full consumer demand. They have to be accessible to low-income households. In addition, they can constitute either energy generators or distributors that participate in everything from energy consumption to energy storage. Members may be individuals, local authorities, companies, or any combination of these role-players. Recent research contributions [22] do not elucidate the link between RECs and vulnerable citizens, particularly those suffering from energy poverty. Moreover, these authors emphasized that the so called flexibility, such as demand response events, active network management, and storage, is a key factor in improving the capacity and economics of RECs. RECs have been implemented in multiple ways and for various purposes in Europe. However, their establishment has not yet been fully indorsed in the national laws of all EU member states. At the international level, current regulations have a general tendency to continuously adapt to European guidelines as European legislation evolves [23,24]. Studies focusing on REC have shown the existence of complex interactions between actor-institutional, material-economic, and discursive factors [25]. A schematic overview of European Ecs for each EU member state is presented in [26], including Belgium, Croatia, Estonia, Greece, Germany, Italy, the Netherlands, Poland, Portugal, Slovenia, Spain, and Sweden. Various studies on Ecs in Europe have shown increasing interest in this sector in recent years [27–33]. RECs are derived from the cooperatives of "prosumers" based on renewables throughout Europe. Most are grouped under the Re Co-op Federation, which consists of more than 1,500 cooperatives (more than one million members) and that provides marketing, mobility, efficiency, electricity generation, and heating services. The long history of energy cooperatives in northern European countries explains why the majority of identified Ecs are involved in self-consumption and surplus generation trading [34]. In addition to the advantages offered by Ecs, a number of obstacles are currently identified that may slow down their development: (i) the lack of a regulatory framework or insufficient degree of its development; (ii) changes in regulations or decreases in incentives; (iii) complexity when carrying out administrative procedures; (iv) difficulties in accessing expert knowledge; (v) challenges in securing financing (e.g., lack of investor confidence, high risk, or negative investor perception); and (vi) low motivation on the part of community members. Among the key success factors, supportive governance has been identified as a decisive factor. The role of subnational policy actors is considered essential; these include state, regional, provincial, and local governments [35–37]. According to a number of studies, this role is decisive for the viability and success of Ecs development. [38] highlighted experimentation, articulation of demand, learning of policies, and coordination between actors as key enabling factors. The implementation of Ecs is expected to be linked to the largest investments in distributed renewable energy resources [39].

Regarding the Spanish case study, an EC is defined as a legal entity based on open and voluntary participation and effectively controlled by partners or members who are natural persons, companies, or local entities. These partners or members are responsible for developing renewable energy resources, energy efficiency, and mobility projects. These projects are aimed at providing environmental, economic, or social benefits to these partners or members or to the local areas in which they operate, as opposed to financial gains. Other communities that focus on the development of renewable energy resources, energy efficiency, and sustainable mobility projects may also be considered Ecs. Moreover, Ecs may be established either by national or applicable European regulations on ecological transition or the energy sector. The REC (Article 6 of Law 24/2013 [40] and RDL 23/2020) has a broader scope. The concept of a citizen energy community has not yet been included in the Spanish legal system. It is defined in EU Directive 2019/944 [23] as a common standard for the internal electricity market, and its scope is broader than that of a renewable energy community. In Spain, the first renewable energy consumer cooperative was established less than ten years ago [41] (excluding the historic Valencian cooperatives), and there are currently approximately 120,000 members distributed across cooperatives with headquarters in ten distinct autonomous regions. The IDAE [42], gathers and frequently updates information on the locations and characteristics of more than 280 established Spanish Ecs as well as those projects that are currently planned. In a recently published report by Red Eléctrica de España, the Spanish TSO [41] provides information on 15 rural Ecs in Spain. Some of these rural Ecs and their primary objectives are presented in Table 1. The general objective of these Ecs is to promote a more sustainable, decentralized, and participatory energy system. These objectives are pursued by encouraging shared self-consumption, promoting sustainable development, and strengthening community governance. Only in the ECs of the Rupiá (Catalonia), Albalat dels Sorells (Valencian Community) and Río Monachil (Andalusia), is one of the primary objectives to combat energy poverty by providing renewable energy generated in the community to families in need. However, there are differences in ownership, participation, and distribution between these communities. In the Rupiá EC, the city council is the sole owner of the installation and determines the distribution of energy among consumers. In the Río Monachil EC, the PV installation is located in a public building ceded to the EC without being a part of it. With respect to the Albalat dels Sorells EC, energy cooperatives constitute the owners of the PV installations. There are significant innovations in the present case study. Here, the city council does not participate in the EC, whereas the public building housing the PV installation is considered a participant. In addition, they and the other participants share the costs of the renewable installation. In [43], the creation and development processes of three Spanish Ecs are detailed in three different modalities: (i) the Mediona Energy Community (rural), (ii) the Community Bufalvent Industrial Estate (industrial), and (iii) the Vilanoveta Energy Community (private urban). Energy poverty mitigation is gaining significance in the context of Ecs in the southern and eastern European member states. Project DECIDE [44] published "Energy Community Monitors," which provides an overview of the regulatory developments related to Ecs in all 27 EU member states. Greece has explicitly embedded the reduction of energy poverty as a primary objective of Ecs within its legal framework. In particular, this included the incorporation of low-income households in the Greek net metering scheme without the requirement of EU membership [5]. Portugal, Bulgaria, and Hungary plan to focus on energy poverty in their upcoming legislation on Ecs, according to their national energy and climate plans. Initiatives such as POWERPOOR [45] stand out, which aims to support energy-vulnerable citizens in 11 European countries in implementing energy-saving measures and on participating in joint initiatives to nurture Ecs. This project is coordinated by the National Polytechnic University of Athens. Among the few cases identified, the EC Torreblanca Ilumina [46] in Spain and the Spanish initiative 'La Energía del Cole' [47], which aims to combat energy poverty by producing enough renewable solar energy through PV panels installed in a rural school to also serve the families of children, stand out. The EC Torreblanca Ilumina [46] is unique among Spanish Ecs in that it was originally established with the aim of combating energy poverty. This EC launched solidarity measures to alleviate energy vulnerabilities and guarantee the right to energy for a portion of the residents of that Spanish city. Energy poverty is a multidimensional concept that reflects the disparity between the energy needs of many European families and their economic situation [48–50].

The factors that affect energy poverty levels are: household income, price of energy and degree of energy efficiency achieved in households [51,52] among others. There is no just one indicator to measure energy poverty. Energy poverty not only impacts the functionality of homes but also it affects several other aspects, including health and the social stigma faced by the affected groups [53]. Solidarity and participation are levers that must be integrated, along with initiatives to improve the quality of life for the portion of the urban population living in energy poverty in order to create a more sustainable society [54,55].

2.2. Electrical rates and collective self-consumption

The electrical market is divided into a free market and a regulated market for buying and selling energy, which are distinguished by domestic energy and power prices. There are common parameters for both markets: power fixed term (€/kW), including distribution and transport taxes and other charges; energy fixed term (€/kW); supplier profit margin; electrical fee; value-added tax (VAT); and measuring equipment rental fee. The Spanish regulated market established by the 2021 Royal

Table 1
Spanish rural Energy Communities.

Region	**Rural EC**	**Description**	**Participants***	**Website**
Andalucía	ALUMBRA	Energy community with shared self-consumption installations and focused on promoting sustainable development in their rural area and citizenship empowerment	Residents, local businesses, and energy cooperatives	https://www.tierra.org/comunidades-energeticas/alumbra-un-proceso-de-participacion-y-dialogo-en-arrollomolinos-de-leon-huelva/
	Monachil Comunidad Energética del Río Monachil	Public-private-citizen association with collective self-consumption on a roof on loan from a municipal sports center. A part of the energy produced is allocated to vulnerable citizens	Residents, SMEs and associations	https://cermonachil.org/
Aragón	Luco Energia Comunidad Energética	First rural energy community partially financed by members, crowdfunding, and crowdlending. It is shown as a cooperative local business model	20 families, City Council and local business	https://www.germinadorsocial.com/projectes/luco-energia/
Castilla y León	Comunidad Energética Local de Agés	Initiative to promote renewable energy and community governance to meet the challenge of population loss	Local public administrations, residents and some local business	https://www.germinadorsocial.com/projectes/ages-comun-es-el-sol-y-el-viento/
	Comunidad Energética Renovable de Vega Valcarce	Pilot project focusing on self-consumption, sustainable agriculture, and digital connectivity	Residents and local SMEs	https://revieval.org/es/pilot-community-esp/
	Hacendera Solar	Prototype of a model that seeks synergies between the different facilities in the village. It aims to reduce carbon emissions and energy use for the area and the residents	City Council building, museum, doctor’s surgery, and a renovated house	https://www.ree.es/es/sostenibilidad/proyectos-destacados/innovacion-social/primer-modelo-autoconsumo-comunitario
Cataluña	Comunidad local de energía de Rupià	Promotion of collective self-consumption, distributed resource management, and digital platforms for data and energy management. It aims at reducing energy poverty by incorporating families in energy poverty situations within the EC	Town Council, residents, local businesses, and some families in energy poverty situations	[41], https://adegua.com/wp-content/uploads/2021/09/CLE-DiGi-Castellano-1.pdf
Comunidad Foral de Navarra	GARES BIDE. Comunidad ciudadana de energías	Initiation of a collective self-consumption project driven by citizens	Residents, local businesses, and SMEs	https://www.garesenergia.org/wpdes/garesbide/
Comunidad Valenciana	Comunidad Energética Local de Albalat dels Sorells	A community energy project seen as a cooperative to make the municipality a sustainability leader in Valencia, with citizen involvement in energy management and support for families in energy poverty situations	Citizens and any local business that want to enter in the EC will become a partner of Sapiens Energia	https://sapiensenergia.es/project/comunidad-energetica-albalat-dels-sorells/
Galicia	Comunidade enerxética de Tameiga	The energy community aims to promote collective self-consumption with simplified surplus compensation and grid sales while incorporating generation capacity in households, intelligently managing energy data, and developing storage projects	Parish, City Council and Citizens of the commune	https://www.tameiga.com/
País Vasco	EKINDAR Comunidad energética local de Azpeitia	The EC is a public-cooperative model that focuses on local energy self-consumption through a solar installation in a solar garden format	400 families	https://ekiola.eus/es/azpeitia-ekindar/
	Comunidad de energías renovables de Hernani	Model focused on achieving local energy sovereignty, promoting renewable energy adoption, improving energy efficiency, and fostering citizen participation in the energy transition	Residents, SMEs, Municipality of Hernani and local associations	https://burujabe.hernani.eus/es/energia
	Comunidad Energética de Lasierra	EC pilot project based on a shared PV self-consumption installation. The governance follows the “one meter one vote” principle	12 residents and the owner of the renewable generation source	https://www.udalbiltza.eus/es/hartueman/comunidad-energetica-de-lasierra

** Promoters and partners have not been included.*

Legislative Decree 1/2019 was recently modified. The various electrical rates of the PVPC (Spanish acronym of voluntary price for small consumer) were consolidated into a single rate termed 2.0TD, and the maximum nominal power capacity per household is 15 kW. In this tariff three energy periods (peak, off-peak, and standard) are considered, and their price differentiated. The power periods were categorized into peak and off-peak periods, with the possibility of modifying the energy consumed during these periods. Currently, only eight reference suppliers offer PVPC. The National Commission for Markets and Competence (CNMC for the Spanish acronym) is the entity that establishes the tolls for the tariffs. In addition, CNMC can impose penalties based on hourly consumption during periods of peak energy demand [56]. Each electrical supplier establishes its own rates based on the free market. They can introduce potential price changes, such as offering a fixed price for energy or power or a stablishing a variable price depending on the time period, as well as other economic decisions [56]. There is a social bonus based on various types of discounts in the electrical bill, and it is necessary to have a PVPC rate that meets the requirements set by Act 24/2013 [40], December 26. Owing to the current energy crisis, the Royal Legislative Decree 18/2022, of October 18 [57] established the energy justice social bonus.

In Spain, collective self-consumption is currently divided into various modalities depending on whether there exist energy surplus, there is connection to the external grid, or if they include compensation (Law 24/2013 [40]). Fig. 1 summarizes the current Spanish collective self-consumption modalities. Note that two factors, namely distribution coefficients and compensation type, are parameters to take into consideration in these Spanish classification. Utilizing distribution coefficients, the energy produced by the self-consumption installation is distributed among the participants. Prior to the new proposal of Royal Decree, the coefficients were always constant, maintaining the same distribution throughout the year for users. This new order approves dynamic coefficients. Therefore, users of self-consumption installations agree on variable distribution coefficients, with distribution percentages

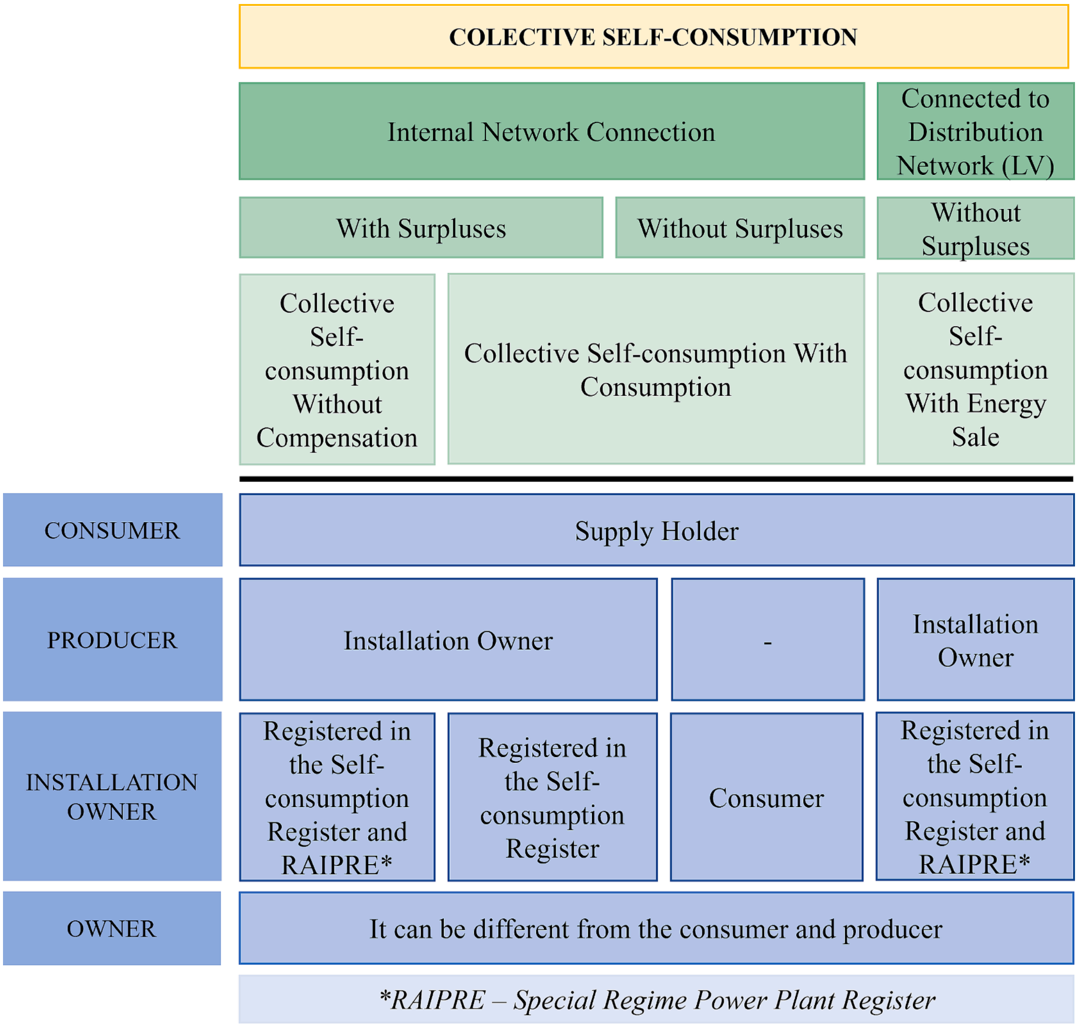

Fig. 1. Overview of collective self-consumption modalities.

that can be modified every four months [58].

To simplify the compensation process, the power rate of each installation must be lower than 100 kW [59]. In addition, users of collective self-consumption installations must consider the following main aspects: (i) participants and installations must be registered in the same cadastral reference; (ii) low-voltage distribution and transformers must be considered for participants and generation unit installations; (iii) the maximum distance between the generator and consumers is 500 m; and (iv) the total power of the installation corresponds to the inverter or group of inverters. Note that with the recent Spanish Plan + SE, some of these aspects were modified to improve the promotion of collective self-consumption, with a maximum distance of 2 km currently allowed between the generator and the potential consumers [60,61].

3. Methodology of study

Before delving into the following subsections of the methodology about the citizen-led initiative in Getafe (Madrid, Spain), a comprehensive overview of the methodology employed is provided in Fig. 2.

The methodology starts with the analysis of the local situation in Getafe, which serves as the focal point for the case study of the citizen-led initiative on collective self-consumption EC. Two specific neighbourhoods were chosen, and within them, four public buildings were selected. Subsequently, there are presented the solar resource study, orientation analysis, and definition of various scenarios for the installation of photovoltaic systems on the rooftops of the public buildings. Subsequently, the sizing and simulation of the photovoltaic installations are carried out. Following this, the subsection corresponds to the data consumption collected which belongs to public buildings and households (including both vulnerable and non-vulnerable households). They would form part of the energy community. Finally, it is presented the selection of the final public building where the photovoltaic system for the collective self-consumption of the EC would be installed. In addition, the final distribution of the energy community is described in the technical and economic result section.

3.1. Location

As mentioned in the abstract, this work considered a case study on the suburbs of Madrid (Getafe). This specific location was chosen as suburbs surrounding big cities are highly numerous all over the world, and they host in many cases a substantial number of residents under the risk of energy poverty. Therefore, the methodology can be adapted for each suburb considering the legal and technical characteristics fo the country. As previously mentioned in Section 2, the identification of energy poverty is not carried out through a single measure. The European Union provides a tool that incorporates various indicators to help measure the level of energy poverty in member states. Some of the indicators used by the EU include the inability to keep the home adequately warm, being at risk of poverty or social exclusion, and arrears on utility bills, among others. Analysis of these indicators reveals that countries with a high prevalence of the first indicator in 2022 are

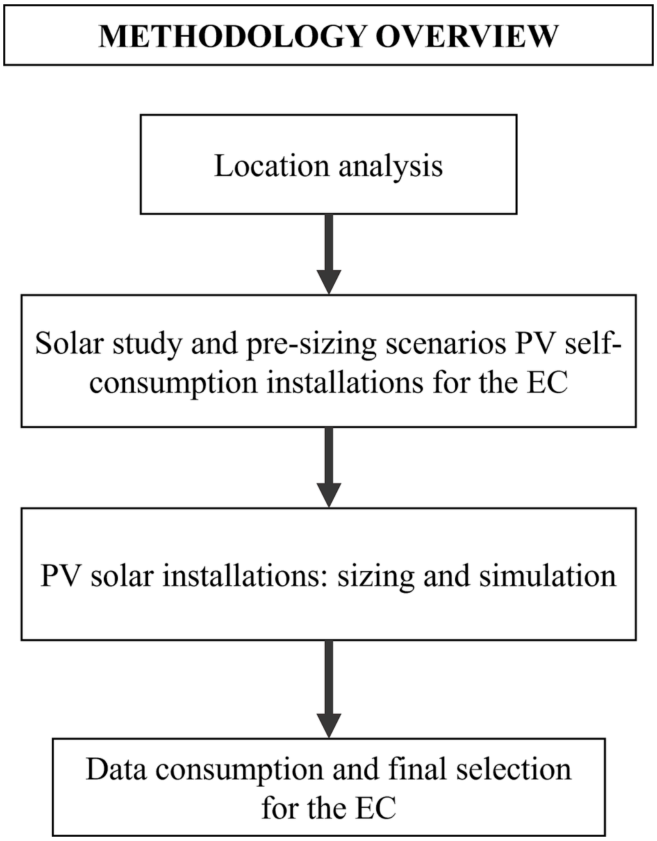

Fig. 2. Methodology overview.

primarily Bulgaria, Greece, Portugal, Lithuania, and Greece (ranging from 22% to 17%), followed by Spain, Romania, and France (ranging from 17% to 11%), and subsequently by Italy, Latvia, Ireland, and Slovakia (approximately around 8%) [50]. In the UK, data from 2021 indicates that in the West Midlands, Yorkshire and the Humber experienced the highest rates of fuel poverty among all regions, being 18.5% and 16.5%, respectively. After them, there are the regions of the South East with 8.4%, South West with 11.9%, and London with 11.9% of fuel poverty. In the city of London, areas with significant levels of energy poverty include Newham, Waltham Forest, and Barking and Dagenham. It is likely that the older Victorian housings, in less affluent areas, play a significant role in energy poverty in London. This type of housing **is** often characterized by solid walls and lack of insulation [62].

The population of Getafe has an energy vulnerability rate approximately 30% higher than the average rate for the Community of Madrid. In our case study, hidden energy poverty, which is estimated to affect around 15–30% of the households (i.e., 55,677 Getafe residents), is exacerbated by the wage structure of the people living in that area, with an average income that is €5,071 smaller than that of the rest of the Community of Madrid [63]. It has been found that 19.88% of the inhabitants had an average monthly electricity consumption of less than 100 kWh. Also, as an important fact, it should be noted that more than 55% of the residences in our case study were constructed prior to 1980. This study focuses on Las Margaritas and La Alhóndiga neighbourhoods because of their high rate of collective housing, poor construction quality (prior to 1979), small size, inadequate heating and their similarities with other suburbs. Economic vulnerability is concentrated in the most vulnerable sections at the energy and building levels. Furthermore, around 48% of households lack a heating system, and households are occupied by vulnerable groups facing social exclusion [63].

3.2. Solar study and pre-sizing scenarios of PV self-consumption installations for the EC

Four public buildings in the Las Margaritas and La Alhóndiga neighborhoods of Getafe (Madrid, Spain) were evaluated and analyzed as potential locations for installing PV solar systems on their roofs and constituting an Energy Community. Fig. 3 depicts pictures of the roofs of these public buildings: the *Juan de la Cierva* Municipal Sports Center (JCMSC) and Las Margaritas' Civic Center (MCV), located in Las Margaritas; and La Alhóndiga's Civic Center (LACC) and the Education Delegation of the City Council of Getafe (EDCCG), located in La Alhóndiga. The PV solar energy producer was intended for collective self-consumption and to supply both the building itself and the households within a distance of 500 m from the PV solar, constituting in this way an EC.

The Photovoltaic Geographical Information Software (PVGIS) [64], in conjunction with the SARAH-2 database, was used to evaluate the best location for the PV solar generated and its size and orientation. To achieve this aim, the solar resource in Getafe (40.305°, −3.731°) was considered with a completely horizontal tilt angle of 0° and compared to the annual irradiation calculated with PVGIS for the optimal tilt angle of Getafe: 37°. With an optimal tilt angle of the PV panels, the irradiance was higher throughout the year without a remarkable change during the summer months, when the irradiance was similar for the two tilt angles. The total annual irradiance was 1,799.64 kWh/m^2 and 2,109.19 kWh/m^2 at 0° and 37°, respectively. Based on this initial solar-resource analysis, preliminary calculations were performed for each building. Two power-capacity scenarios were estimated based on the roof slope and orientation. In both cases, the available surface area and slope of each roof were determined using Google Earth. The selected PV solar panel was considered to be a commercial Jinko mono perc half-cell module solar panel (Cheetah HC 72 M 410 W). In the following the different scenarios, named as cases, that have been seen as options are described:

CASE A: If the roof was sloping, coplanar PV solar panels were installed to take advantage of the surface area. Case A involved the building of Las Margaritas Civic Center with a slope of 22°, which was the tilt angle specified for the PV solar panels. The preliminary maximum annual energy production was determined using Eq. (1).

$$Max.annualprod.(kWh) = \mu\hat{A}\cdot Availablesurface\left(m^2\right)\\ \hat{A}\cdot AnnualIrradiation\left(\frac{kWh}{m^2}\right) \tag{1}$$

being $Max.annualprod.$ the production of energy in kWh, μ the efficiency of the solar system, *Availablesurface* the surface of the PV solar panel, and *AnnualIrradiation* the solar irradiance (resource) in kWh/m^2.

CASE B: Two options were considered for Case B, both with the optimal tilt angle but different PV solar panel orientations: (B1) south orientation at 0°; and (B2) orientation according to each roof structure distribution. PVsyst [65] was used as a pre-sizing tool for PV solar system energy estimation based on several parameters for evaluating Case B: (i) meteorological location with the SARAH database, (ii) horizon line of Getafe, and (iii) PV installation based on the surface area of each available roof, tilt angle and the azimuth of solar modules, and distance between each array of PV panels in order to avoid undesirable shadows. This was calculated in accordance with Annex III of the Technical Conditions for Grid-Connected Installations of the IDAE (the Spanish public entity of the Institute of Diversification and Savings of Energy). The PVsyst pre-sizing tool did not account for energy losses or shadows caused by trees or other buildings but they were assumed to be minor. The distribution of the PV solar modules for Case B2 was based on covering the largest roof surface parallel to the walls defining the building. Thus, they were oriented between the south and west. PV generation typically supplies the greatest domestic consumption, usually after the working day (afternoon onward). There were additional

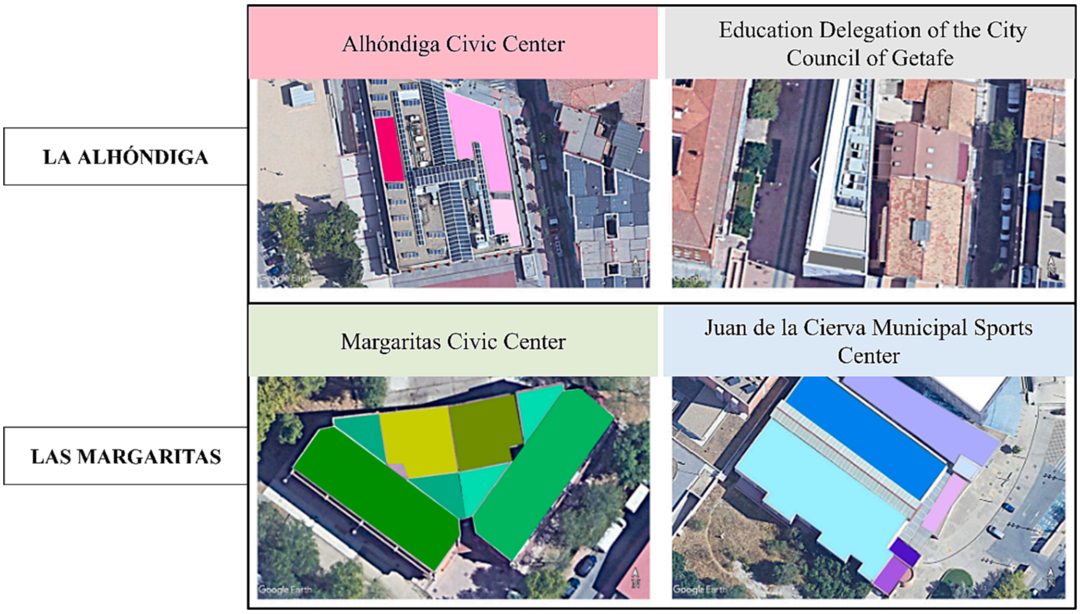

Fig. 3. Roofs of the public's buildings in Las Margaritas and La Alhóndiga (Getafe, Madrid, Spain).

technical characteristics required to complete the pre-sizing process for both options, such as the type of PV module, technology, ventilation, and mounting arrangement (flat or inclined roof). The other three buildings were not included in Case A and there were no significant slopes on the building roofs.

3.3. PV solar installations: Sizing and simulation

The PV solar installation sizing and simulation of each building were performed using the PVsyst software package. Considering the commercial Jinko solar panel (410 Wp), the minimum power installed in the inverter was calculated based on the number of PV solar panels estimated by considering the available surface of each building. The calculation method can be seen in Eq. (2).

$$P_{installed} > 0.8\hat{A}\cdot(N_{PVsolarpanels}\hat{A}\cdot P_{PVsolarpanels}) \quad (2)$$

The following process was considered for each building simulation case: (i) Meteorological data from Getafe (Madrid, Spain). (ii) Differentiation of pre-sizing cases: A, B1, and B2. (iii) Orientation and tilt angle in each case study. (iv) Definition and selection of each PV array and inverter. For the case of the Civic Center "Las Margaritas," where there were different orientations with the same slope, an inverter with several MPPT[1] inputs were favorable to the design. MPPT inverters allow the connection of different orientations, allowing energy production to be wider and more stable during the day owing to the east–west design. (v) The building structure was designed with AutoCAD and Sketchup PRO for the 3D dimension to be imported into PVsyst to design the potential external shadows (of buildings and trees). (vi) Simulation of PVsyst and acquisition of the results. Table 2 summarizes the energy production results of the corresponding PVsyst simulations for cases A, B1, and B2.

3.4. Data consumption and public building final selection

According to the case studies described in the previous sections, it is necessary to consider that power generation must be split between residential units and public buildings in order to develop a collective self-consumption installation. The consumption data for public buildings and certain groups of households were provided by the city council of Getafe. The city council was a data source for public buildings and was not considered a case study participant in this study. Therefore, the data were supplied as part of the Getafe city council's participation in the European project of the Urban Innovative Actions program entitled EPIU "Getafe Healthy Homes" [63], which aimed to identify and reduce energy poverty in the neighborhoods of La Alhóndiga and Las Margaritas. These data cannot be disseminated for any other purpose or use other than thenvoicet investigation and the results presented in this work. With respect to data from the city council of Getafe and owing to COVID-19, the data used for public buildings corresponded to the year 2021. Table 3 lists the total power and costs of each public building in 2021. Regarding residential power demand data, two households with average domestic power consumption were considered. A contracted power supply of 5.50 kW for each house (Houses 1 and 2), relating to the Community of Madrid (Spain), was assumed, along with two additional energy-poor households: 3.30 kW (two individuals) and 3.45 kW (four individuals) of contracted power. Fig. 4 displays the monthly demand consumption of the corresponding vulnerable and non-vulnerable households in 2019. The final building selection was based on the assumption that the power demand of Las Margaritas Civic Center was lower than that of the other three public buildings. It was assumed that a significant percentage (if not all) of the building's power demand would be met. Subsequently, the La Alhóndiga Civic Center and the Juan de la Cierva Sport Center were not considered. An additional reason was that the Delegation of the Council Center had given poor power generation values for both cases B1 and B2, with more than 10% undesirable shading losses, as defined in the Technical Conditions for Grid-Connected Installations of IDAE. However, Las Margaritas Civic Center provided lower shading shadows, 2.53%, and it was subsequently selected as the energy producer and a public entity participant in the collective self-consumption model installation. The EC was therefore created around this building.

Finally, in order to qualify as a collective self-consumption system with a surplus and a simplified compensation model according to national regulation,[2] the maximum installed power must not exceed 100 kWp. The PV solar installation of Las Margaritas Civic Center was

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[1] A common characteristic of inverters, the acronym stands for Multiple Power Point Tracking.

[2] RD 244/2019.

Table 2
Energy production results from PVsyst simulations of cases A, B1 and B2.

Case	Building (Acronym)	Orientation	N_{T_PV}	Inverter	Energy production (kWh/year)	PR	Total installed power (kW)
A	MCV	22/35 and 22/-54	192	1 × huawei SUN2000-70KTL-INMO	179,000	0.84	107.50
		22/126	56	1 × Sunny Tripower 20000TL-30			
		22/-145	56	1 × Symo 17.5–3-M			
B1	JCMSC	37/0	342	2 × SMA Sunny Tripower 60–10	221,000	0.80	60
	LACC	37/0	72	1 × Fronius ECO 25.0–3-S	47,600	0.82	25
	EDCCG	37/0	18	1 × Fronius Symo 7.0–3-M	10,068	0.70	7
B2	JCMSC	37/35	192	1 × Sunny Highpower-SHP 75–10	235,000	0.79	144
		37/35	170	1 × Sunny Tripower 60-US-10			
		37/-45	22	1 × SMA Sunny Mini Central 9000 TL			
	LACC	37/-10	72	1 × ECO 25.0–3-S	47,630	0.82	25
	EDCCG	37/10	18	1 × Fronius IG Plus 80 V-3	10,074	0.70	7

Table 3
Total power and costs for each public building during 2021.

Building (Acronym)	Total power (kW)	Total costs (€)
MCC	61,272	10,462
JCMSC	842,112	115,721
LACC	321,664	53,894
EDCCG	138,572	24,071

initially designed with 107.5 kWp of rated power. This PV solar installation was then resized in PVsyst by altering the number of solar panels and inverters, reducing the installed power to 95 kWp. As shown in Table 4, the total annual production was 162,000 kWh/year from 264 solar panels. As previously stated, the PV solar installation was subsequently designed using a commercial 410 Wp PV solar panel model JKM390-410 M−72H provided by Jinko Solar. There were three inverters consisted on one three-phase inverters: SHP 75–10 Sunny Highpower Peak1 of SMA with 75 kW and two inverters SUN2000-10KTL-M0 of Huawei with 10 kW each. Coplanar structures of the SolidRail System of k2-Systems were used for the inclined roofs.

4. Technical and economic results

Assuming that the annual total energy consumption of Las Margaritas Civic Center was 62,000 kWh/year and that the housings that benefited from the PV solar energy production were within the 500 m distance of the public building, the 95 kW of total installed power was divided between these households and the public building.

It was established at a tentative value of 60% to achieve self-consumption by the public building. The remaining 40% would be consumed from the electrical grid. PVsyst tool was used to simulate the public building as the only consumer of the PV installation. The amount of energy consumed by the public building was obtained to be 43,653 kWh, which was generated by the rooftop PV installation. Este valor supera el porcentaje previamente comentado de autoconsumo por parte de dicho edificio. Consequently, the remaining solar energy produced is allocated to the households. This corresponds to a 77% of the 162,000 kWh produced by the PV installation. This percentage has been used as a reference for the economic aspects. It was assigned a 77% of the investment costs of the PV installation to the households, while the remaining percentage will be assumed by the public building.

Table 4 provides an overview of the energy output of the PV solar installations. A static coefficient has been chosen to determine the proportion of electricity that goes to each one of the consumers, this is a common practice in Spain in the negotiation with the DSO. The selected static coefficient was 0.140 kWh, which corresponded to the production of two PV solar panels. Subsequently, a group of 100 dwellings were considered to constitute the EC, which was determined by considering the amount of energy produced by the installation, 14.24 kWh, over the static coefficient.

As the study we performed had to represent accurately the Spanish building stock on suburbs, we classified the 100 households on several groups that represent archetypes, and we assigned them with realistic proportions. Spanish differentiation of housing units with different electrical rate models was used to determine the economic savings in electric bills (PVPC rates). From the initial group of 100 households, 30 were considered to experience energy poverty with PVPC, 15 had a 2-

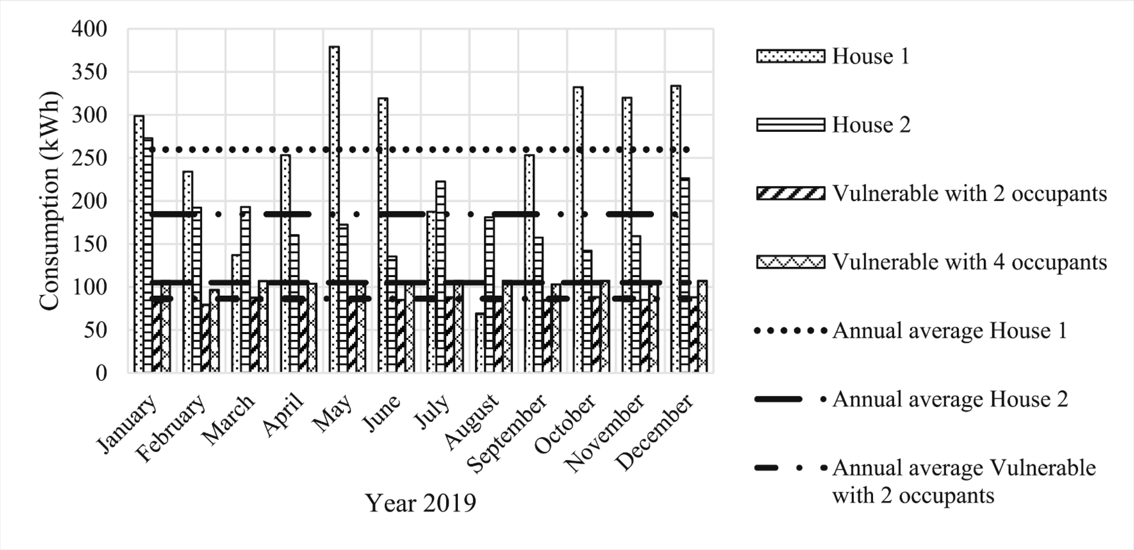

Fig. 4. Monthly consumptions of houses in 2019.

Table 4
Production of the PV solar installation in the selected public building of Civic Center Las Margaritas.

Civic Center of Las Margaritas			
Orientation Tilt angle /azimuth (°)	22/35 and 22/-54	22/126	22/-145
N° of solar panel in series	17	15	15
N° of solar panel in parallel	12	2	2
Inverter model	SMA SHP 75–100	HUAWEI SUN2000-10KTL-M0	HUAWEI SUN2000-10KTL-M0
N° of inverters	1	1 with 2 MPPT	1 with 2 MPPT
Rated power (kW)	75	10	10
Energy production (kWh/year)	162,000		
Specific solar production (kWh/kWp/year)	1,497		
Performance ratio	0.85		
Total installed power (kW)	95		

Table 5
Costs of the components of the PV solar installation.

Type of device	Model	Cost (€/unit)[1]	Year warranty	N_T	Total cost (€)	Total investment (€)
Inverter	HUAWEI SUN2000-10KTL-M0	1,944.27	10	2	3,889	66,768
Inverter	SMA SHP 75–10	5,472	5 years extendable up to 20 years	1	5,472 + 1,714	
Solar panel	CheetahPerc JKM390-410 M−72H	178.60	12	264	47,150	
Structure support	Solar Graus estructura coplanar	32.36	25	264	8,543	

[1] Taxes included

person housing load profile, and 15 had a 4-person housing load profile. The remaining households (70) were divided as follows: 43 households had a fixed price rate (consumption model of house 2) and 27 households had a PVPC rate model (consumption model of House 1). These data are consistent with the Spanish 2020 report, showing that 40% of electricity consumers were in the regulated market and 60% were in the free market, which is considered a fixed price for the present case study [66].

The initial investment was divided into two parts: main component costs and labor, assembly, commissioning, monitoring, health and safety, research, construction, and other expenses. They were derived by analysing a 99 kWp self-consumption project of Sigma Energy Consulting [67]. The main components of the installation were estimated at an investment of 66,768 € with other costs of 20,000 €. Table 5 summarizes the component costs of the corresponding PV solar installations. The total investment was 86,768 € and allocated proportionally identical to that of the PV solar installation. An important detail was that the economic component to be paid to households would only apply to the 70 non-vulnerable housing units over a 15-year amortization period.

As the objective of this EC was to reduce energy poverty by increasing the energy savings in the electric bills of vulnerable households, they were exempt from paying any monthly fee for the amortization of the PV installation. The payback period of Las Margaritas Civic Center was calculated, to obtain an approximate figure as 60% of the cost savings of the total investment. The equation to calculate the payback can be seen on Eq. (3).

$$Payback_{years\&month} = \frac{Investment_{byCCM}}{Costsavings} \tag{3}$$

The payback period for Las Margaritas Civic Center was approximately three years and two months (as this was an approximate estimation no net present value calculations have been done). This public building would save money corresponding to its energy consumption produced without a PV self-consumption installation. In addition, under an energy surplus, a compensation system for surpluses should be applied, accounting for 0.051 €/kWh. In contrast, each non-vulnerable household should pay a monthly fee of 5.30€ for 15 years calculated in Eq. (4).

$$Fee_{monthly} = \frac{77\%\hat{A}\cdot Totalinvestment}{Payback._{years}\hat{A}\cdot 12_{months}\hat{A}\cdot n\hat{A}^{o}houses} \tag{4}$$

Electricity bills associated with different rates were simulated to determine economic savings by comparing two scenarios: without and with collective self-consumption. The price of the surplus energy was 0.051 €/kWh; electricity rates (5.11%) and taxes (VAT: 21%) were the ones established by the regional government (Community of Madrid, Spain). The monthly bill models for the regulated and free markets were the same. However, internal prices and fixed costs changed: House 1 type and energy-poor housing were subject to the PVPC rate, while House 2 type were subject to the free market. Table 6 details the electricity bill model for the Spanish region and the method used to determine global prices.

- PVPC-2.0TD. Energy prices change hourly. Real price data was used of one day during the week, on June 1, 2021, which was the first day of the new PVPC regulations, and on one of the weekends. Both days were scaled for the entire month, distinguishing between weekend and non-weekend days. All price data were obtained from the Spanish Electricity Grid Operator (Red Eléctrica de España).
- The PVPC rate prices were fixed at 30.6727 €/kW and 1.4244 €/kW per year for peak and off-peak periods, respectively. Furthermore, there was a fixed supplier margin of 3.113 €/kW per year for Spanish electrical housing supplier companies (Curenergia and Energia XIII) and a fixed rent of the metering equipment of 0.02663 €/day; the same rent was applied to the fixed price rate.
- Fixed Price Rate (Free Market). Energy and power prices were fixed and imported from Endesa (2021 data); peak power prices were 2.815472 €/kW month, off-peak power prices were 0.378113 €/kW month, and energy prices were 0.149641 €/kWh month [68].

For each household type, the month selected to estimate the electric bill was the one in which the average monthly consumption was closest to the annual average. Several aspects were considered when applying the hourly prices corresponding to their contracted rates for the month: (i) When the hourly energy consumption was lower than the energy corresponding to the self-consumption installation, the electric bill was established as null, in accordance with the Resolution of the Directive General for Energy Policy and Mines of April 28, 2021, and RD 244/

Table 6
Electricity bill model.

ELECTRICITY BILL (With/without self-consumption)		
Name of the house	———	
Rate plan	PVPC/Free market rate	
Billing period	——— day	
Contracted power	——— kW	
		€/month
Invoicing for contracted power		
Peak period power	——— kW × ——— €/kW year × (———/365) day	
Off-peak period power	——— kW × ——— €/kW year × (———/365) day	
Fixed supplier margin	——— kW × ——— €/kW year × (———/365) day	
Invoicing for energy consumption[1]		
Peak period energy	$\sum_i$((———$_i$ kWh (total consumption) –	
Off-peak period energy	———$_i$ kWh (self-consumption)) × ———$_i$ €/kWh) [2]	
Ordinary period energy		
Invoicing for surplus energy from self-consumption	– (——— kWh × ——— €/kWh)	
Subtotal (without taxes and meter rental)		
Electricity tax	5.11%	
Meter rental	0.02663 €/day × ——— days	
Total (without government tax)		
VAT	21%	
Total (without monthly fee)		
Monthly fee[3]	5.30 €/month	
TotalnvoIcee amount		———

[1] Regulated market: energy term changes every hour and day
Free market: depending on the type of rate contracted by the supplier
[2] "," as each period types of consumption: peak, standard and off-peak
[3] To be pay ONLY by the non-vulnerable households to amortise the solar installation investment.

2019 of April 5 [59]. (ii) Social bonuses[3] were not considered in the PVPC rates for vulnerable housing. (iii) House 1 and House 2 types' of bills included a monthly fee for PV solar installation amortization. Each type of house displayed economic savings in comparison to self-consumption or without it. Houses 1 and 2 types accounted for savings of approximately 19–20 €/month: 19.42 €/month and 19.76 €/month, respectively. Regarding the households experiencing energy poverty, the economic savings were about 15.7 €/month for the 2-person house and 16.4 €/month for the 4-person house.

5. Discussion

This paper entails the formation of an EC that promotes collective self-consumption between public buildings and dwellings, including those occupied by individuals experiencing energy poverty. This initiative aims to empower citizens to actively contribute to the alleviation of energy poverty in their local communities by reducing energy consumption and costs. The success of this model depends on the active participation of citizens and their engagement with ECs. Effective approaches for engaging citizens and facilitating their participation are crucial for the development and evolution of both the ECs and the larger community. Therefore, using the various tools presented in Table 7, it would be feasible to provide citizens with information, guidance, investment support, and aid that foster awareness of ECs and incentivize their active involvement in this domain. Nevertheless, citizens face several challenges in achieving the widespread integration of ECs. These challenges include the following: (i) Awareness and Education: Raising awareness and educating citizens about the benefits of ECs and their role in reducing energy poverty is one of the key challenges. This involves disseminating information regarding the operation, benefits, and requirements of ECs, as well as their rights and responsibilities as

Table 7
Tools to approach citizens and to engage them in Energy Communities.

Year	Proposition	Entity / Author	Reference
2018	Creative tools for communication, such as gamification	Vilawatt	[69]
2019	Information and communication tools that include a "single window" (i.e., basic information and legal-administrative advice to carry out all the necessary and opportune formalities)	IDAE	[70]
2020	A practical guide for citizens to reclaim power	Friends of the Earth Europe	[71]
2020	Collective action initiatives for citizen engagement	Delvaux S.	[72]
2020	Workshops, "citizen juries," and citizen assemblies	Energy Cities	[73]
2021	Energy offices, innovation hubs, and private consultants	Ren21	[74]
2021	Community participatory process to identify problems/needs, complete a diagnosis of the situation, establish priorities, and promote local actors	Pacheco, A. et al.	[75]
2022	Citizen guide to participating in the energy transition	Conoma Foundation	[76]
2022	Promotional campaigns	Compile Project	[77]
In constant updating	Toolbox	Rescoop.eu	[78]
In constant updating	Public participation platforms to enhance the link between citizens and the municipal government and agencies	Energy Cities	[79]
Plan Horizon 2030	Creation of motor groups to involve individuals who take on responsibility and provide mutual support by following the "snowflake" approach. Providing monthly meetings and dynamic activities	Navarra Government	[80]

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[3] As mentioned in Section 2 the Spanish government has a system of bonuses for those suffering fuel poverty if they are in the PVPC.

participants. (ii) Economic Barriers: Another challenge is the economic barriers faced by citizens regarding the upfront investment required to participate in ECs. This includes the cost of installing renewable energy systems and energy storage devices, which can be prohibitively expensive for some households. There is also a need for incentives and financing mechanisms to enable citizens to overcome these economic barriers.

(iii) Technological Complexity: Many citizens lack the technical expertise required to fully understand and participate in ECs. This necessitates the simplification of the technical requirements and the provision of user-friendly tools and platforms that enable citizens to participate in these communities. (iv) Regulatory and Legal Framework: The regulatory and legal frameworks governing ECs are still evolving, and there is a need for defined guidelines and regulations that promote the development and integration of ECs. This includes addressing the issues related to ownership, governance, and liability. (v) Social Acceptance: Finally, social acceptance is a challenge that must be addressed. ECs require a collective effort and commitment from citizens, and there is a need for citizens to develop trust and confidence in these ECs. This requires engagement and collaboration with citizens and other stakeholders, as well as addressing concerns and misconceptions regarding ECs.

We have seen that the final EC model corresponding to the case study involves the selected public building of Las Margaritas' Civic Center hosting 95 kW PV solar installation on its rooftop in self-consumption Spanish operation mode. A group of 100 houses was selected, 30 of them considered in energy poverty situation (vulnerable households). The rest of the houses (70) were divided into 43 houses with a fixed price rate and 27 houses with a PVPC rate model. There were two different consumption demand profiles depending on the number of cohabitants: two and four cohabitants. From the results, the electricity bill of vulnerable households (in June/2021) was reduced 15.69 €/month for two people household type and 16.40 €/month for four people house hold type respectively. Such reduction was addressed as a consequence of changing from individual connection to the grid without any PV installation to self-consumption.

6. Conclusion

This study highlights electricity cost savings and promotes environmentally sustainable ECs. The results of the case study show that the implementation of the energy community as a citizen initiative with a shared self-consumption solar power system led to significant savings in the electricity bills of households experiencing energy poverty in Getafe (Madrid). This study provides a viable model that can be employed in other vulnerable areas and covers economic, social, and energy considerations. Various tools, such as gamification, information platforms, workshops, and citizen participation initiatives, can engage citizens and facilitate their active involvement in ECs. The utilization of own resources and business models, in conjunction with suitable regulations, is critical in facilitating effective adaptation of existing and operational ECs while not impeding the establishment of new ECs. This analysis can be extrapolated to other public buildings with the goal of promoting ECs with different characteristics encompassing economic, social, and energy considerations.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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