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Towards a Balanced Energy Community. Matching Energy Supply and Demand Curves. Ways of Governance

Paula Bisordi Hüwel [1] | Adolf Sotoca [2] | Mariana Palumbo [3]

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Abstract

Energy Communities (EC) are a core element in any energy transition policy. They increase the security supply, allow for a decentralized distribution and reduce consumption, thus delivering environmental and social benefits. The Clean Energy Package (CEP), adopted by the European Commission in 2019, paved the way for the recognition and support of EC within the European context. This paper focuses on the ongoing urban regeneration of Besòs, a neighbourhood located in Barcelona, Spain. And it does so by framing the intervention within the European energy policies, analysing how the EU directives have been only partially transposed to the Spanish context and, lastly, by testing a potential EC that has not been considered so far in the urban regeneration program. An hourly consumption, iterative graphic analysis was utilised to test the most efficient combination of different sizes of communities and renewable energy generation (wind and solar). It was concluded that 64.58% of self-consumption could be achieved. However, by implementing simple behaviour change measures, 90.15% of the energy demand could be self-generated. Furthermore, two potential pathways for governance, which consider ownership and investment possibilities, are also discussed in the paper.

Keywords: energy community; NextGen EU; self-consumption; renewable energy; hourly electrical demand

Citation

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Hacia una comunidad energética equilibrada. Comparación de curvas de oferta y demanda de energía. Formas de gobernanza

Resumen

Las comunidades energéticas son un elemento central en cualquier política de transición energética. Aumentan la seguridad del suministro, permiten una distribución descentralizada y reducen el consumo, entregando así beneficios ambientales y sociales. El Paquete de Energía Limpia (CEP), adoptado por la Comisión Europea en 2019, allanó el camino para el reconocimiento y apoyo de la CE dentro del contexto europeo. Este artículo se centra en la regeneración urbana en curso del Besòs, un barrio ubicado en Barcelona, España. Y lo hace enmarcando la intervención dentro de las políticas energéticas europeas, analizando cómo las directivas de la UE se han transpuesto al contexto español solo parcialmente y, por último, ensayando un potencial CE que no ha sido considerado hasta ahora en el programa de regeneración urbana. Se utilizó un análisis gráfico iterativo de consumo por hora para probar la combinación más eficiente de diferentes tamaños de comunidades y generación de energía renovable (eólica y solar). Se concluyó que se podría lograr el 64,58% del autoconsumo. Sin embargo, implementando medidas simples de cambio de comportamiento, el 90,15% de la demanda de energía podría autogenerarse. Además, en el documento también se analizan dos caminos potenciales para la gobernanza, que consideran la propiedad y las posibilidades de inversión.

Palabras clave: comunidad energética; NextGen EU; autoconsumo; energías renovables; demanda eléctrica horaria

[1] MD, Universitat Politècnica de Catalunya, Escola Tècnica Superior d'Arquitectura del Vallès (ORCiD: 0000-0002-4075-5438), [2] PhD, Serra Hunter Fellow, Universitat Politècnica de Catalunya, Escola Tècnica Superior d'Arquitectura del Vallès. (ORCiD: 0000-0002-7948-0988), [3] PhD, Serra Hunter Fellow, Universitat Politècnica de Catalunya, Escola Tècnica Superior d'Arquitectura del Vallès (ORCiD: 0000-0002-9157-0943). Correo de contacto: paula-bisordi@hotmail.com

1. Introduction

There has never been a more favourable scenario for a redesign of the energy sector in Europe. The increasing environmental awareness and the geopolitical situation have led the EU to, on the one hand, turn from fossil fuels to renewable energies and, on the other, reconsider how, where and by whom energy is produced, distributed and consumed. A more decentralized, secure and efficient energy system is required. One in which energy communities may play a fundamental role.

The primary goal of developing an energy community is to create resilient and self-sufficient local communities. This will eventually result in more local renewable energy being produced, reducing carbon emissions. By fostering a shift in behaviour brought about by greater energy awareness among the population, it will also lower emissions. Energy communities (EC) can also result in improved resource efficiency since choices are made locally and because renewable energy systems can be installed on underutilised areas. Local generation and consumption can help to cut down on transmission losses. Reduced energy poverty can also result from lower energy expenses and greater resilience to rising energy prices (Community Energy England, 2022; Tarpani *et al.*, 2022).

Energy community can be defined as groups of people that organise collective and citizen-led energy activities with the aim of a clean energy transition (European Commission, 2022). However, this definition is broad and may lead to oversimplification. Although there is not yet a consensus on the nomenclature to be used and its specific meaning, in practice, the term "Energy Communities" is used as a paraphrase to encompass various types of organisations with different roles in the energy market, with different governance schemas and which may or may not have legal and/or administrative recognition. In this sense, the term has been used to encompass concepts such as sustainable energy communities, community energy, community microgrid, community-based virtual power plant, prosumer-community groups, community-driven energy projects, renewable-based community projects, energy co-ops, collective solar models, local self-consumption projects and a long etc (Moroni *et al.*, 2019; F.G. Reis *et al.*, 2021).

The advantage of using an encompassing term is that enables the recognition as players in the energy market of a wide range of organisations. Nevertheless, at the same time, it can lead to operational problems, for example, when proposing effective policies aimed at such a wide diversity.

Despite the difficulties, the European Commission is determined to promote the development of ECs and is doing so in the framework of the Clean Energy Package (CEP) (European Commission and Directorate General for Energy, 2019), published on July 2019, which sets explicit provisions that place EC as fundamental players in the EU energy transition and establishes general principles for their implementation (Caramizaru, 2020). The Renewable Energy Directive (RED), a 2018 recast of the previous 2009 Directive, and the Internal Electricity Markets Directive (IEMD), both included in the CEP, define two specific types of energy communities: renewable energy communities (REC) and citizen energy communities (CEC).

The RED defines REC as warrants of community owned renewable energy. The directive stablishes that all Member States must enforce the legal framework “[…] to promote and facilitate the development of renewable energy communities.” (art. 22.4). Member States are also required to “[…] take into account specificities of renewable energy communities when designing support schemes in order to allow them to compete for support on an equal footing with other market participants (art. 22.4 (European Parliament and European Council, 2018). The RED does not require Member States to implement a renewable energy support program, but it demands them to tailor their policies so that RECs may be able to play on the same level as larger competitors in the market.

The IEMD, published only half a year after the RED, defines the broader term CECs as players in the energy transition. The directive does not explicitly link it with renewable energy sources, but defines their rights and obligations in a wider scope (European Parliament and European Council, 2019). As defined in the CEP framework, both REC and CEC are legal, non-commercial entities that can be made up of citizens, small companies and public authorities that participate openly and voluntarily.

However, the RECs are more restrictive regarding: energy sources, which must be renewable; the scope of action, which must be local; and the type of organisations that can take part, which excludes large companies and energy-focused ones (F.G. Reis *et al.*, 2021).

1.1. Sud-Oest del Besòs as a case study

SOB is a housing estate built between 1960-1967 at the east end of the city of Barcelona. The neighbourhood comprises 5.188 housing units where 24.660 inhabitants live, according to the municipal statistics of 2021. The buildings are arranged in repeating patterns with public space in between and sparse ground-floor commercial spaces either connected to residences or occasionally in freestanding (Ejigu, 2011).

The original inhabitants of Besòs-Mar were forcibly relocated by the Franco regime from informal settlements on the edges of the city in El Somosrrostro and Camp de la Bota (Guerra Mirón, 2015), thus conditioning the social and economic development of the area from its origins. The neighbourhood still shows high indicators of urban vulnerability (Foment de Ciutat *et al.*, 2017). It is mainly suffering from major structural and thermal pathologies, such as aluminosis, lack of insulation, and badly performing windows (Antich Garcia, 2010). SOB is also categorized as a low-income neighbourhood with high unemployment and low education rates (Ajuntament de Barcelona, 2020). These physical and social issues have led to severe energy poverty issues in the neighbourhood.

2. Methodology and development

The overall goal of the analysed energy community was to test the technical and social feasibility of an EC in SOB. An efficient energy community is defined in this study as one that can provide self-consumption, has a well-established governance system and has no issues in terms of regulatory constraints.

This study utilised mixed methods of quantitative and qualitative approaches to present multiple findings about the hypothesis. Different types of renewable energy sources were compared to understand the feasibility of implementation in SOB. At the same time, energy profiles for public buildings and residential areas were analysed.

Some of the data collected was secondary data from external sources. Data such as energy profiles for residential buildings, renewable sources energy generation, etc. All the data from the public buildings was collected from the entities themselves in partnership with the Institut Municipal d'Urbanisme (IMU) and thus correspond to actual consumptions.

All data was compared using graphical analysis through an iterative process. The different steps are described below.

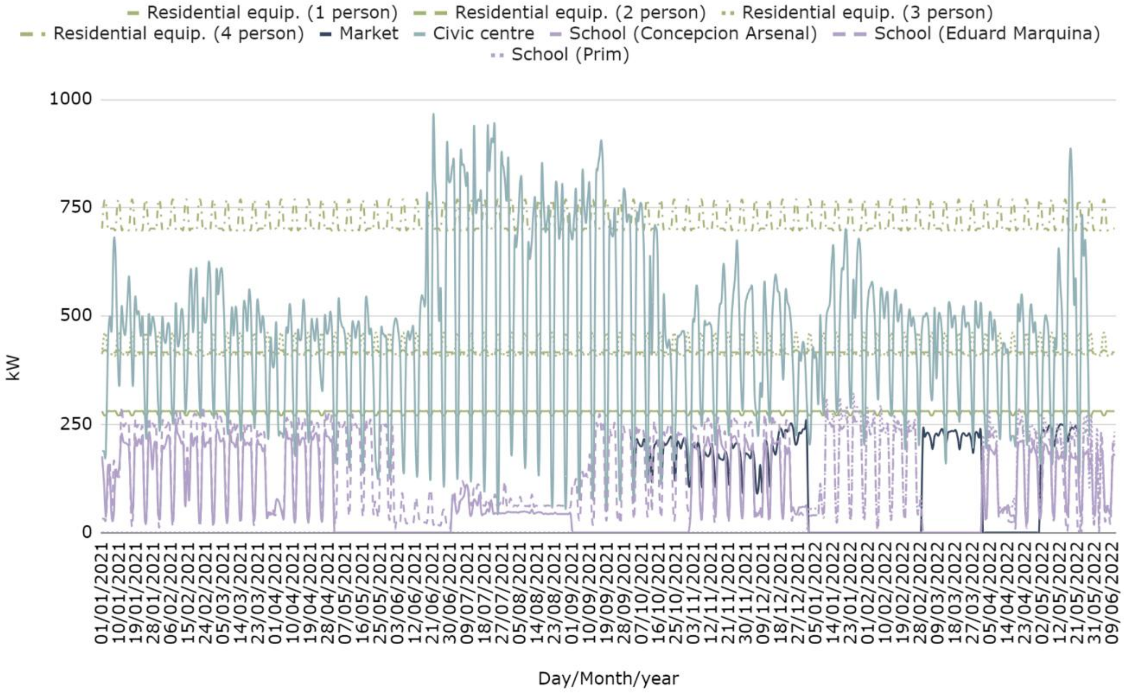
2.1. STEP 1: Data preparation and homogenization

The available data for the different building typologies was not homogeneous. Some of the data collected, i.e., demand of the residential sector and production rates for each technology, was secondary information obtained from external sources (European Commission, 2019; Escobar *et al.*, 2020; Open Power System Data, 2020). All the data from the public buildings was collected from the entities themselves in partnership with the Institut Municipal d'Urbanisme (IMU) and thus correspond to actual consumptions. The graphs below show the energy demand data sets (Figure 1).

The annual electrical demand per building type was plotted to understand the neighbourhood's consumption

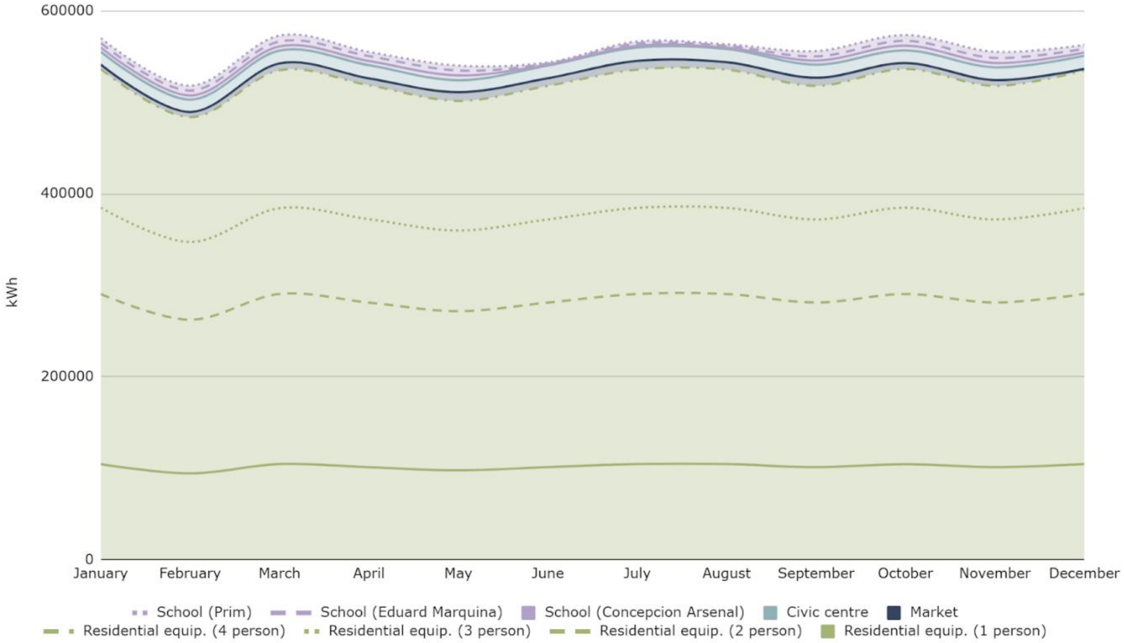
Figure 2 & Figure 3: detailed graph with public building demand). The residential values obtained from (Escobar *et al.*, 2020) provide information for 1, 2, 3 and 4 people households. Therefore, the annual consumption for the neighbourhood was plotted utilising the total amount of dwellings in the neighbourhood and considering the statistics by INE (2020) to determine the number of inhabitants per household.

Figure 1. **Energy demand data sets**



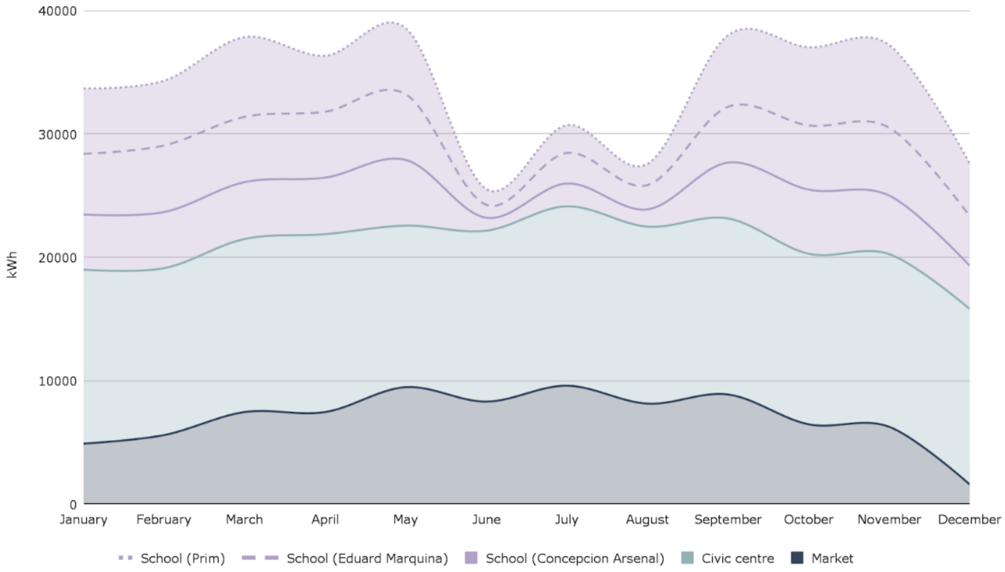
Source: adapted from (Escobar *et al.*, 2020; Institut Municipal d'Urbanisme, 2022).

Figure 2. **Annual electrical demand per building type - public buildings and residential**



Source: drawn by the authors.

Figure 3. **Detailed annual electrical demand per building type - public buildings**



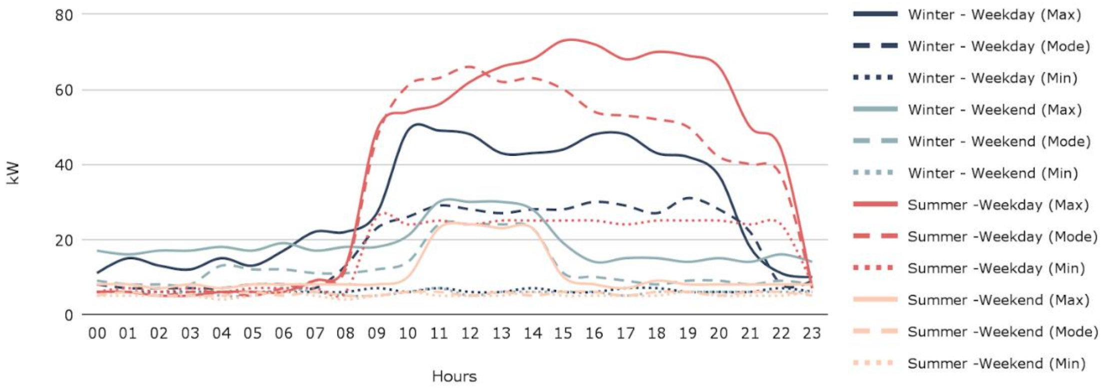
Source: drawn by the authors.

There wasn't enough data available from all data sets to calculate the yearly combinations. Therefore, four typical days were established to represent the annual energy demand and supply: winter weekday, winter weekend, summer weekday and summer weekend. As explained previously, cooling and heating values were not considered, hence the main difference in electrical use are driven by occupancy and not temperatures. Hence, the typical days were selected considering occupancy profiles.

As shown in the civic centre data (Figure 1), the summer and winter values are clearly defined. However, for the other energy profiles, the data is constant throughout the year. Therefore, the days of the year to be counted as winter and summer were defined as per the civic centre data for consistency.

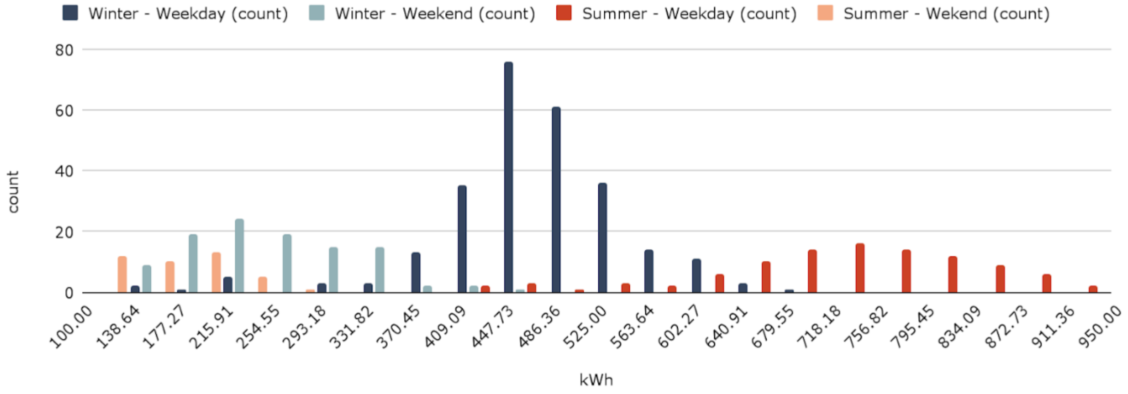
The days to be studied were then selected according to the mode for each profile. It is assumed that if the mode usage curve can be balanced, then the curve can be matched for most of the year. In addition, if all the mode days are matched for the energy usage and supply, then it is assumed this set of values will happen more frequently as a combination. The civic centre calculations are shown as an example below (Figure 4 & Figure 5). The same calculations were plotted for all energy profiles.

Figure 4. **Max, Min and Mode consumption days - Civic Centre**



Source: drawn by the authors.

Figure 5. **Histogram energy demand - Civic Centre**



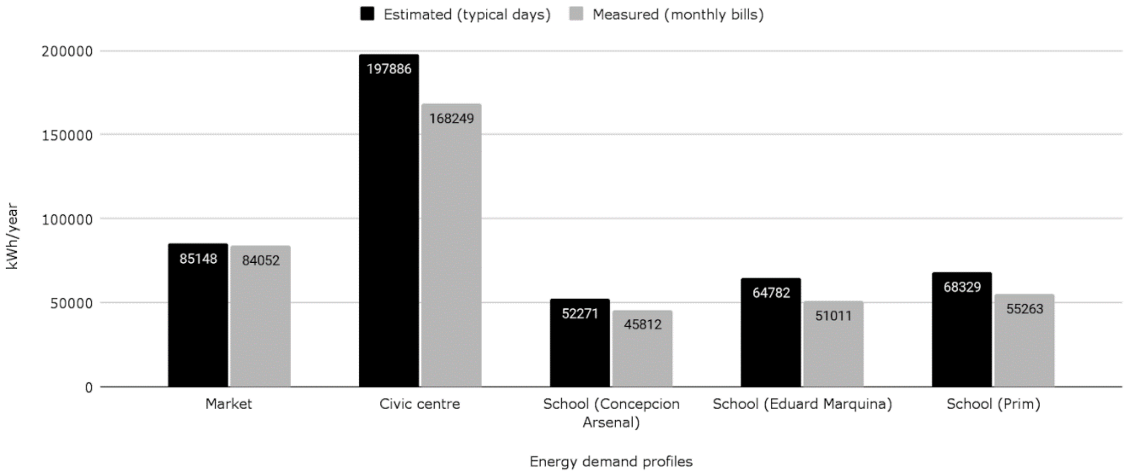
Source: drawn by the authors.

2.2. STEP 2: Data validation

As explained previously, there were several gaps in the hourly data received from the buildings. Therefore, typical days were selected to replicate the annual data. Monthly energy bills were also obtained from the IMU; however, hourly data is required to balance different types of consumption and generation profiles. Therefore, estimated annual consumption was calculated by multiplying the typical days by the number of times they repeat each year. This was then used to compare the annual data obtained from monthly bills.

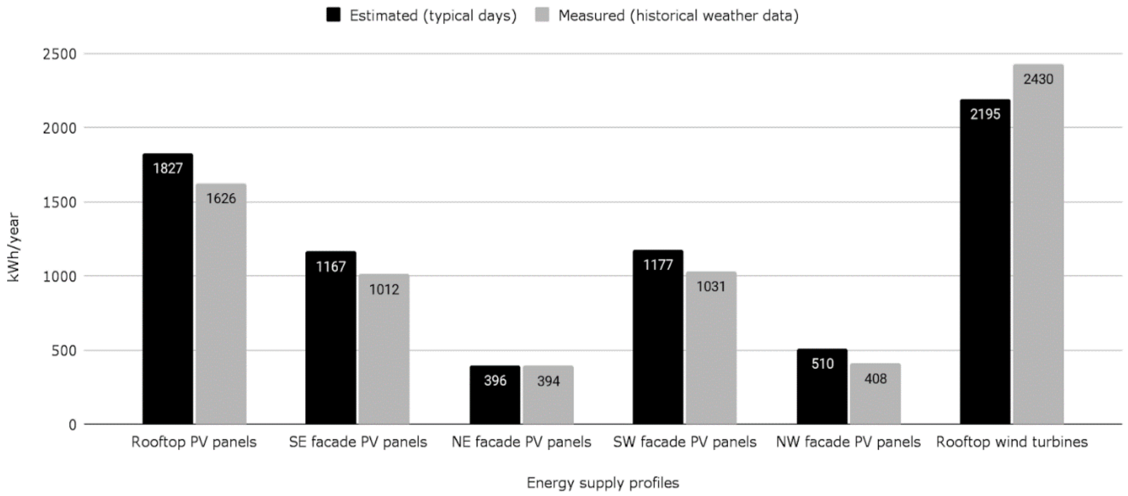
In order to establish whether replicating annual data by utilising only four typical days per profile is accurate enough, the overall annual consumption calculated from the typical days was compared with the monthly energy bills that were obtained from each building (Figure 6 & Figure 7). The differences between the estimated (annual data replicated from typical days) and measured values (data from monthly bills) are minimal (always below 20% and above the measured data both in demand and supply sides) and hence, considered negligible. Therefore, it was considered that the estimative data to be utilised in this study is valid and will yield useful results.

Figure 6. **Data validation energy demand - estimated vs. measured annual values**



Source: drawn by the authors.

Figure 7. **Data validation energy supply - estimated vs. measured annual values**

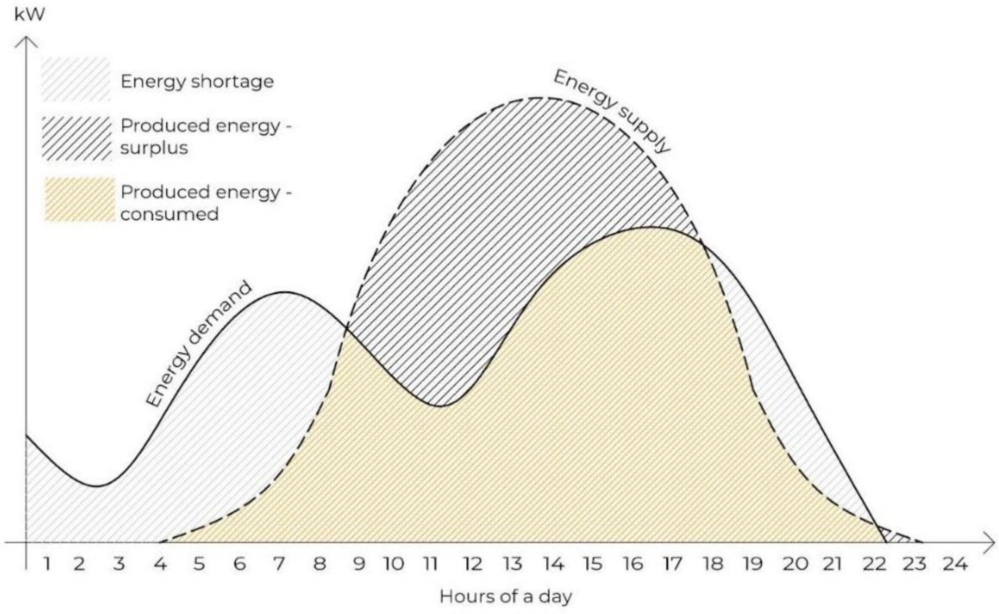


Source: drawn by the authors.

2.3. *STEP 3: Fitting demand and production iterations*

All data was compared using graphical analysis through an iterative process. The aim of the iterative process was to analyse the best combination of energy supply and demand profiles for the neighbourhood (Figure 8).

Figure 8. **Energy shortage, surplus and self-consumption conceptual diagram**



Source: drawn by the authors.

In total, 4 Iterations were conducted. The results of each Iteration were used to define the scope and nature of the following one, aiming at the matching of the supply and demand curves.

- Iteration 1. Included demand and potential energy production of the Civic Centre.
- Iteration 2. Included also all the residential buildings in the SOB.
- Iteration 3. Included the Civic centre, part of the residential buildings and the market.
- Iteration 4. Included also the 3 schools of the neighbourhood.

2.4. STEP 4: Analysis of potential reductions of mismatching periods from the consumption side

Once the demand and the supply curves were balanced, the resulting graphs were analysed to understand any further improvements or strategies that could be implemented to make the system more efficient.

2.5. Regulatory constraints

After analysing the technical dimensions, the regulatory constraints (see 0 Source: drawn by the authors, information from: (Bisordi Hüwel, 2022; Caramizaru, 2020; Rühl, 2014).

Legal framework in Spain for more information) were considered to understand the overall feasibility of the proposed energy community in Barcelona, Spain.

2.6. Governance types

The governance was investigated by examining the technical constraints of the balanced energy community. The property rights defined by Ando (2012) were utilised as an analysis matrix in Table 1.

Table 1. **Property rights**

Property right	Concept	Description
ENTRY	The right to enter the resource	This can be achieved by buying a ticket to access the resource, declaration by the government that all citizens can access that resource or by inheritance of joint use rights. How do you enter this cooperative?
WITHDRAWAL	The right to take some units out of the resource pool	A permit can be purchased to extract some resource units. Do the members have access to the resource or reduced bills?
MANAGEMENT	The right to change the physical structures in a resource system	How do the members make the decisions, especially when it comes to surplus resources?
EXCLUSION	The right to determine who else would use the resource and what their specific rights would be	Who has physical access to the resource, (e.g. right of way)?
ALIENATION	The right to sell one or more of the first four rights permanently or for a given time period	Is the right assigned to the person or the household/building?

Source: modified from (Ando, 2012).

Once the demand and the supply curves were balanced, the resulting graphs were analysed to understand any further improvements or strategies that could be implemented to make the system more efficient. The “balanced” energy community was compared with already existing local renewable energy sources to understand the implications of implementing this community in Sud-Oest Besòs, both in terms of area, size and visual impact. Finally, the governance was investigated by analysing the case studies mentioned above and by examining the technical constraints of the balanced energy community.

3. Literature review

3.1. Renewable energy sources analysis

The study is going to try to evaluate different types of renewable technologies to investigate their hourly power generation and how it compares to the energy demand of different communities. Different energy profiles will have different requirements in terms of which technology is more suitable.

Therefore, the most common renewable electricity generation technologies will be investigated to understand which of these options are feasible within the neighbourhood. Based on the analyses by Budak et al. (2019), improving energy efficiency and development of solar and wind energy are the three most preferred energy alternatives whereas nuclear and hydroelectric are the least preferred energy alternatives.

Based on the studies done by Thirugnanasambandam, Iniyan and Goic (2010); Gitano-Briggs (2012); Bhatia, (2014); Fields *et al.* (2016); Jacobson and Jadhav (2018); Popa *et al.* (2020); Pedrero, Hernández and Martínez (2021); Richter (2021); Saavedra *et al.* (2021); Ocean Energy Council (2022), Table 2 was produced showing a summary of the constraints involving the implementation of each type of technology in Sud-Oest del Besòs. PV panels, solar thermal and wind turbines seem to be the most feasible solutions for SOB due to available installation space (almost every building in the neighbourhood has flat roofs and it was design with large spaces in between buildings), governmental support and ease of access to resources.

Table 2. **Constraints involving the implementation of each type of renewable energy**

	Access to resource	Cost	Regulation's constraints
PV Panels	Easy	Medium – 1644 €/kW	Easy
Solar thermal[1]	Easy	Medium	Easy
Wind	Medium	Medium – 2000 to 4217 €/kW	Easy
Biogas	Not feasible		
Geothermal	Medium	Difficult – 4140 €/kW	Difficult
Biomass	Not feasible		
Low-impact hydroelectricity	Difficult	Difficult – depends on physical constraints	Difficult
Wave or tidal power	Not feasible		

Source: by the authors.

Note 1: It is unclear whether solar thermal technologies are more efficient than electrifying all systems. Also, if solar thermal is indeed less efficient, it is also unclear whether they would still be necessary in the future to decarbonise the energy supply chain, as more variability and flexibility might be needed. Hence, analysing the pros and cons of connecting domestic hot water and heating to the electrical system or to a solar thermal system is outside of the scope of this work. Also, if solar thermal technologies were analysed, the methodology utilised for the study would vary greatly, as hourly curves will have to take into consideration water storage.

Through the analysis done, it was concluded that the technologies that will be investigated in this report are solar panels (rooftop and façade) and wind turbines. Cabello *et al.* (2022) also compared several local energy projects and found that photovoltaic and wind power are the favourites energy generation technologies.

Wind turbines

The technology used at the global production level for the domestic market has not been taken advantage of as PV panels have been, so the costs remain high. While solar panels have an affordable price, mini wind turbines do not. On the other hand, the solar panels will always be silent, but the windmills can cause noise issues. Also, there is no good manual on how to install wind turbines and very bad results have been given when they were mounted incorrectly or in places where it was not possible to benefit from the wind. Although it is legal to install a wind self-consumption system at home in Spain, there aren't enough incentives or regulations to promulgate this (TW Energy, 2022).

However, wind energy has a much more constant generation curve, whilst PV panels generate electricity in large peaks, making it hard to match demand profiles with the generation profile. In addition, wind turbines have a much lower carbon footprint than PV panels (BEG Wolfhagen, 2022). Also, they might be able to be implemented in places where PV panels can't (shaded areas, north facing areas, etc.).

Although the physical constraints in a city, such as SOB, are high for this type of technology, newer technologies are being designed specifically for urban environments, which normally have low velocity turbulent wind conditions (European Commission, 2018). Some innovative technologies solve not only the problem of where to locate microturbines in an urban area, but also the issue of them being seen as a non-aesthetic object. For instance, some turbines imitate trees (Hewitt, 2015).

Solar panels

Traditional PV (silicon-based) production procedures have roots in the electronics sector; many of the chemicals present in e-waste, such as lead, brominated flame retardants, cadmium, and chromium, are also found in solar PV (Cáceres Gómez, 2012; Dubey, Jadhav and Zakirova, 2013; Yadav, Kumar Saraf and Singh Rathee, 2023).

Also, several hazardous, flammable, and explosive compounds are used in the production of solar cells. Many of which are hazardous to the health of personnel involved in the production process. In addition, Solar panels are often in competition with agriculture and can cause soil erosion. Therefore, the disposal and utilisation of electronic products is becoming an escalating environmental and health problem in many countries (Dubey, Jadhav and Zakirova, 2013).

However, studies conducted by a number of organisations and researchers have concluded that PV systems can produce the equivalent amount of energy that was used to manufacture the systems within 1 to 4 years. Most PV systems have operating lives of up to 30 years or more (U.S. Energy Information Administration (EIA), 2022). The carbon footprint emission from PV systems was found to be in the range of 14–73 g CO2-eq/ kWh, which is 10 to 53 orders of magnitude lower than emission reported from the burning of oil (742 g CO2-eq/kWh from oil) (Tawalbeh *et al.*, 2021).

Irradiation is fairly constant across Spain, and the higher values in southern Spain are in part compensated by lower performance of the PV modules due to high temperatures (Izquierdo, Rodrigues and Fueyo, 2008). Therefore, even though the information obtained utilises specifically the Sud-Oest del Besòs radiation information, this can be replicated to the rest of the Spanish territory for further studies.

Vertical PV panels will be analysed within this study. Although façade PV panels are not placed in the most efficient orientation, some works show their suitability in balancing demand and production curves (Curreli *et al.*, 2013) (Moghaddam *et al.*, 2017). The results published in the journal Solar Energy by (Díez-Mediavilla *et al.*, 2019), indicate that vertical photovoltaic installations are viable and that the appropriate combination of available surfaces will be key to achieving buildings with net zero energy consumption. The study underlines the suitability of all vertical surfaces for the installation of PV facilities, which would produce relatively high energy values in seasons in which the production on the horizontal plane is low.

Spain's location in the northern hemisphere and latitude makes it an ideal place for vertical PV panels. The vertical panels will generate more energy in the winter than in the summer and during early and late daylight hours (when the sun is lower in the sky). A building will typically face opposite orientations, so the maximum energy produced by the solar panels on each façade will occur at a different time of day, distributing power production peaks throughout the day and achieving a closer match to the ideal load diagram than would otherwise be the case (Díez-Mediavilla *et al.*, 2019). Although the buildings consume continuously, the façades receive energy at different times depending on their orientation.

The study has concluded that, in the winter months, the south façade receives more energy than the horizontal surface in the same location. The north façade produces approximately 25% of the horizontal surface (Díez-Mediavilla *et al.*, 2019). The east and west façades produce approximately half of the horizontal surface, because one receives the sun in the morning and the other in the afternoon. However, between all these surfaces, the production could be distributed throughout the day (Díez-Mediavilla *et al.*, 2019).

3.2. *Analysis of existing energy communities in the EU*

The first step was to examine different types of energy communities already developed in the EU. The report from the (European Commission, 2022) was utilised as a base to establish important aspects of energy communities to be investigated. A total of six EC in the EU was selected from the report (see Figure 9). These were located in very different latitudes and climatic conditions and covered both small- and large-scale schemas. Some examples did not correspond entirely to the EU definitions of an energy community (REC or CEC); however, they were included as they presented some specific aspects that where relevant for the case study.

Figure 9. **Case studies locations**

Source: drawn by the authors.

As explained previously the aim was to test the feasibility of an EC in SOB. Thus, the examples were examined in two different aspects a) types of energy renewable technologies; b) governance models. Also, due to energy poverty being identified as an issue in this neighbourhood, how to include marginalised areas will be analysed as a transversal consideration. Because of space constraints, only a summary of the results and the main conclusions drawn are presented here. The extended work, including a more detailed description of the examples, can be found in (Bisordi Hüwel, 2022).

Several existing EC were analysed to understand their constraints and benefits both regarding technical and governance aspects. A summary of the examples analysed, and their key points is presented in Table 3. Below, the key general learnings extracted from the analysis are presented.

- The amount of solar irradiation and wind available is not the only factor contributing to the installation of solar panels or wind turbines. In other words, the location does not need to have the highest number of resources to be able to install a viable system with a mix of renewable sources.
- Some of the biggest challenges were the regulatory constraints and the neighbourhood objections.
- Most of the case studies apply the "one person = one vote" system, even if members can purchase more than one share.
- It is important to have participation not only of members, but also the utility companies and the city council.
- It is important to consider different types of renewable energies to provide more variability and hence, resiliency of the system.
- A lot of projects are not only about installing local renewable technologies but are also geared towards raising awareness and behavioural change.

Table 3. **EC Key points to consider for each of the EC analysed.**

	Year	Country	Members	Generation technologies	Energy generation	Governance	Key points
Edinburgh Community Solar Limited	2007	UK	541	PV panels	1.12 GWh/year	Non-profit, member owned organisation	Community engagement activities
Marstal Fjernvarme	1994	Denmark	2,300	Solar heat collectors, wood chips & heat pump	32 GWh/year	Non-profit customer owned enterprise	Integration of several energy sources
Svalin co-housing complex	2018	Denmark	80	Solar panels, geothermal heat pumps & electric vehicles	Unknown	Energy collective project (Co-housing community)	Awareness of CO_2 emissions
BEG Wolfhagen	2005	Germany	500	Solar panels & wind farm	55 GWh/year	“Cooperative participation” - joint ownership of the municipality and a citizen-led cooperative	Innovative form of governance and change of regulations to implement wind farms
Enercoop	2005	France	70,000	Wind farms, PV panels	249 GWh/year	Société Coopérative d’Intérêt Collectif (SCIC)	Governance type and how to organise energy communities
Som Energia	2010	Spain	59,320	Mostly PV panels	13.56 GWh/year	Cooperative	Understand different ways to help marginalised communities

Source: drawn by the authors, information from: (Bisordi Hüwel, 2022; Caramizaru, 2020; Rühl, 2014).

3.3. *Legal framework in Spain*

The CEP also stablishes that all Member States must acknowledge and support both CECs and RECs and, in the case of RECs, financial instruments must also be implemented. To that end, not only the above-mentioned directives, but all eight legal acts included in the CEP must be transposed into the Members’ national legislation. As for now, no member state has fulfilled the process. Spain ranks in the average progress, both in terms of RECs and CECs definitions and in terms of enabling frameworks & support schemes (REScoop.eu, 2021).

In 2019 a "Guide for the development of instruments to promote *local energy communities"* was drafted by The Institute for Energy Diversification and Saving (IDAE). This term appeared for the first time in the Proposal for a European Directive COM (2016) 864, but has been displaced by the term CEC, with the approval of the IEMD.

A year after, the RDL 23/2020 amended Law 24/2013 to introduce RECs as a new subject of the electricity sector, with a definition similar to that of RED. The figure of the CECs is not yet included in Spanish legislation, although RDL 23/2020 does include the figure of the independent aggregator, a figure that needs to be regulated in detail and which allows ECs to participate in the electricity market in an aggregated manner. In 2021, the Barcelona Provincial Council published a guide to the promotion of EC in which the legal and administrative context is compiled (Diputació de Barcelona, 2021). This report mentions, in addition to RECs and CECs, other types of organisations that can fall under the definition of energy communities and that are recognised in the Spanish administrative and/or juridical framework, such as collective self-consumption or the energy communities of the former primary special regime (EC-FPSR).

Although there are several collective self-consumption projects in Spain already functioning, their scope is limited both geographically (to a radius of, at most, 500 m) and in terms of management: the distribution coefficients are fixed for the same billing period, instead of being hourly coefficients depending on actual consumption, which would allow for better use of the energy generated within the community. Regarding EC-FPSR, these were funded between 2007 and 2011 by the Spanish government but were subsequently threatened by juridical insecurity, as the legislation was modified with retroactive effect.

Yet, in Spain, the creation and growth of energy communities has been much slower than in other EU countries. Energy communities have contributed very little to the development of renewable energy. This is due to the fact that incentives to implement this type of technology have been greatly undercut (Romero-Rubio and de Andrés Díaz, 2015)

3.4. NextGeneration funding

Even though ECs are recognized by the CEP, the RED and the IEMD, the partial transposition of the legal framework at the Member States level hinders their full development. Legal uncertainty and the lack of a clear roadmap heighten the financial risks involved in creating an EC (Arnould and Quiroz, 2022). Therefore, private investment is only accessible to high and middle-income strata, thus excluding vulnerable populations from that possibility. In such cases, like the one we develop in this paper, additional support in the form of public investment is needed.

The economic, environmental and health crisis occurred in recent years have triggered the exceptional allocation of financial resources from the part of the EU. On top of the €392 billion provided to the Cohesion Funds for the period 2021-27, an additional amount of €723.8 billion are to be allocated for the period 2020-26 under the name of the NextGenerationEU (European Commission and Directorate-General for Budget, 2022). Both financing sources set goals in energy transition and socially sustainable policies, therefore offering a fertile ground for ECs deployment. Following the Next Generation funds, the New EU Strategy for Energy Integration was published in July 2020 (European Comission, 2020).

The new strategy stated that "[…] Renewable energy communities can provide a sound framework for the use of such energy in a local context" (section 3.1) and states that "[…] the Commission will use the new recovery instrument Next Generation EU to support the continued deployment of renewable energy" (section 3.2). In the subsequent deployment and guidance notes, references to policy reforms, risk insurance and mitigation schemes for investments in renewable energy abound.

It is in this context in which the ongoing Urban Regeneration Program in Barcelona is framed. The city is the second largest in Spain, which ranks first among Member States beneficiaries after been granted with €69,5billion out of the total €328 billion in grant allocations (≈ 21%) (Directorate-General for Budget (EU), 2021). In June 2022 the City Council of Barcelona launched its Next Generation Plan for the city, amounting a total budget of € 41 million granted by the NextGenEU and € 29,5 million added by the municipality. The main objective is to increase the energy efficiency of the housing stock both at the building and the neighbourhood scale (CoAC and Barcelona City Council, 2022).

Based on previous urban vulnerability studies (Foment de Ciutat *et al.*, 2017) the plan designates six vulnerable areas where most of the interventions will be implemented. The Besòs neighbourhood is the first to go through regeneration, as by the end of 2022 some executive projects are already approved, and the works are under progress.

So far, however, the program has only considered the energy performance at the building scale and ECs have not been implemented yet. The Municipal Institute of Urbanism (IMU) and the Universitat Politècnica de Catalunya (UPC_BarcelonaTECH) signed an agreement on April 2022, by which UPC would analyse the technical feasibility of a REC in Besòs neighbourhood. The results of the study, developed within the MISMeC master program are shown in the following sections.

4. Feasibility of an energy community in Sud-Oest del Besòs

When defining the technical feasibility of an EC in the SOB, some assumptions were made which define the scope and limitations of the analysis.

a) The study is focused on self-consumption, which means that the use of batteries for energy storage is not considered.

Utilising batteries for storage are not ideal due to the harmful materials to be utilised and the issues of disposing with such batteries (Krebs, Zurich and Stolz, 2020). Dihydrogen (H2) batteries, commonly named ‘hydrogen’ batteries are increasingly recognised as a clean and reliable energy vector for decarbonisation by various sectors (Wei, McMillan and de la Rue du Can, 2019; Osman *et al.*, 2021). However, the existing literature shows that setting up a hydrogen-based microgrid in a small-scale installation is unviable today, mainly due to the high cost of hydrogen generation and consumption equipment (Navas, Cabello González and Pino, 2022).

b) From the demand side, 4 different uses are included: residential, civic centre, market and schools.

Recent studies (Fina, Auer and Friedl, 2019) suggest that the more diverse the load profiles, the greater the benefits and cost savings possibilities. Taking into consideration big customers, such as public buildings, may greatly boost the profitability of the installation as well as helping balance large peaks. Therefore, the study is going to include public buildings and residential buildings within the neighbourhood. Hourly consumption data for each of the public buildings was provided by the Institut Municipal d’Urbanisme (IMU) and residential data was extrapolated analysis from other studies that provided standard household energy consumption profiles in Spain (Escobar *et al.*, 2020).

c) Only the services that are currently provided by electricity are considered.

This is mainly driven by the lack of data available on domestic hot water and heating consumption of the studied buildings, as domestic hot water and heating in Spanish households are usually fuelled by gas and there was no hourly data available for gas consumption.

However, even if the data was available, it is unclear whether these services should be electrified or solar thermal technologies should be used. The ideal solution for a specific project necessitates a thorough understanding of the system's performance and the interplay of its components, rather than just technological efficiency. The system's performance is determined by the building envelope, load patterns, solar radiation availability, roof area availability, energy pricing, and policies. As a result, each project in each climatic zone should undergo a case-by-case examination (Ayadi and Al-Dahidi, 2019).

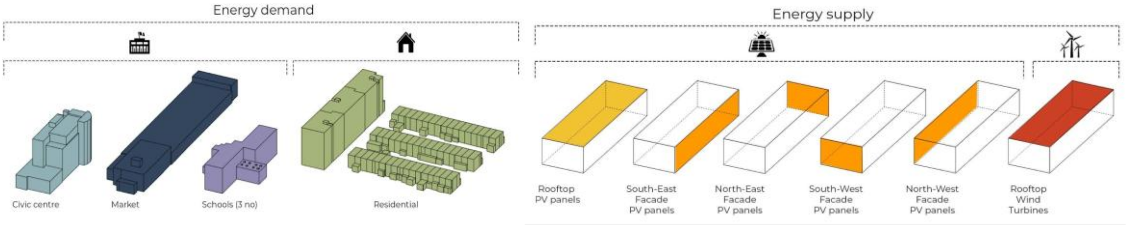
In addition, if solar thermal is indeed less efficient, it is also unclear whether they would still be necessary in the future to decarbonise the energy supply chain, as more variability and flexibility might be needed (Tarroja *et al.*, 2018; Vaishnav and Fatimah, 2020; O’Shaughnessy *et al.*, 2022). Hence, analysing the pros and cons of connecting domestic hot water and heating to the electrical system or to a solar thermal system is outside of the scope of this work.

d) Generation profiles are built combining vertical and horizontal PV panels and wind turbines.

It should be noted that Sud-Oest del Besòs neighbourhood was designed to achieve sun exposure and good ventilation by orienting the buildings and openings accordingly. The organisation of the buildings also responds to the Detailed Plan for the area (Comisión Superior de Ordenación Provincial de Barcelona, 1959), which followed the criteria established by the Regional Plan of Barcelona (Comisión Superior de Ordenación Provincial de Barcelona, 1954). This plan defined the organisation of the urban fabric into free-standing buildings or traditional blocks, the latter with a maximum occupancy of 70% of the land (Rosselló Nicolau, 2011). Therefore, both the design concept and the regulations of the time made the neighbourhood an ideal urban morphology for solar technologies and wind turbines in today’s market (López-Ordóñez *et al.*, 2017)

In summary, this study is going to try to investigate different energy profiles that are currently fed by electricity to combine them in a way that all energy produced is consumed, without the need of storage or selling the surplus back to the grid. It is going to investigate vertical and horizontal PV panels and wind turbines, as generation profiles. This is synthetized in Figure 10.

Figure 10. **Energy supply and demand profiles**



Source: drawn by the authors.

5. Results and discussions

5.1. *Results from Sud-Oest del Besòs analysis*

Technical: most efficient combinations between energy demand and generation profiles

Table 4 below shows the summary of each iteration. The final iteration will be discussed in more detail at the end of this section.

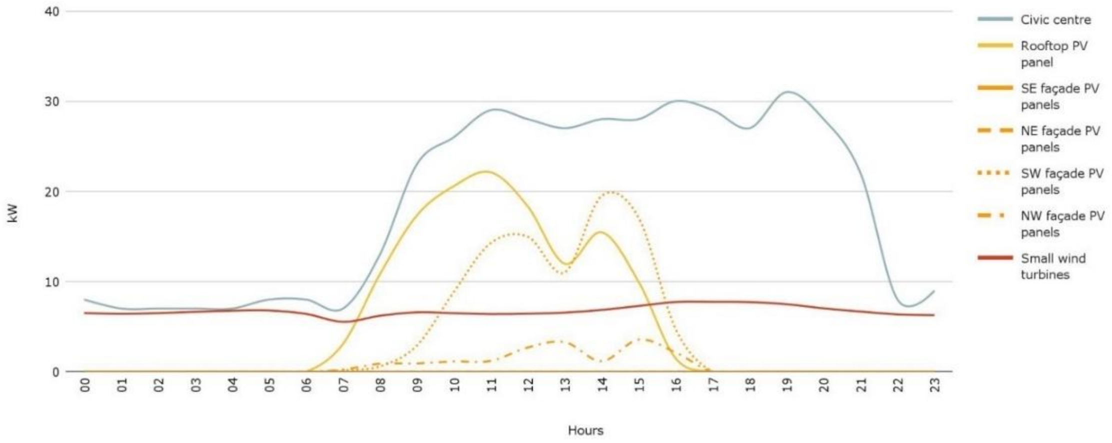
Table 4. **Iteration summary**

Iteration	Analysis
Iteration 1: Civic centre	The civic centre has one of the highest energy loads in the neighbourhood. Therefore, this building was assessed on its own to understand the space required in terms of renewable energies to satisfy this building's load. It was concluded that there was enough potential production capacity to add more buildings to the EC.
Iteration 2: Civic centre, residential buildings and market	The next step in the study was to analyse the combination of profiles: residential, market and civic centre. This analysis aimed at flattening the curve of the civic centre, specially where there wasn't enough production from the PV panels. It was concluded that the residential afternoon peaks were too large to be met by any generation profiles.
Iteration 3: Civic centre, reduced residential buildings and market	There isn't much benefit in mixing such a large number of residential buildings with the public buildings. The residential building's load is so large, that the curve is mainly driven by the households. Therefore, in this iteration, the number of households was reduced to minimise the large peaks in the graph. It was concluded that the afternoon peaks were still too large to have a system driven by self-consumption.
Final iteration: Civic centre, residential buildings, market and schools' analysis	The study added schools to investigate how this affects the demand curve shown previously, which included the market, the civic centre, and the reduced household load within a 500m radius, which was the Spanish regulatory limitation at the time when the study was done.

Source: by the authors.

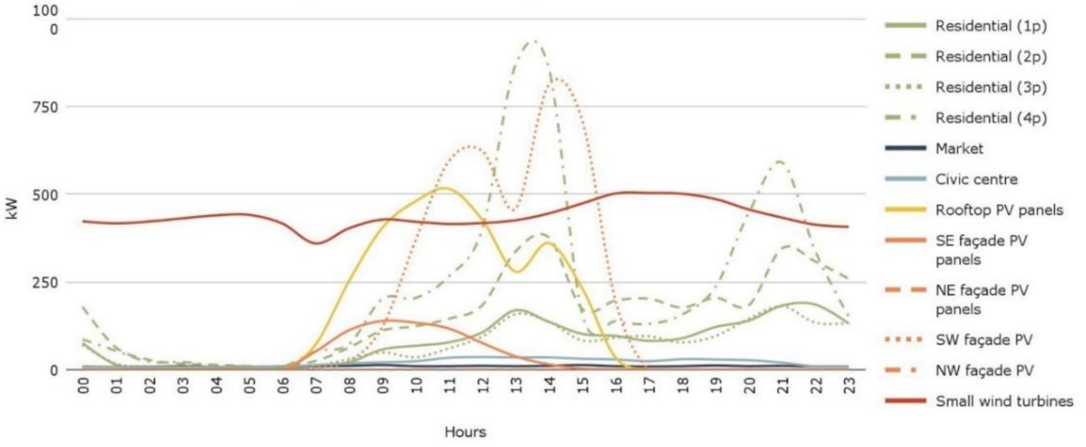
Iteration 1 (Figure 11), Iteration 2 (Figure 12) and Iteration 3 (Figure 13) are shown below for comparison with the final iteration. The winter weekdays were illustrated as it is the typical day that repeats the most during the year.

Figure 11. **Detailed energy demand and supply profiles - Iteration 1 (Winter + Weekday)**



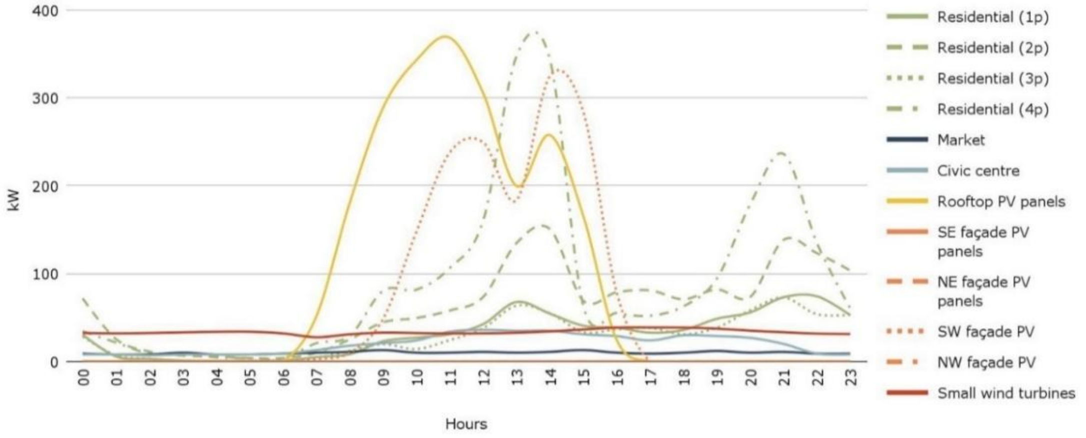
Source: drawn by the authors.

Figure 12. **Detailed energy demand and supply profiles - Iteration 2 (Winter + Weekday)**



Source: drawn by the authors.

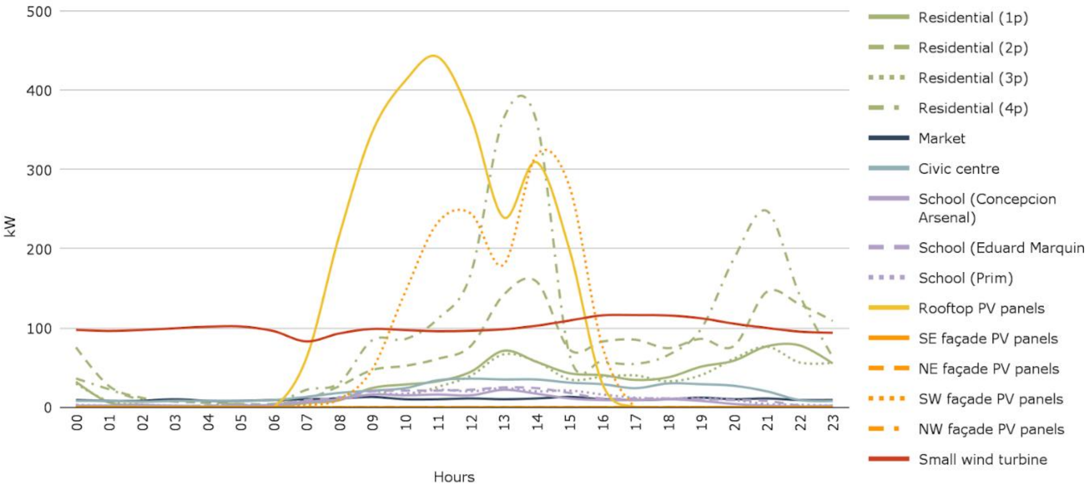
Figure 13. **Detailed energy demand and supply profiles - Iteration 3 (Winter + Weekday)**



Source: drawn by the authors.

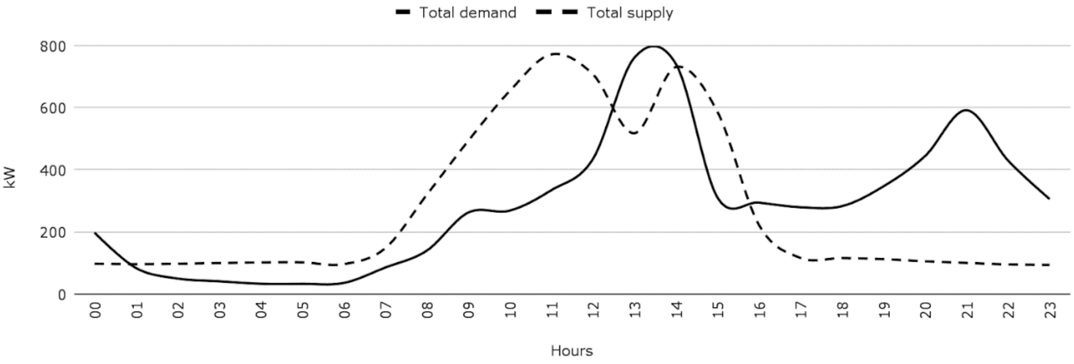
The most efficient combination, the final iteration, of supply and demand profiles was calculated for all typical days (winter weekday, winter weekend, summer weekday, summer weekend). Winter weekday graphs are shown as an example below (Figure 14 & Figure 15).

Figure 14. **Detailed energy demand and supply profiles - Final iteration (Winter + Weekday)**



Source: drawn by the authors.

Figure 15. **Total energy demand and supply curve - Final iteration (Winter + Weekday)**



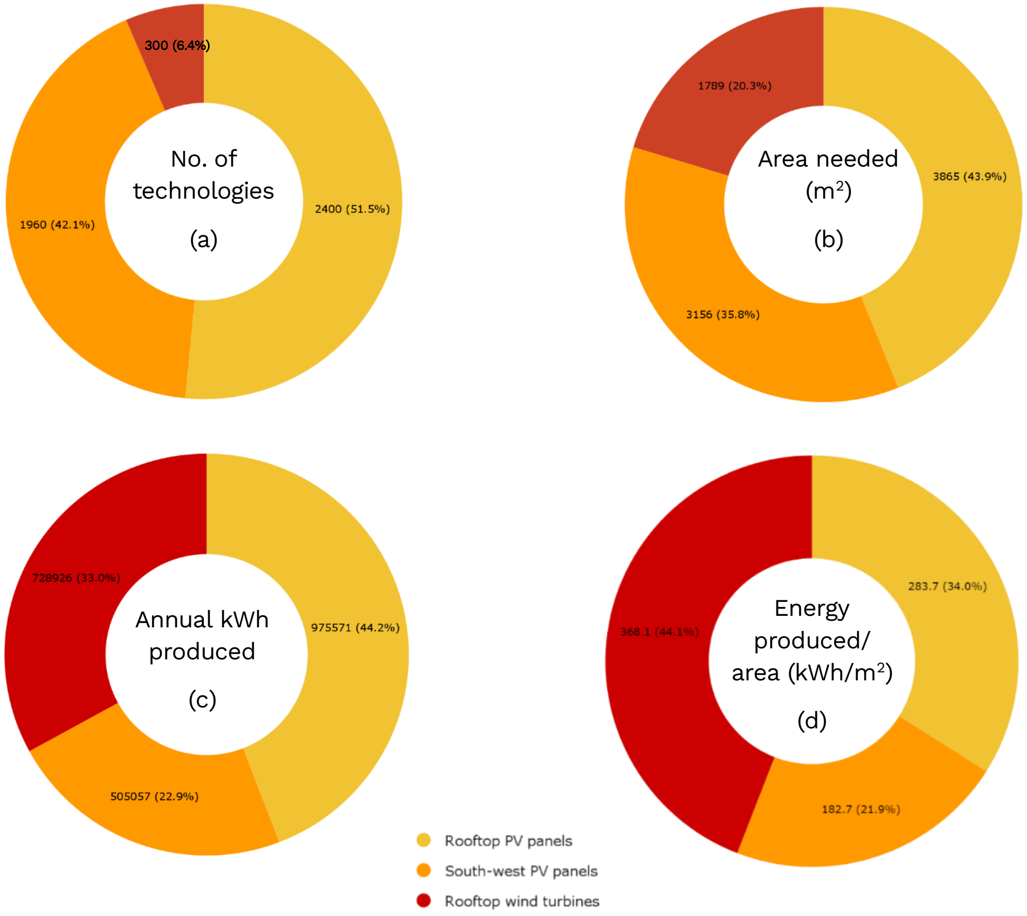
Source: drawn by the authors.

The technical feasibility for energy supply was analysed. The results are presented in Figure 16. The figure shows the number of renewable technologies (a), the area needed (b), the annual energy generation for the final iteration (c) and the Energy produced per area in kWh/m^2 (d) was plotted.

It should be noted that the area study below should be developed as a more detailed study, which considers the physical constraints of the site to establish if the area available is indeed sufficient. Also, as explained before, installing rooftop wind turbines within the site is rather difficult and would need a lot more investigation into the overall physical and regulatory constraints.

Once it was established that the amount of technology required is feasible compared with the amount of area available, the overall annual energy was investigated (both supply and demand). Utilising the latest iteration (civic centre, schools, 42% of the number of households within the 500m radius & market) (Figure 17), the annual supply and demand were calculated. The analysed energy community has an installed capacity of 1390 kW and will produce approximately 2210 MWh annually. On the other hand, the annual demand is 2272 MWh per year.

Figure 16. **Final iteration results**

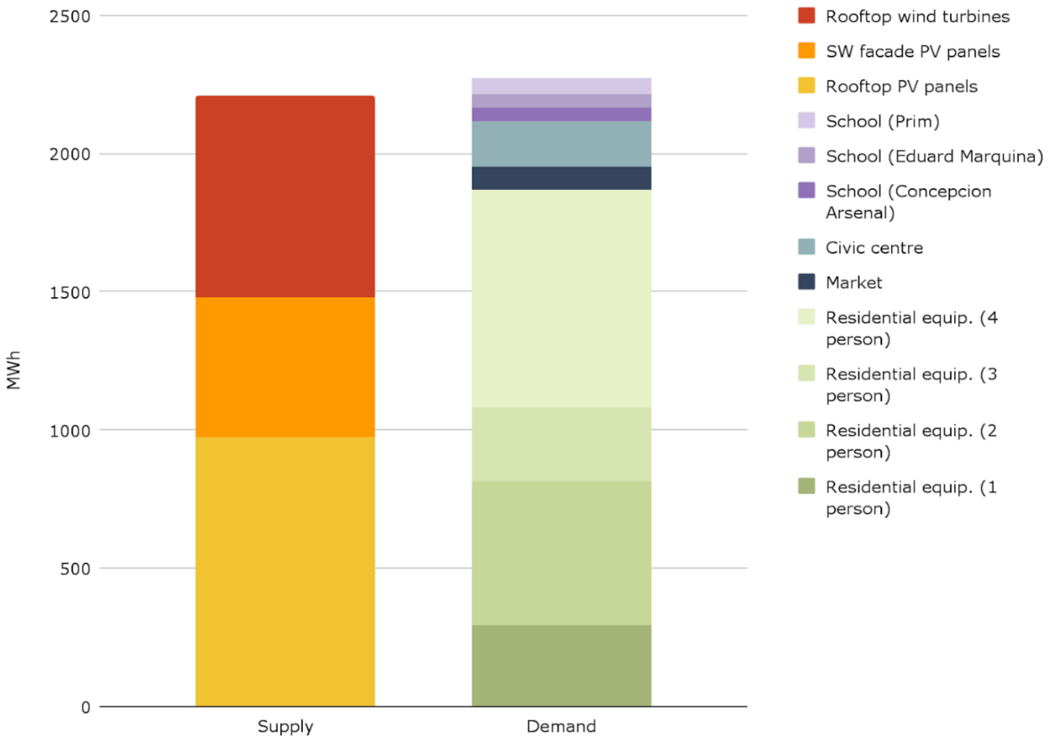


Source: drawn by the authors.

Figure 17. **Final iteration map**

Source: drawn by the authors.

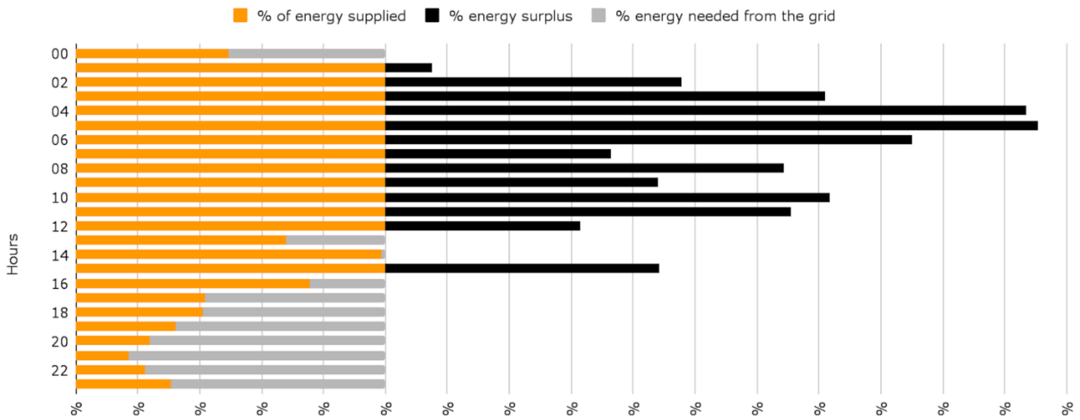
Figure 18. **Total annual amount of energy supply and demand - Final iteration**



Source: drawn by the authors.

Figure 18 is rather optimistic. Even though 98% of the energy demand could be supplied locally, the supply curve and the demand curve do not match in any of the iterations. Hence, the next step was to calculate the percentage of the hourly energy that would be supplied by renewable technologies and the percentage that would still be provided by the national grid. In addition, the surplus energy by renewable technologies was calculated (winter weekday values shown as an example below) (Figure 19).

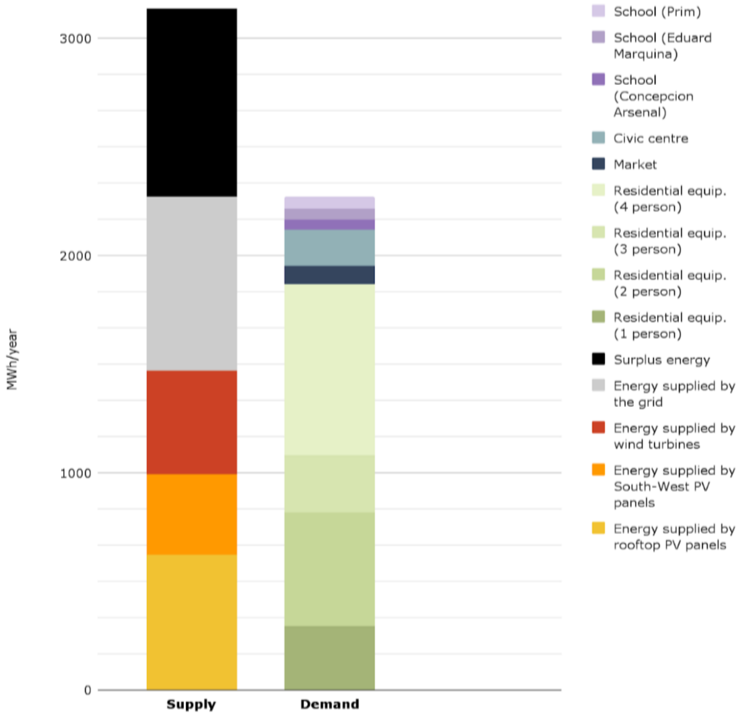
Figure 19. **Hourly percentage of energy self-consumed, surplus and shortage (Winter + Weekday)**



Source: drawn by the authors.

Figure 20 below shows the surplus energy, the energy provided by rooftop PV panels, south-west PV panels and wind turbines; and the energy required from the national grid due to lack of electricity generation by the local technologies at certain times of the day. It was calculated that only 65% of the energy can be self-consumed.

Figure 20. **Total annual amount of energy supply and demand, including shortages and surpluses**



Source: drawn by the authors.

Regulations: possibilities and constraints for self-consumption and surplus energy usage

Self-consumption installations must abide to one of the following modalities: compensation by which the surplus electricity is sold back to the distribution grid in exchange for a compensation on the energy bill or open market modality by which electricity produced in exchange for money, as one more energy producer (IDAE, 2019).

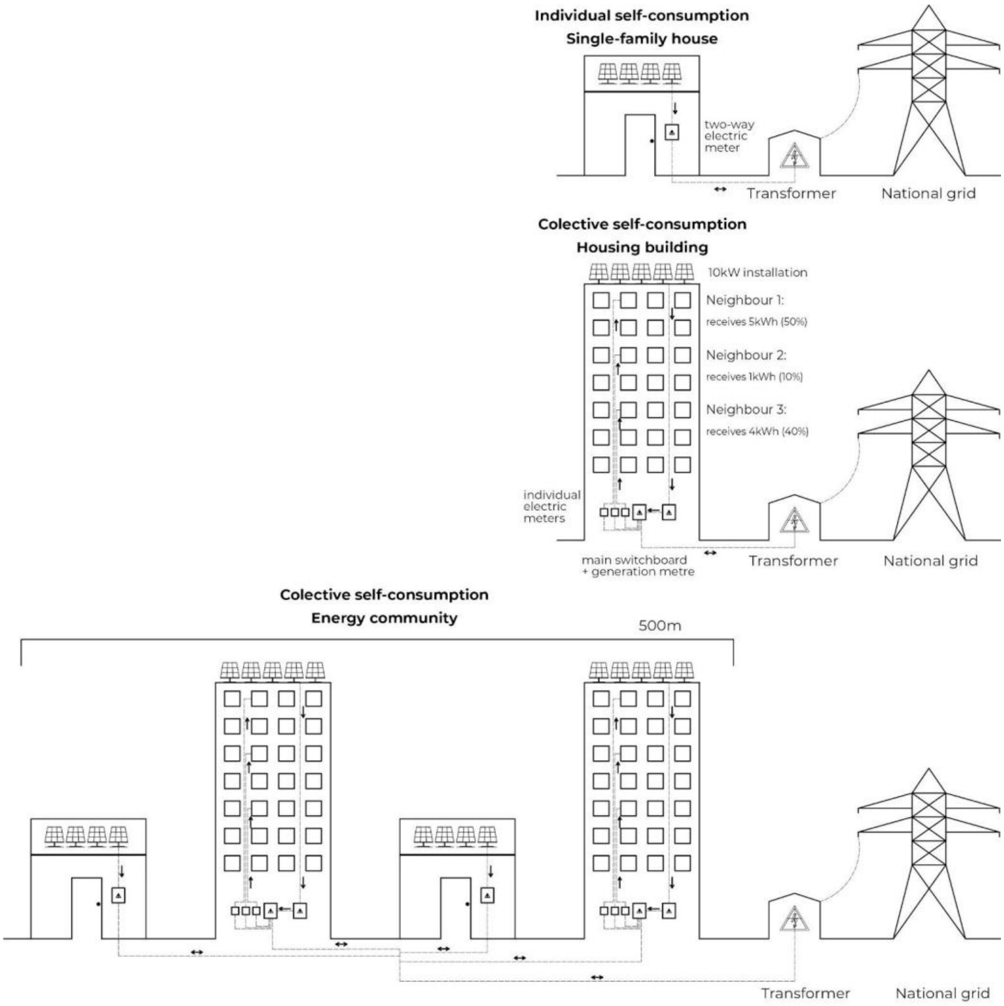
In rural settings, with no previous electrical connections, a microgrid would be installed. However, in a neighbourhood such as Sud-Oest del Besòs, with existing infrastructure in a consolidated urban area, the existing grid will be utilised. As the energy community will have to use the existing inner network, it can only apply for the open market modality. The price that energy can be sold for in the open market is not constant and it depends on factors such as amount of demand, amount of supply, prices of energy in other countries that normally trade with Spain, etc (Saavedra *et al.*, 2021).

The energy community will not pay any tolls for the usage of the national grid when it is used for self-consumption. However, the trading company will charge tolls when buying the electricity (tolls account for approx. 40% of the bill) (Endesa, 2018). Hence, making the price for the energy bought higher than when sold (Álvarez Alonso *et al.*, 2019; Pascual, 2022). This is the main reason why a large self-consumption percentage is key when installing an energy community.

Currently there isn’t a proper definition within the Spanish regulations for energy communities, therefore there are no laws that fully encompass the requirements that these associations will need. It is expected that between this year and the next a new “Real Decreto” will be released that defines these entities and sets out the stage for their implementation (Álvarez Alonso *et al.*, 2019; Pascual, 2022). A major issue with the current regulations is that all surpluses, self-consumption and energy shortage values are calculated monthly, not hourly. This is due to the distribution coefficients being static, which means that they are established by a long-term contract (Álvarez Alonso *et al.*, 2019; Pascual, 2022).

This means that energy can't be distributed to the user that needs it at that point in time. When trying to take advantage of different types of user profiles to balance the curve, a monthly balance will not be beneficial. It is expected that this will change soon, when the new regulations are in place. Should that be the case, the distribution coefficients will become dynamic and that the charges for surplus/energy shortage will consider the supply and demand need on an hourly basis, making the system more efficient (Diputació de Barcelona, 2021).

Figure 21. **Self-consumption arrangements**



Source: drawn by the authors, information from (IDAE, 2022).

Governance: possibilities and constraints

When applying the classical theory on the rights and rules to urban commons, governance becomes a critical issue to be studied (Schlager and Ostrom, 1992). Due to this, (Ando, 2012) studied already governance models in order to avoid conflicts, especially when talking about common-pool resources. In this case, the common-pool resources are considered to be in between spaces, roofs, façades and any other elements that can give open access to the sun and wind. (Ando, 2012) have established five property rights in use, which were analysed together with the case studies (Table 5).

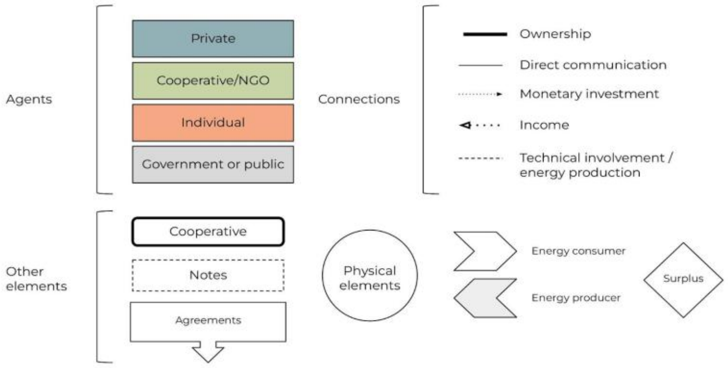
Utilising the case studies, the municipal guide by (Diputació de Barcelona, 2021) and considering the regulations, two possible governance pathways for Sud-Oest del Besòs were established. The first image shows the legend (Figure 22) and the next two show the two options presented (Figure 23 & Figure 24).

Table 5. **Analysis of each case study governance in terms of property rights**

Case study	Entry	Withdrawal	Management	Alienation
Edinburgh Community Solar Limited	Any citizen can buy shares	Return on share capital (5%, rises with RPI annually). Surplus reinvested	1 member = 1 vote. Decisions on surplus profit distribution decided at AGM by members and board of directors	Members can't withdraw shares within the first 3 years. Afterwards, the Board can allow shares to be withdrawn. Shares can be inherited
Marstal Fjernvarme	Members can buy shares if they own a household that is part of the network	Lower costs of energy bills	1 member = 1 vote. Members elect a board of directors. Major decisions are made at AGM	Shares are sold/inherited as part of the household
Svalin co-housing complex	By buying or owning a house in the co-housing community	Direct energy use	Peer-to-peer	The houses can be sold or inherited
BEG Wolfhagen	Any member of the utility company can buy shares. No more than 40 shares are allowed per member.	Return on share capital and reinvestment on higher domestic efficiency projects	1 member = 1 vote. The general assembly meets at least once a year to elect the members of each of the 3 boards (Supervisory, Executive and Advisory). The boards make the decisions throughout the year.	Shares can be terminated with a 2-year notice or they can be sold to someone that meets the requirements. In case of death, the shares can be terminated or transferred to an heir.

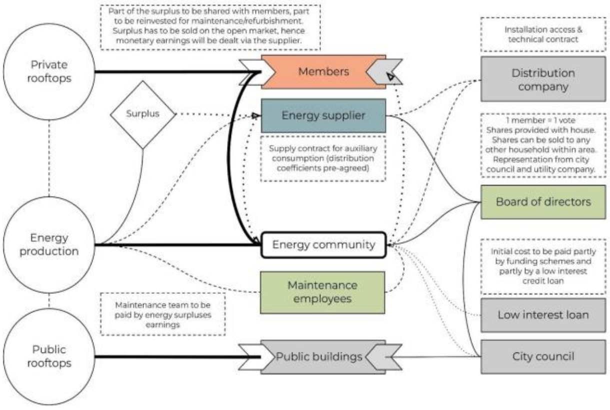
Source: by the authors.

Figure 22. **Legend for governance options**



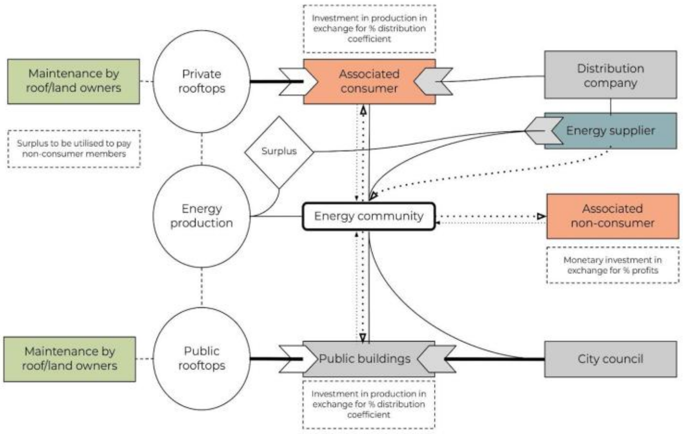
Source: drawn by the authors.

Figure 23. **Option 1 - Shared self-consumption via cooperative with surpluses**



Source: drawn by the authors.

Figure 24. **Option 2 - Shared self-consumption with private investment**



Source: drawn by the authors,

5.2. *Discussion*

As it was shown in the previous sections, in the EC proposed in the SOB, there are times of the day where there are large energy surpluses and times where there is energy shortage. The surpluses and shortages account for almost the same amount of energy, but the regulatory context prevents for the compensation of these. If dynamic coefficients were utilised, could we provide a more efficient EC? If some energy intensive activities were moved to times of the day where energy generation is higher, how much of an impact would this have on the overall curve? Could the generation curve match the demand curve?

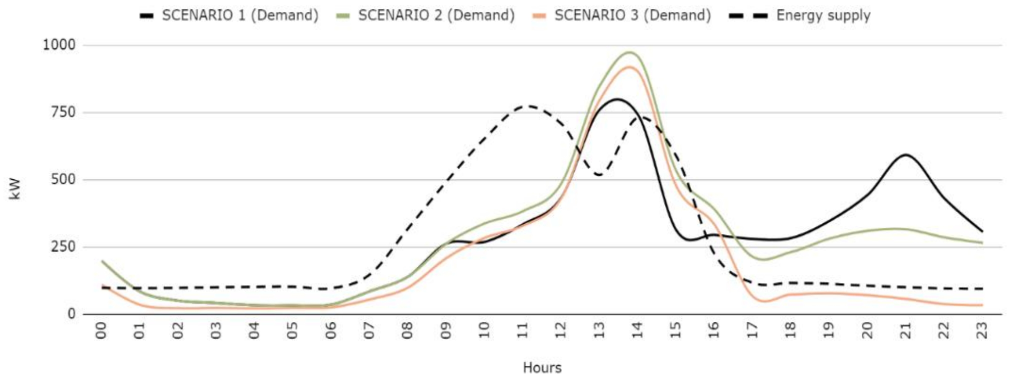
The demand peaks that are the most difficult to balance with renewable technologies are the ones happening in the afternoon. These peaks are mostly posed by the residential buildings. Some very high residential loads are due to TV usage, dishwasher and cooking. Could the occupants perform lower energy entertainment activities, such as reading, in the afternoon? Maybe using a laptop instead of the TV, which has battery storage and can be charged at a different time? Could the dishwasher be used at noon when energy surpluses are high? Can cooking be performed at lunch time to then have the leftovers for dinner?

In order to assess the benefits of changing household activities' timetables, it was assumed that all dwellings would make the changes mentioned above. Then the same energy generation curve was compared with the updated energy usage curve (SCENARIO 2). In addition to changing the shape of the demand curve, reducing the area of the curve could also help achieve a more balanced system. In other words, reducing the energy use on top of moving the demand to different hours of the day would have a significant impact on the overall balance (SCENARIO 3). According to Endesa (2017), utilising real time monitors would reduce 15% of the energy demand. (Dietz, Stern and Weber, 2013) estimate that the opportunity for home decisions to minimise fossil energy usage is significant. They have estimated a 7% decrease, which they have described as a worst-case scenario and that it could be considerably higher. According to Red Eléctrica de España (2020) if stand-by power is eliminated and low consumption lightbulbs are installed, the domestic energy consumption could be lowered considerably.

Figure 26 shows the amount of energy that was self-consumed, the amount of energy that would be needed from the national grid and the surplus generated.

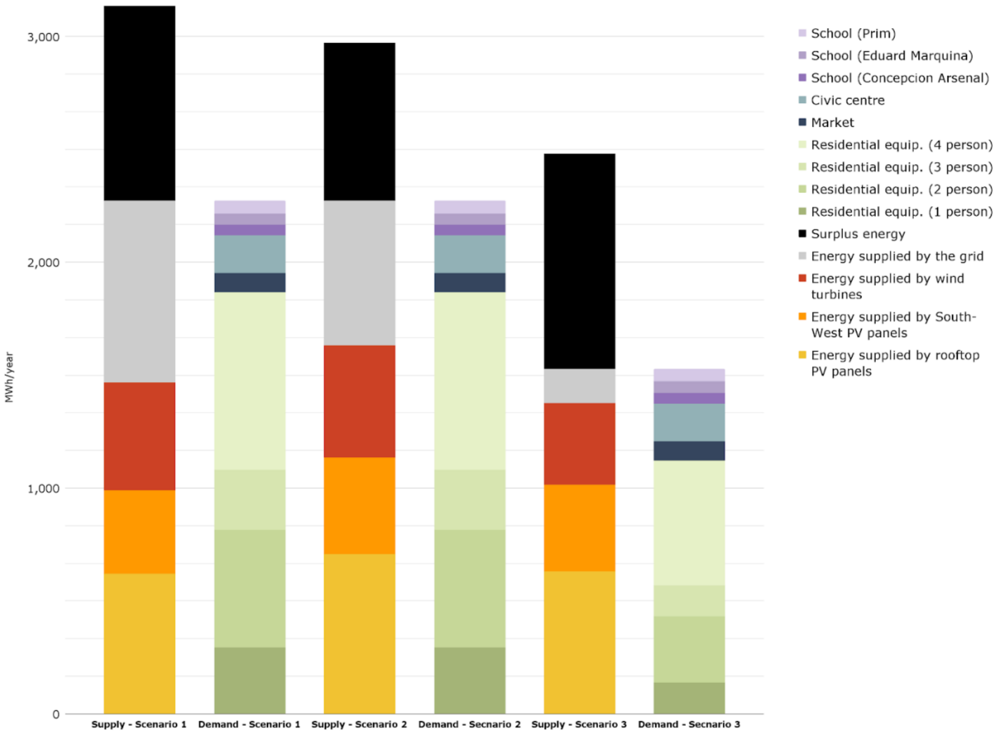
- Scenario 1: Current demand
- Scenario 2: Behaviour change by moving activities to times of the day where there is more supply
- Scenario 3: Behaviour change by reducing domestic energy demand due to better management.

Figure 25. **Scenario 1, Scenario 2 and Scenario 3 for typical day: Winter + Weekend**



Source: drawn by the authors.

Figure 26. **Total annual amount of energy supply and demand, including shortages and surpluses (current, behaviour change and lower demand scenarios)**



Source: drawn by the authors.

Changing activities to earlier hours of the day, when the generation is high together with lowering the energy demand shows that approximately 90.1% (1377 MWh) of the energy demand could be supplied by the local renewable technologies, 9.9% (150 MWh) would still have to be supplied by the national grid and there will be 955 MWh of energy surplus that could be sold back to the national grid.

It should be noted that the values above are highly unlikely for several reasons. One of the main reasons is that residential values were taken as average values from Spain instead of using individual values from each neighbour in SOB. In addition, different households will have different needs and schedules. Another point to add is that some home improvements for scenario 3 were applied for every household, when it is known that every home has been renovated and changed though the history of the neighbourhood. However, the authors believe that this calculation shows how impactful behaviour change and energy consumption awareness could be.

Although the strategies stated above seem like simple solutions to a big problem, behaviour change is not usually easy, especially if the occupants aren't fully on board with the strategy. However, a rising amount of research in academic literature shows that measures aimed at behaviour can save energy (European Environment Agency, 2013). According to (Cabinet Office, 2011) individuals' behaviours can differ significantly and achieve a model in which people objectively consider the costs and advantages of investing time and money in 'greening' their houses and becoming more energy efficient. Social, cognitive, and behavioural variables play a role in explaining why many individuals have yet to implement adjustments that may help them enjoy cosier homes and reduced energy expenses.

Changes in behaviour that minimise emissions have significant advantages. First, unlike significant infrastructure modifications, which may take years or even decades, the advantages can be seen quickly. Second, they can be quite inexpensive. Third, they can directly deliver savings and other advantages to citizens (Cabinet Office, 2011). Therefore, these types of solutions should be considered in future scenarios.

The current energy system asks occupants to utilise energy when there is low usage (mostly at night time), which is a model that tries to spread energy demand throughout the day. However, the strategy proposed by the study tries to concentrate energy use at certain times of the day according to peak generation. Hence, this study's model puts emphasis on understanding the supply curve on top of the demand curve. This is important because energy consumption and energy supply are dynamic, the curves will change throughout the year. These curves depend not only on meteorological factors, but also the occupants' needs. Therefore, if a model is established where there is more occupant flexibility, then changes in the generation curve should be easily met.

6. Conclusions

The examples analysed have demonstrated that community building surveys to discover possible energy efficiency upgrades and ideal locations for renewable installations can be very beneficial. Promoting awareness and monitoring can also provide very positive results to the community. In addition, identifying funding and potential ways for the government to support the project is key when installing an energy community in a marginalised neighbourhood.

The renewable technologies that were deemed more suitable for Sud-Oest del Besòs were both horizontal and vertical PV panels and rooftop wind turbines. Mixing wind turbines with rooftop and vertical PV panels made the system more efficient. The energy generation curve was able to reach more hours of the day in contrast with having only rooftop panels. Specifically, energy demand early in the day and late in the afternoon was only supplied by wind turbines and vertical PV panels.

Mixing different types of renewable energies is also beneficial, each technology has different types of physical constraints. Hence, the overall area could be assessed to install each technology where it's more suitable, e.g., shaded areas for wind turbines.

It was concluded through this study that residential units should be connected with other types of buildings, such as schools, markets and civic centres. This is due to the fact that residential buildings tend to have high peaks in the afternoon, which is a time where it is difficult to generate energy locally with renewable technologies.

The most balanced energy community consisted of 42% of the number of residential buildings within the 500m area (24% of the neighbourhood), the market, three schools and the civic centre. As storage was deemed not viable either due to ecological reasons, space or cost, the renewable technologies could only supply approximately 65% (1470 MWh) of the demand.

However, besides the implementation of renewable energy generation systems, behavioural changes seem to be of remarkable potential, both by means of moving energy intensive activities to times of the day where there is more generation and also by means of reducing energy demand overall.

If these simple strategies are implemented approximately 90.1% (1376 MWh) of the energy could be self-consumed and only 9.9% (150 MWh) would need to be supplied by the national grid, making the system extremely efficient. In addition, 955 MWh will be surplus energy that could be sold back to the grid or the amount of equipment needed could be reduced.

It is important to self-consume as much of the generated energy as possible. When selling the energy back to the grid, only the kWh generated will be paid. However, when buying energy from the grid, the kWh needed plus tolls (which account around 40% of the energy bill) will be charged. Therefore, the energy bought has a higher rate than the energy sold, making self-consumption the preferred system. In addition, as shown by the examples investigated, prices and regulations related to surplus energy vary greatly in time. Therefore, given the current regulatory framework, the projected EC should not rely on the benefits of the surplus energy in order to succeed if the regulations are not changed. The current regulations make the system less efficient, as the distribution coefficients are static instead of dynamic. It is expected that in the near future this will change, making it possible to sell, buy and share energy on an hourly basis, as analysed by this study. Should the regulations change, new paths for more efficient EC would be devised.

In terms of governance, it was concluded that including the city council and the utilities companies within the decision-making process is important to generate cohesive and connected projects within the community. Also, a “1 member, 1 vote” system was proven by the examples analysed to be the most inclusive. All members will have the same weight when it comes to making decisions, regardless of economic power. This is an important aspect, especially in a marginalised neighbourhood such as Sud-Oest del Besòs. It is recommended that part of the profits is utilised to implement domestic rehabilitation, which has been shown will make the system even more efficient, allowing for even more self-consumption, energy surplus and, hence profits and lower energy bills.

It is expected that installing an energy community and utilising the profits to reinvest in a more sustainable neighbourhood will lower energy poverty issues, improve social cohesion and improve the living standards of the neighbourhoods overall.

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Authorship

First author: Writing, research, data gathering and plotting, methodology interpretation of results. The Second author: Writing, research, review. Third author: (PhD): Writing, research, review.

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