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Using urban building energy modeling data to assess energy communities' potential

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ABSTRACT

The decentralized solar deployment will play a crucial role in the energy transition, especially in urban areas where high electricity consumption density is found. By implementing local generation systems, such as photovoltaic panels in buildings' roofs, energy communities (EC) arise as an innovative and cooperative strategy to share these decentralized energy resources.

This work develops a modeling framework to assess the potential of EC creation, by combining Urban Buildings Energy Modelling (UBEM) capabilities and building's rooftops potential for solar generation. Hence, three EC case studies, with multiple building typologies, have been simulated and analyzed for three energy sharing scenarios: individual self-consumption outside an EC and collective self-consumption without and with a central battery storage, both inside an EC.

The case study results demonstrate that self-sufficiency in buildings increases when going from individual self-consumption to collective self-consumption, having the best results when combining diverse demand profiles. Self-sufficiencies achieved at a community level range from 16% to 34%. Moreover, results show that when considering battery storage systems, self-sufficiency increases 16 percentual points, however decreasing the economic viability.

By considering UBEM outputs the developed model allowed a valuable assessment of EC performance, constituting a valuable step in enhancing its implementation.

1. Introduction

According to the Energy Performance of Buildings Directive (EPBD), buildings consume 40 % of primary energy in the European Union (EU) and are responsible for about 36 % of energy related CO_2 emissions [15]. Both citizens, private and public institutions are called to take part in the energy transition for a future energy system that should not only be sustainable but also decentralized and democratically governed [56]. Energy Communities (EC) that allow for energy sharing and/or trading among participants are thus proposed in the Clean Energy Package for all Europeans [17], as a transversal solution to guarantee a sustainable energy transition in urban areas, aiming for the decarbonization of cities, implementing new strategies for energy demand and local energy production, into a renewable and decentralized energy paradigm [53].

In the Portuguese context, the regulation of EC deployment is still recent (DL 162/2019 [43]) and the number of ECs remain significantly low, exception made for some research and pilot case studies trying to assess its potential and motivations [6,8,49]. However, EC study results tend to be extremely case study derived, and getting access to accurate data is pointed out as a great challenge [29]. Furthermore, Soeiro & Ferreira Dias [52] state that "*citizens are willing to participate in an EC, as long as they recognize that it brings benefits to the community where the renewable energy project will be installed and to the environment*". As such, to fill the gap between assessing EC potential and its deployment, economic, energy, and environmental outputs should be modeled to best match participant motivation and expectation.

Urban building energy models (UBEM) are being increasingly used to simulate the energy consumption of large building stock, from hundreds to thousands of buildings, while considering their diversity in construction, geometry, and uses [2,22,47]. Although the value of UBEM tools for energy planning and building stock' decarbonization is clear and widely used, there is still the need for incorporating new technologies and systems that can help stakeholders on implementing energy efficient solutions [20]. Thus

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Nomenclature

Acronyms

CBESS	Central Battery Energy Storage System
CEA	City Energy Analyst
EC	Energy Community
KPI	Key Performance Indicator
SOC	State of Charge
UBEM	Urban Building Energy Modelling

Variables

B_{cap}	Battery capacity (kWh)
B_{level}	State of charge of the storage system (kWh)
$CHAR$	Charge (kWh)
d	Discounted rate (%)
$DISC$	Discharge (kWh)
E_C	Energy available for charge (kWh)
E_D	Energy available for discharge (kWh)
$E_{demandn}$	Energy demand (kWh)
$E_{generation_n}$	PV energy generation (kWh)
E_{grid_n}	Building's energy demand from the grid (kWh)
E_{net_n}	Net energy demand (kWh)
EC_{demand}	EC energy demand (kWh)
$EC_{surplus}$	EC energy surplus (kWh)
EC_{toGRID}	EC export to the grid (kWh)
GHG_{index}	Greenhouse gases emission factor (gCO$_2$/kWh)
$GRID_{toEC}$	EC import from the grid (kWh)
I_{0n}	Initial building's PV investment (EUR)
IRR	Internal Rate of Return (%)
η_{charg}	Charging efficiency (%)
$\eta_{discharg}$	Discharging efficiency (%)
NPV	Net Present Value (EUR)
P_{bat}	Maximum CBESS power (%)
p_{EC}	Energy price in EC (EUR/kWh)
p_{surpl}	Selling energy price (EUR/kWh)
SC_{EC}	EC self-consumption rate (%)
SOC_{min}	Minimum SOC level (%)
SOC_{max}	Maximum SOC level (%)
SS_{EC}	EC self-sufficiency rate (%)
Δt	Duration of the timestep in hours (h)
$X_{sharing_n}$	Surplus sharing coefficient (%)

UBEM creates the perfect environment to combine EC modeling, helping to bridge between EC research and implementation.

This work presents a modeling framework that calculates relevant parameters for assessing energy communities' performance from a given building stock after its urban energy modeling. This framework uses an UBEM tool for modeling the building stock comprising different typologies and end-uses, to provide hourly resolution data on building's energy needs and production and calculates EC key performance indicators (KPIs) by which the EC performance will be assessed and compared. The modeling framework is tested on an urban neighborhood in Lisbon, Portugal.

The work is organized as follows: section 2 presents related work on EC and UBEM, while section 3 presents the development of the modeling framework methodology. In Section 4 the EC scenarios and case studies are presented while section 5 discusses the results. Final statements are made in section 6.

2. Background

Building's energy consumption plays a significant role in global energy supply and demand. Nevertheless, significant energy savings can be achieved in buildings if they are properly designed, constructed, and operated, and if solutions that maximize energy efficiency and renewable energy production are implemented. Urban Building Energy Modelling is an essential line of research to achieve the reduction of energy demand in buildings and model its behavior [7]. At the same time, energy communities' deployment lack access to systematized demand and rooftop solar potential data to better estimate potential economical and potential gains. Thus, integrating UBEM by assessing energy demand and production for a given building set, with energy communities could allow increasing buildings and community energy self-sufficiency.

2.1. Energy communities

Energy communities are expected to pave the way to more inclusive energy systems by giving citizens democratic control and ownership over their energy supply, enhance social mobilization and community empowerment, and tackle fuel poverty on remote areas [28]. Energy communities can also cooperate with system operators to increase the resilience of the energy grid. This resilience is achieved by taking a full advantage of the large number and different building typologies involved, i.e. benefiting from the aggregation of demand response, and offering flexibility to the system operator [24].

Nowadays, EU legislation considers two approaches for defining energy communities: Renewable Energy Community (REC) [18] and Citizen Energy Community (CEC) [19]. In Portugal, Decree Law 162/2019 [43] states the regulatory framework for energy communities. Moreover, the transposition of Directive (EU) 2019/944 (European Parliament 2019) on common rules for the internal electricity market, and, partially, Directive (EU) 2018 /2001 (European Parliament 2018) on the promotion of the use of energy from renewable sources resulted on the Portuguese Decree-law n° 15/2022 (Conselho de Ministros 2022). Despite the specific legislation, the real potential and challenges of energy communities are still being revealed through pilot case studies, namely in a few industrialized and developed nations [23]. There is still a need for understanding and evaluating the different impacts of energy communities both at the individual building level as to the whole community. Partly, this is related to the convention of taking buildings individually instead of considering their interdependencies with surrounding buildings [5,46]. Furthermore, the lack of trust in market-based and state-led solutions concerning EC is pointed as an obstacle to EC implementation [30].

Dóci & Vasileiadou [10] surveyed German and Dutch citizens regarding their motivation for participating in Energy Communities and the most frequent motivations were "*cutting energy costs, expected lower energy prices after the projects, and saving some money in the long run*". Besides the cost reduction, people also hoped for getting some profit from the investment. To engage citizens and other stakeholders on participating on energy communities is crucial to provide detailed analysis on energy demand reduction, profit, and economic viability analysis [9]. However, one of the main issues when defining energy communities is the collection and analysis of the necessary data. Kazmi et al. [29] tackled this problem by providing a detailed overview of publicly available datasets, models and tools that can be used to optimize design and operation of local energy communities. Also, in Braeuer et al. [4] a mixed-integer linear programming (MILP) optimization model is developed for assessing the implementation of multi-energy systems in an energy community in multi-family buildings with a special distinction between investor and user. The results show the strong influence of the heat demand on the system layout and that the implementation of energy communities differs greatly by country. Regarding the last trends on storage technologies in energy communities, according to Terlouw et al. [55], there is an increasing interest due to beneficial economies of scale and optimal storage sizes when compared to individual storage. It is expected that community energy storage will offer distributed applications and energy trading in electricity markets more efficiently, since the controlling of collective storage is expected to be more convenient than the controlling of individual storage [39]. In fact, Roberts et al [50] show that scenarios modelled with community storage achieve higher self-consumption and self-sufficiency values than when considering individual storage. The need to provide detailed information on EC performance, with and without storage, is pointed as an essential step to enhance EC implementation. Techno-economic feasibility assessments must be performed, and energy modelling or optimization are valuable computational tools that can provide insights on the operation of power systems while allowing to compare the impact of their assumptions in their optimal configuration [40;41].

2.2. Urban building energy modelling

Urban building energy modelling is defined as a bottom-up, physics-based approach to simulate thermal and energy performance of new or existing neighbourhoods and cities. The overall goals of UBEM are to provide data-driven insights for different urban-level use cases, such as urban planning and new neighbourhood development, stock level carbon reduction strategies, and buildings-to-grid integration [2,21,22,47].

Being able to realistically model the energy performance in buildings is essential to achieve building's energy efficiency goals [35]. In their work multi-detail archetypes for the Portuguese building stock context, are generated and applied to a neighbourhood in Lisbon showing the potential for energy reduction scenario analysis.

Hong et al. [22], on their review and challenges for UBEM, highlight that these tools can estimate the potential of renewable power generation from photovoltaics (PV) located on rooftops or integrated into building facades and that may provide unprecedented value to the design and operation of low-energy buildings and communities in cities.

UBEM is considered a potential technological trigger to support kickstarting energy communities, especially as early-stage decision- and design-support tool [5]. This work addresses the knowledge gap on accessing systematized building's energy demand and rooftop solar generation data to best assess EC deployment potential, by combining urban modelling to generate data to feed an EC model and testing it for different EC configurations and energy sharing scenarios.

3. Methodology

The methodology followed in this work is illustrated in Fig. 1. First, the necessary data for building characterization is collected. Then, the inputs for building modelling with City Energy Analyst (CEA) are introduced [21], and building's energy demand and PV generation files are produced (Section 3.1). After, different EC configurations and energy sharing algorithms are defined, together with its main defining parameters (Section 3.2). Finally different EC case study scenarios are simulated, and its performance is assessed by the introduced Key Performance Indictors (KPIs) (Section 3.3 and 3.4).

3.1. UBEM framework

The energy performance of the buildings is modelled through CEA, with its framework defined in [21]. Regarding the building data, QGIS tool [45] has been used to create the inputs for CEA, which are shapefiles that contain the building plans, construction standards and uses, for each building in a certain urban area. To assign the type of use and the energy supply for each building, data is retrieved from Portuguese statistics [26]. The weather data for Lisbon is collected from Energy Plus Weather Database (Energy [14] and shadows from surrounding buildings are created in CEA, with data from Open Street Maps [38]. CEA creates one file per building with the hourly energy demand data for a year in.csv format.

Regarding the PV generation potential in buildings' rooftops, the implementation of PV panels was assumed in every building if their rooftops receive a minimum threshold of radiation per year, using CEA features.

With the georeferenced data and the weather file, CEA calculates the incident horizontal solar radiation for the rooftops of all buildings. The output files are also hourly and in.csv format. By defining the minimum threshold, CEA considers panels only on surfaces that receive a yearly horizontal radiation above a pre-defined value in kWh/m^2/yr. The optimum slope to install the panels was decided through PVGIS tool [44] as the one with the highest yearly in-plane solar irradiation (kWh/m^2). It is important to mention that economic factors (PV investment and maintenance cost) were not considered when implementing photovoltaic panels, being its viability only restricted by incident radiation and available area of building's rooftops.

Fig. 2 shows the inputs and outputs used in CEA for the calculation of electricity demand and PV generation in buildings.

3.2. Energy community framework

The electricity fluxes for each building and in the EC are presented next.

The hourly net electricity E_{net_n} for each building n, is calculated by Equation (1):

$$E_{net_n}(t) = E_{demand n}(t) - E_{generation_n}(t)\,[kWh] \tag{1}$$

The electricity demand and PV surplus of the EC after self-consumption, are calculated by Equation (2) and (3), respectively. These are also valid for individual buildings n that make part of the community.

$$if\ E_{net_n}(t) \geq 0\,;\, EC_{demand}(t) = \sum_{1}^{N} E_{net_n}(t)\,[\mathrm{kWh}] \tag{2}$$

$$if\ E_{net_n}(t) < 0\,;\, EC_{surplus}(t) = \left|\sum_{1}^{N} E_{net_n}(t)\right|[\mathrm{kWh}] \tag{3}$$

At community level, the electricity demand will be firstly covered with surpluses from the EC and when demand is not satisfied, electricity will be supplied by the grid. Equation (4) defines the calculation for the electricity that would be exported to the grid and Equation (5) defines the electricity that the energy community would still need to import from the grid, in each timestep.

$$if\ EC_{surplus}(t) \geq EC_{demand}(t);\ EC_{toGRID}(t) = EC_{surplus}(t) - EC_{demand}(t)[\mathrm{kWh}] \tag{4}$$

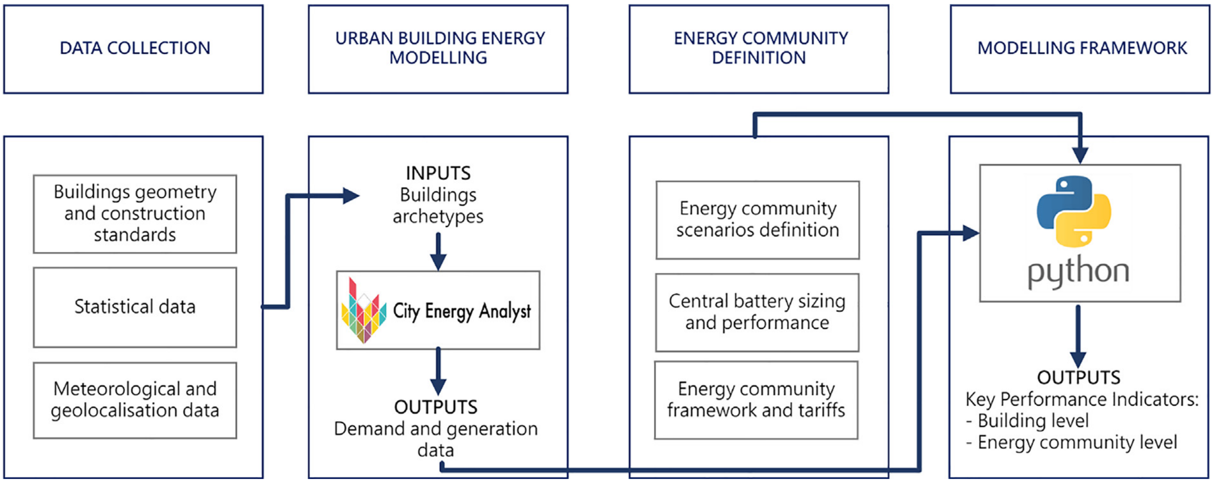

Fig. 1. Methodology: UBEM inputs and outputs, Energy community definition and modelling outputs.

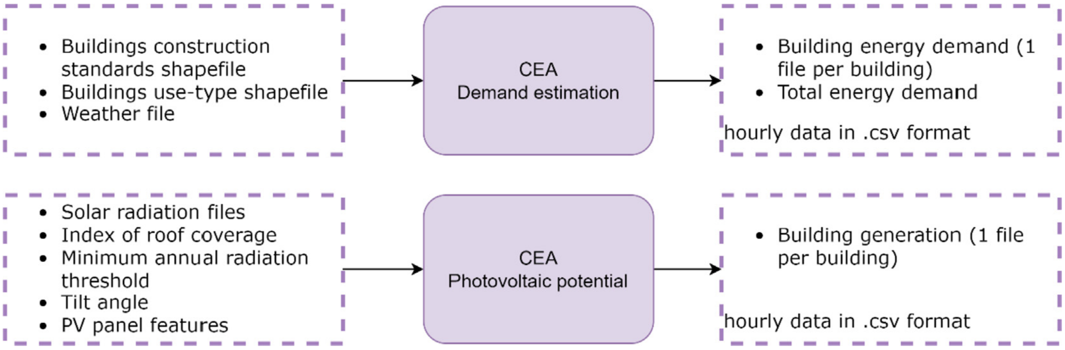

Fig. 2. CEA demand and generation estimation: inputs/outputs.

$$if\ EC_{surplus}(t) < EC_{demand}(t);\ GRID_{toEC}(t) = EC_{demand}(t) - EC_{surplus}(t)[\mathrm{kWh}] \tag{5}$$

The distribution coefficient of PV surplus among EC participants $X_{sharing_n}(t)$, is done proportionally to the building demand (Equation (6)). The electricity that each building would need to import from the grid after PV surplus sharing, $E_{GRID_n}(t)$, is calculated in Equation (7).

$$X_{sharing_n}(t) = \frac{max(E_{net\,n}(t);0)}{EC_{demand}(t)}\ [\%] \tag{6}$$

$$E_{GRID_n}(t) = max(E_{net\,n}(t) - X_{sharing_n}(t) * EC_{toGRID}(t)\,;0\,)[\mathrm{kWh}] \tag{7}$$

3.3. Community battery energy storage system (CBESS) framework

However, if in presence of a Central Battery Energy Storage System (CBESS), Equation (4), (5) and (7) change to Equations (9), (10) and (11).

When the energy community is demanding electricity and there is enough energy in the CBESS, a discharge can occur, while when there is PV surplus available, no more EC demand to cover and the battery is not at the maximum capacity, CBESS can be charged.

The algorithm to calculate the performance of the CBESS in each timestep is presented in Table 7 from Appendix A. Therefore, for each timestep the electricity that the energy community still needs from the grid $GRID\_B_{toEC}$ and exports to the grid $EC_B_{toGRID}$is obtained by Equation (9) and (10), respectively. At a building level, the electricity consumed from the grid $E_B_{GRID_n}$would be proportional to the building demand in each timestep (Equation (11)).

$$GRID\_B_{toEC}(t) = max(GRID_{toEC}(t) - DISC\,(t)\,;\,0)[\mathrm{kWh}] \tag{9}$$

$$EC\_B_{toGRID}(t) = max\left(EC_{toGRID}(t) - CHAR\,(t)/\eta_{charg}\ ;0\right)[\mathrm{kWh}] \tag{10}$$

$$E\_B_{GRID_n}(t) = X_{sharing_n}(t) * GRID\_B_{toEC}(t)\ [\mathrm{kWh}] \tag{11}$$

It is important to highlight that temperature effects and losses due to self-discharge and batteries life cycle of the were not considered.

3.4. Energy communities' scenarios

This work considers three different scenarios for the configuration of energy communities:

3.4.1. Scenario 1 (SC_1): Building without EC

This scenario considers that each building benefits only from its own PV generation, without being part of an energy community. Grid consumption occurs when the demand cannot be covered by PV generation, and PV surplus export to the grid when there is no more demand to supply.

3.4.2. Scenario 2 (SC_2): Building in EC

Scenario 2 considers that each building profits from its own PV generation but also shares or receives PV surplus from other buildings' that are part of the energy community. The sharing coefficient

($X_{sharing_n}$) that each building can receive in each timestep is proportional to the building demand and defined in Equation (6). When the EC still has demand after PV surplus sharing, electricity is imported from the grid. Also, if the EC still has PV surplus after sharing with all energy community buildings, electricity is exported to the grid.

3.4.3. Scenario 3 (SC_3): Building in EC with central battery energy storage system (CBESS)

This scenario considers that each building electricity demand can be covered by 1) its own PV self-consumption, 2) with other buildings PV surpluses, 3) with energy from the CBESS, and 4) with imports from the electricity grid. The CBESS is only charged with EC PV surplus and discharged with EC demand needs.

Table 1 resumes and compares the scenarios features.

Grid imports are subject to retail tariffs as the ones reported by the Portuguese Energy Services Regulatory Entity [16] to the regulated market. PV surplus exports to the main grid are sell for 90 % of the monthly average daily price from Iberian Nominated Electricity Market Operators [37], as established by Portuguese regulation (DL 162/2019 [43]).

Table 1
Typology of self-consumption for the different scenarios.

Scenarios	Surplus sharing	Storage sharing	Public grid use
Scenario 1 (SC_1): Individual self-consumption	×	×	✓
Scenario 2 (SC_2): Collective self-consumption	✓	×	✓
Scenario 3 (SC_3): Collective self-consumption with storage	✓	✓	✓

3.5. Energy and economic key performance indicators

The energy Key Performance Indicators (KPIs) considered to assess the different configurations considered for energy communities are the Self-Sufficiency rate (SS), GHG savings and Self-Consumption rate (SC).

The Self-Sufficiency rate (SS) represents the ratio of demanded electricity provided from PV panels and battery in relation with the total electricity demand, providing information of how much the total electricity demand is covered by PV generation (Equation (12)), where $Egrid_{EC,t}$ represents the consumption from the grid for the whole EC. Depending on the scenario considered (EC without or with CBESS), $Egrid_{EC,t}$ is defined as $GRID_{toEC_t}$ or $GRID\_B_{toEC_t}$, respectively.

$$SS_{EC} = 1 - \frac{\sum_{t=1}^{8760} Egrid_{EC,t}}{\sum_{1}^{N}\left(\sum_{t=1}^{8760} Edemand_{n,t}\right)} [\%] \tag{12}$$

Self-consumption rate (SC) is also a key performance indicator calculated. This rate refers to the consumed electricity produced by PV panels in relation with the total PV production. Self-consumption ratio provides information about the allocation of the electricity surpluses. At an energy community level, the self-consumption rate is calculated as defined in Equation (13). Depending on the scenario considered (EC without or with CBESS), $Esurplus_{EC,t}$ is defined by EC_{toGRID} or EC_B_{toGRID}, respectively.

$$SC_{EC} = 1 - \frac{\sum_{t=1}^{8760} Esurplus_{EC,t}}{\sum_{1}^{N}\left(\sum_{t=1}^{8760} Egeneration_{n,t}\right)} [\%] \tag{13}$$

Electricity from the grid has inherent GHG emissions, as consequence of a diversified mix of fossil and non-fossil fuel resources in its origin, which results on the definition of a certain GHG emission factor (GHG_{index}). In the scope of this work, electricity produced by the photovoltaic panels is considered to have a zero-emission factor. Thus, GHG savings for each scenario are calculated by Equation (14), where EC_{demand} represents the EC yearly electricity demand and $GRID_{toEC}$is the yearly electricity imports from the grid for each EC scenario (without or with CBESS).

$$GHG\,savings = GHG_{index} * (EC_{demand} - GRID_{toEC})[gCO2] \tag{14}$$

The emission factor considered for the electricity from the grid, GHG_{index}, is 270.42 gCO_2/kWh [13], which refers to 2021, from the largest low-voltage electricity provider in Portugal.

Regarding Economic KPIs, Net Present Value and Internal Rate of Return are evaluated. Annual energy costs, savings and PV income are also assessed for the different scenarios.

Annual energy costs E_{Cost_n} for each building are calculated by Equation (15) for the different scenarios considered (building without EC, building in EC or building in EC with CBESS), being the percentage savings given by Equation (16).

$$E_{Cost_n} = \sum_{t=1}^{8760} (E_{GRID_{n,t}} * p_{EC_t})[EUR] \tag{15}$$

$$\%\,savings = \frac{E_{Costbase_n} - E_{Cost\,n}}{E_{Costbase\,n}} [\%] \tag{16}$$

Incomes due to the sale of PV surplus to the grid are also included in the model and calculated in Equations (17) and (18). Equation (17) defines the building incomes when it is not part of an EC (Scenario 1). $E_{surplus_{n,t}}$ represents the building surpluses and price for the sale of the surpluses in each timestep is defined as p_{surpl_t}.

$$INCOME_n = \sum_{t=1}^{8760} (E_{surplus_{n,t}} * p_{surpl_t})[EUR] \tag{17}$$

In the scenarios of the building in EC and EC with CBESS, incomes are defined proportionally to the surpluses of each building regarding the total surpluses generated at the energy community level. Equation (18) defines the income of buildings, being $EC_{surplus}$ the energy community surpluses injected to the grid in each scenario (without or with CBESS).

$$INCOME_n = \frac{\sum_{t=1}^{8760} E_{surplus_{n,t}}}{\sum_{t=1}^{8760} EC_{surplus}} * \sum_{t=1}^{8760} (EC_{surplus} * p_{surpl_t})[EUR] \tag{18}$$

Net Present Value (NPV) (Equation (19)) represents the net profit generated by an investment, calculated from the discounted sum of future costs and revenues. The project is considered feasible when the NPV is greater than zero with a considered discount rate.

$$NPV_n = \sum_{t=0}^{T} \frac{Revenue_n}{(1+d)^t} - I_{0n}[EUR] \tag{19}$$

where $Revenue_n$ comes either from the building energy cost savings and the sales of the PV surplus to the grid, I_{0n} is the investment cost, T is the number of years considered, d is the discount rate.

Internal Rate of Return (IRR) estimates the discount rate d at which the NPV equals zero (Equation (20)). Projects are considered feasible when $IRR > d$, where higher IRR, better is the investment [11]

$$\sum_{t=0}^{T} \frac{Revenue_n}{(1+IRR)^t} - I_{0n} = 0\,[\%] \tag{20}$$

A code in Python has been implemented to calculate the KPIs defined above. This code has as inputs the outputs from CEA, which are the electricity demand and the solar PV generation file for each building simulated. Therefore, by applying the Equations defined in

Section 3.2 and considering different scenarios for the buildings (without EC, in EC without CBESS or in EC with CBESS), the code calculates the KPIs. Analysis are made at two levels: at the building level and at the energy community level, comparing the different KPIs for each scenario.

4. Case study

For testing the developed modelling framework, the neighbourhood of Madre de Deus, in Lisbon, Portugal is selected, considering different building typologies (single residential (SR), multi residential (MR) and School) and three building set combination (defined as Case study A, B and C) (Fig. 3). The case studies comply with the Portuguese legislation concerning National Electricity System operation, the Decree-law n.° 15/2022 (Conselho de Ministros 2022) This regulation stablishes a maximum distance between EC participants of 2 km for low-voltage and 4 km for medium-voltage. Also, it is relevant to highlight that no charges for use of the distribution network are issued to EC' participants as preconized by the previous regulation.

4.1. Case studies definition

Three case studies with different buildings typologies are considered as graphically represented in (Fig. 3) and summarised in Table 2.

- **Case study A** - is an EC with only single residential buildings. In this case, 30 single residential buildings are considered among three archetypes.
- **Case study B** – is an EC with single and multi residential buildings. 17 single residential buildings and 13 multi residential buildings are considered.
- **Case study C** – is an EC with single and multi residential buildings, and school buildings. In this case, 15 single residential buildings, 10 multi residential and 5 school buildings are considered.

4.2. Buildings characterization

For Madre de Deus neighbourhood, construction standards for buildings are collected from C-TECH project [34] in a shapefile format. The shapefile contains information about the geometrical characteristics of the building plans (number of floors above/below ground and floors height), construction standards and their use-type (single or multi residential, school, commercial).

Regarding the residential buildings, to define occupational patterns, data is collected from national census information (Geographic Information Reference Base in 2011, with the last data update was in 2018 from Portuguese National Statistics Institute [25]). The energy supply data for the different building typology energy end-use is collected from the Directorate General for Energy and Geology and the National Statistics Institution in Portugal [27]. Further, regarding non-residential buildings, school typology is also considered. The consumption profile is characterized considering the Portuguese schools' profiles on the national energy certification legislation RSECE (DL 67/2006 [42]).

4.3. PV generation characterization

According to PV-GIS tool [44], the horizontal annual solar radiation for the city of Lisbon is 1764 kWh/m^2. CEA has the reference value of 800 kWh/m^2 as the minimum annual threshold. This means that surfaces that receive less radiation, will not be considered as suitable for installing PV panels. In this work a more conservative value was considered (1000 kWh/m^2), although a sensitive analysis shown that the energy production didn't changed significantly.

Regarding the variability of rooftops' orientation, this measure will allow to avoid the installation of panels in shaded and/or not suitable surfaces. The optimal slope angle for Lisbon, according to the PVGIS tool is 33°, which was assumed for the present case studies. The PV panels considered are generic monocrystalline panels, with 16 % of nominal efficiency. The nominal operation cell temperature is 43.5 °C with a cell maximum power temperature coefficient of 0.0035 1/°C [21].

Regarding the PV investment, it has been assumed 1100 €/kWp installed, as implemented in Weckesser et al. [58]. The total length considered for the NPV calculation is 25 years, as this period is the PV panels lifetime [57,1]. The discount rate used is 5 %. It is based on Barbour et al. [3], where energy communities with central batteries are assessed. Inflation is not considered, while a 0,8%/year PV panel degradation rate is implemented, as the efficiency of the solar PV system decreases by about 20 % during its useful time of 25 years [1,57]. Neither Operations and Management (O&M) costs are considered as values found in the literature of around 1 to 3 % were considered negligible [1].

4.4. CBESS characterization

Table 3 gathers the assumptions made for the CBESS definition based on literature review data from [36]. The review is made for

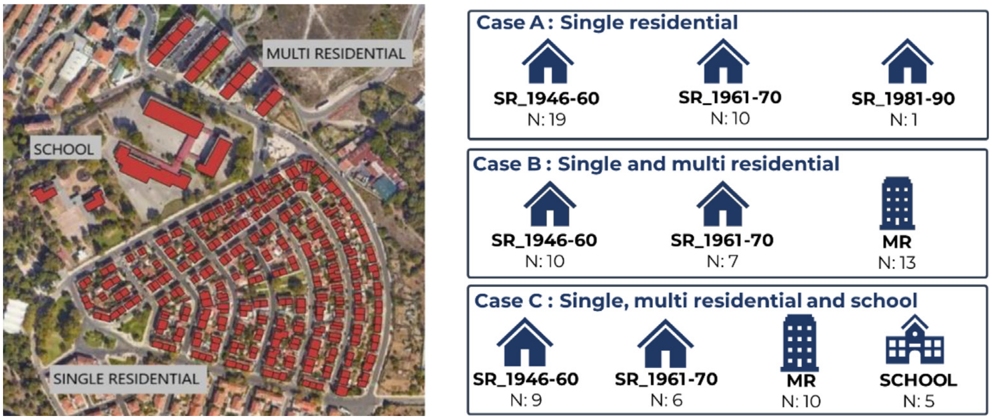

Fig. 3. Madre de Deus neighborhood (Lisbon, Portugal) - building typologies and Energy Communities' building set combination (Cases A, B, and C).

Table 2
Case studies characterization.

Building typology	Nomenclature	Construction period	Electric heating?	Case study		
				A	B	C
Single residential (SR)	SR 1946–1960	1946–1960	NO	19	10	9
	SR 1961–1970	1961–1970	YES	10	7	21
	SR 1981–1990	1981–1990	YES	1	–	–
Multi residential (MR)	MR	1961–1970	NO	–	13	10
School	SCHOOL	1961–1970	NO	–	–	5

Lithium-ion batteries as recommended in [55] for centralized energy storage system.

The criteria for battery sizing were for the CBESS to cover the average daily demand, as it is done by Terlouw et al., [55], by assuming that the battery is extensively used and that there is one daily battery discharge. Hence, this leads to a maximum of 365 cycles per year. The battery capacity, B_{cap}, is defined following the specifications above. Also, according to SOC_{min} and SOC_{max}, the minimum and maximum battery capacities in kWh are defined by B_{min} and B_{max}.

It is considered that the charging and discharging power rate limit P_{bat} is 1/3 of the battery capacity, as applied in Mulleriyawage & Shen [36].

CBESS investment costs in scenario 3 considers a Li-ion central battery with a cost of 337.4 €/kWh with a lifetime period of 15 years as used in Weckesser et al. [58] for a community battery.

5. Results and discussion

In this section, results from the UBEM are firstly discussed, while energy community results are then analysed at building level, reporting the differences observed for each building typology through the different case studies, and the energy community level, and compared for the different case studies and scenarios. Finally, economic KPIs obtained are also discussed.

5.1. UBEM results

In this section the results obtained with CEA are presented regarding the demand and PV generation on the different buildings considered in the case studies. Firstly, average yearly demands for each building typology are gathered in Table 4.

As the second and third type of single residential buildings have electric heating, their average and per m^2 demands are considerably higher than the typology without electric heating. Moreover, it is important to highlight that indoor comfort settings from UBEM result on higher comfort standards than those applied to Portuguese reality, consequently, leads to higher energy demands.

Regarding now the PV generation, Table 5 shows the average of PV capacity installed in roofs and the yearly generation for each building typology.

Table 6 shows the total energy demand and PV generation values obtained in each case study. Demand and generation increase in each case due to the addition of multi residential buildings for case B, and due to the school buildings for case C. The different battery capacities considered are also shown.

Table 3
Assumptions for energy storage (CBESS).

Parameters	ID	Values
Minimum State of Charge	SOC_{min}	10 %
Maximum State of Charge	SOC_{max}	95 %
Efficiency for charge and discharge	η_{charg}; $\eta_{discharg}$	95 %

Table 4
Electricity demand average results by building typology.

Building typology	AVG Demand (kWh/year)	AVG Occupied area (m^2)	AVG kWh/ m^2year
SR 1946–1960	2593	107	24
SR 1961–1970 (electric heating)	14,381	98	150
SR 1981–1990 (electric heating)	14,781	80	185
MR	27,991	1106	25
SCHOOL	39,949	1404	28

5.2. Building level

The energy KPIs obtained at a building level for case study A, B and C are presented on, respectively Fig. 4, Fig. 5 and Fig. 6, when considering the three different scenarios (SC_1, SC_2, SC_3):

For 1946–1960 single residential buildings, differences are only seen in the scenario SC_3, when considering buildings in an EC with CBESS. For this building typology, the demand covered by the CBESS is 33 %, 17 % and 22 % respectively for each case study. For case study B and C, as multi residential buildings have higher demands, benefit more from the storage system, leading single residential typologies to have lower percentages of CBESS coverage comparing to the case study A. Therefore, for this typology, the highest self-sufficiency rate is for the case study A (62 %).

For 1961–1970 single residential with electric heating, differences arise on the percentages of energy sharing and in the CBESS coverage. Regarding the energy sharing, the percentage increases from 3 % for the cases A and B, to the 12 % for case C. This increase is due to the inclusion of school buildings in the EC. As schools do not have demand during weekends and neither during vacations, all the PV generation in schools is allocated to residential buildings. Regarding the CBESS coverage, the percentages are 11 %, 7 % and 8 %, respectively. As mentioned before, the addition of the multi residential buildings in case B and C lead to lower CBESS coverages, due to higher demand-generation match.

For multi-residential buildings, the energy sharing differs from case B and C. In case study B it is 1 %, increasing to 5 % when introducing the school buildings in the EC for case C. Regarding the percentage of CBESS coverage, it increases from 19 % to 24 % respectively, which reveals that multi-residential buildings benefit greatly from the PV surplus stored in the CBESS from the school buildings. Therefore, the building typology that benefits more of being part of an EC without CBESS (SC_2) is the single residential 1961–1970 with electric heating, which has the highest self-sufficiency increase (12 %) when after energy sharing. Also, for this scenario the school buildings achieve a self-sufficiency increase of 10 % by benefiting from PV surpluses from the residential buildings.

Table 5
PV characterization and average generation results by building typology.

Building typology	AVG PV installed (kWp)	AVG Roof area (m^2)	AVG PV Generation (kWh/year)	AVG kWh/m^2 of floor area
SR 1946–1960	3.8	60.7	3283	30.0
SR 1961–1970 (electric heating)	3.8	58.8	3183	32.4
SR 1981–1990 (electric heating)	2.9	48.6	2636	33.0
MR	11.7	192.7	10,395	9.4
SCHOOL	48.0	792.3	42,898	33.2

Table 6
Total demand, PV generation and battery capacity in EC.

Case study	Energy demand (kWh/year)	PV generation (kWh/year)	PV installed (kWp)	Roofs area (m^2)	Battery capacity (kWh)
Case A	201,351	93,582	105	1729	550
Case B	486,798	189,572	213	3512	1240
Case C	595,989	369,266	414	6828	1260

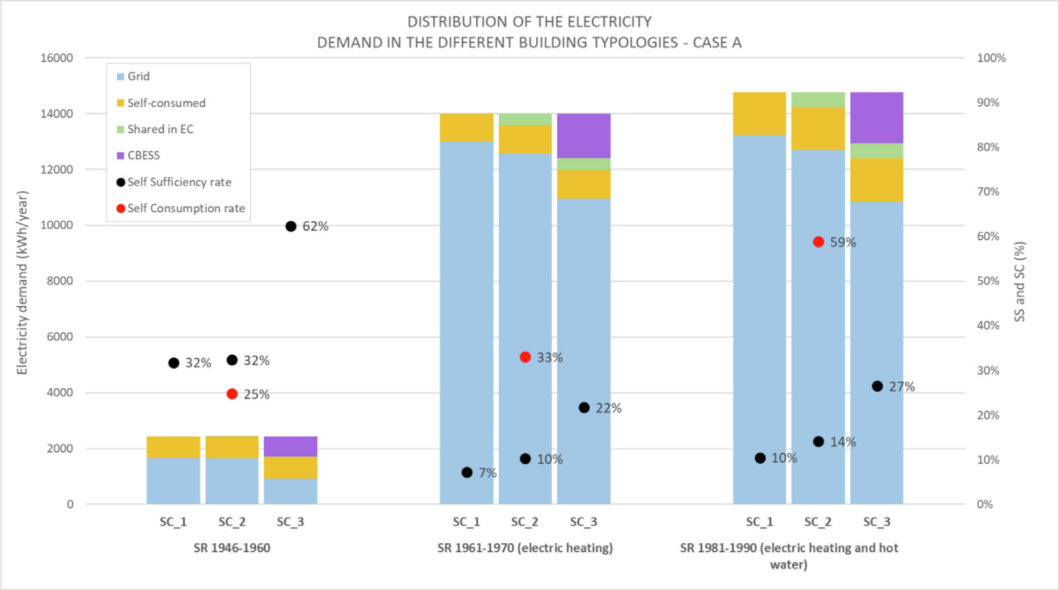

Fig. 4. Case A. Distribution of the electricity demand, self-sufficiency and self-consumption rates.

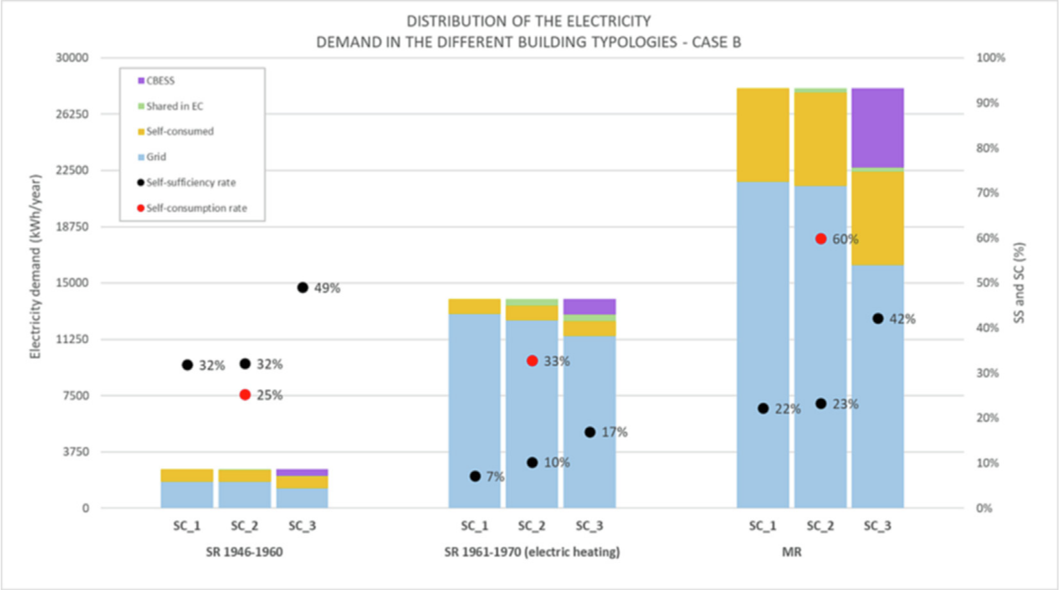

Fig. 5. Case B. Distribution of the electricity demand, self-sufficiency and self-consumption rates.

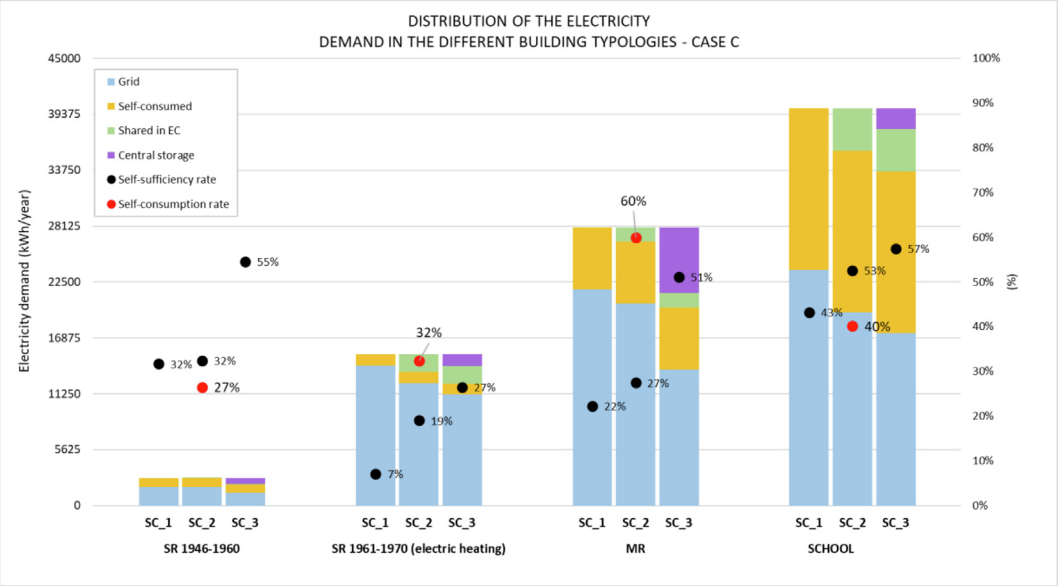

Fig. 6. Case C. Distribution of the electricity demand, self-sufficiency and self-consumption rates.

Nevertheless, for the scenario SC_3 (with CBESS), the typology with the highest self-sufficiency increase is the multi residential.

5.3. Energy community level

The energy KPIs at an energy community level for the three case studies are presented in Fig. 7.

Regarding Fig. 7, when evaluating the results at an EC level, in scenario 2, self-sufficiencies achieved are respectively 16 %, 21 % and 34 % for case studies A, B and C. Case study C is the one with highest percentage of demand during the daylight hours, as its load curve is a mix between residential and school uses. Hence, this leads to a higher self-sufficiency rate. Regarding the self-consumption, percentages obtained for each case study are 34 %, 54 % and 56 % respectively. Also, case A has the lowest self-consumption value due to the high rate of surpluses.

Regarding scenario 3, when considering CBESS in the EC, self-sufficiencies observed are 31 %, 38 % and 49 %. Self-consumption rates observed increase for each case study until 70 %, 100 % and 80 % respectively. As mentioned in the methodology, the CBESS is dimensioned to cover the daily average consumption from the grid of the energy community. Thus, for case B, the CBESS does not reach the maximum capacity, achieving a 100 % of self-consumption due to the similar rates of charging and discharging during the battery cycles.

Comparing the three scenarios, self-sufficiency increases between 15 and 17 pp when storage is added, being the highest (17 %) for the case study B. Regarding the self-consumption, the average increasement is 35 pp, having the highest value in the case study B with 46 pp of increase when adding the storage.

In what concerns to economic KPIs, when analysing collective self-consumption (SC_2), all case studies have IRR values above the discount rate considered (5 %) and positive Net Present Values. It is observed an increase of IRR throughout the different case studies. Case study A, composed only of SR profiles presents the lowest value (8 %). When also considering MR profiles (Case B), IRR

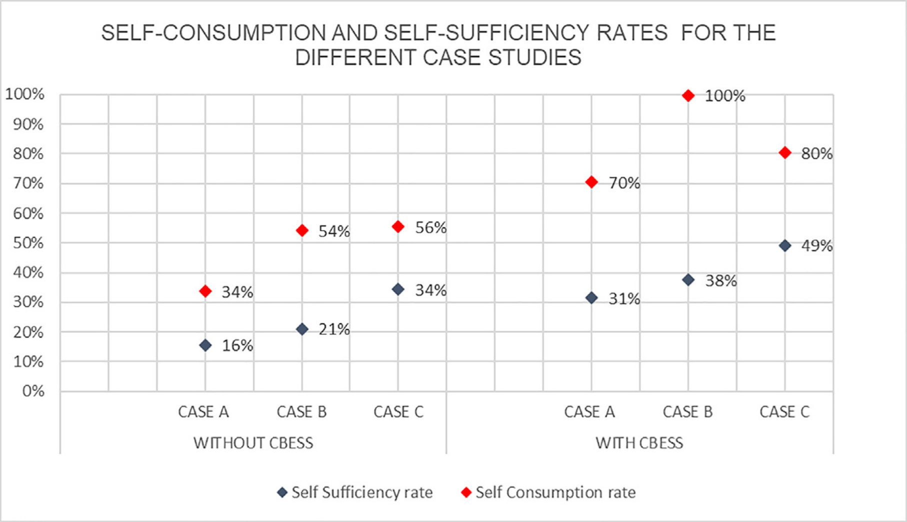

Fig. 7. Self-consumption and self-sufficiency in the 3 case studies.

increases until 9.2 %. Finally, IRR increases up to 9.7 % when the school profile is added to the EC (Case C). Therefore, the more different profiles are added to the EC, better are the results.

Regarding SC_3, all case studies obtain IRR values below the discount rate and NPV is negative for all cases. These results drop down around 7 pp the viability of the investments due to several reasons. First, neither PV systems nor CBESS are sized following economic criteria. CBESS sizing depends on the daily demand of the EC, and is only charged with EC surpluses, not charging with lower electricity tariffs from the grid. Therefore, part of the available storage capacity is not being fully used.

5.4. Comparison with other works on energy communities

When comparing EC results with other works, similarities are found in (Pontes Luz & Amaro e Silva, 2021) where values of self-sufficiency of 31 % are achieved in a small Portuguese city. Nevertheless, results differ from the ones found in [54] with 75 % of self-sufficiency with storage, while in the present work the self-sufficiency with storage is between 31 % and 49 %.

Regarding the self-consumption results, in [31] percentages between 43 and 58 % of self-consumption in EC with residential configuration are achieved, which are aligned with the results found in case A and B, with 34 % and 54 % self-consumption percentages without storage system. Also, when considering shared storage, self-consumption in [31] increases until 72 %, as in case A in this work (70 %).

When comparing the differences between scenarios 2 and 3 (without and with CBESS storage), results from [32] show that the self-consumption increases by 13–24 pp with a battery storage capacity, while in the present work this increment is between 36 and 46 pp. In [48] a growth of the average self-consumption from 50 to 80 % is found, for the case of 10 residential households, with battery storage.

Moreover, regarding economic KPIs in other research works, in [3], IRR falls 4.7 pp when adding a community battery to the scenarios considered. In [33] it is stated that existing community-owned solar projects in the UK commonly return 4.5 % on investment [12,51].

6. Conclusions and future work

The model created within this work allows to compare the performance of various building typologies (individually and as a community) in different energy communities' configurations by considering the outputs of an UBEM tool, (hourly values of building energy demand and solar energy production). By analysing all the results, it is concluded that both environmental and economic benefits are higher when considering energy communities with diverse load profiles (residential and school), since higher self-sufficiency results are achieved due to the sharing rates through buildings. The model allowed different scale of analysis regarding EC performance. First, results at a building level help to analyse the performance and influence for EC on different buildings typologies in the scenarios considered. For the case studies considered in this work, the results point that the typology most benefited of being part of an EC, in the collective self-consumption scenario, is the single residential house with electric heating, as it is the one with highest increase of self-sufficiency due to the surplus sharing. School buildings reach as well high increase of self-sufficiency by benefiting from the surpluses in residential buildings (especially due to not coincident demand profiles). By considering energy storage (CBESS) in the EC, the multi residential typology is the one that most increases its self-sufficiency.

Then, through the analysis of the results at an energy community level, the comparison for different scenarios and case studies was performed. When adding different building typologies, self-sufficiency increases. The highest self-sufficiency value is achieved in case study C. Therefore, these results demonstrate that diversity of demand profiles is beneficial for the EC, as for higher sharing rates self-sufficiency increases. Besides, when considering the scenario with central storage, self-sufficiency increases 16 pp on average for all cases.

From the economic analysis, it is concluded that collective self-consumption with storage (CBESS) leads to all buildings typologies to reach higher savings comparing with the other scenarios. Also, due to the diversity of building use profiles and its higher self-sufficiency, the case with higher energy savings includes residential and school buildings (case study C). However, when assessing IRR and NPV, results are not so promising since the PV systems and CBESS were not sized following economic criteria. The building typology with better IRR and NPV is the multi residential, achieving its maximum investment return when the EC includes school buildings (case study C).

Scenarios 1 and 2 are considered economically viable, nevertheless, when including the CBESS (scenario 3), the economic indicators show lower economic feasibility. Conclusions drawn from the economic results arise the necessity of support by public institutions and funding programs to enhance the viability of these projects.

All in all, this work presents the added value of a model that by using UBEM outputs presents a detailed analysis of an EC performance. The application of this model to the selected case studies showed several advantages for individual buildings on setting up energy communities considering two different configurations: collective self-consumption and collective self-consumption with a central storage system. A reduction on the energy dependency from the grid is ensured, which gains more relevance in the current energy market context and leads to less economic impact by future variabilities on energy costs. Positive social impact could also be a key benefit that need to be mentioned, supporting the relevance of public investment to boost a social and fair energy transition and shift to a decentralized solar energy production.

Future research lines would improve the model such as calibrating UBEM with real monitoring data, considering other EC configurations, testing different sharing coefficients and storage settings and performance (energy losses from energy storage and transmission must be addressed as they may influence Energy Community' KPIs and their viability). Regarding GHG emissions estimation, detailed emissions factors across time must be considered to accurately address EC impact.

This work sets a precedent for the creation of a future dashboard to assess the energy community's performance and viability.

Data availability

The authors do not have permission to share data.

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.

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Table 7
Algorithm for performance of the CBESS.

Steps	Equation	
1	$E_D(t) = max(B_{level}(t-1) - B_{min}(t); 0)[kWh]$	(21)
2	$E_C(t) = max(B_{max}(t) - B_{level}(t-1); 0)\ [kWh]$	(22)
3	$if(E_D(t) > GRID_{toEC}(t)); DISC(t) = min\left(\frac{GRID_{toEC}(t)}{\eta_{discharg}}; P_{bat} * \Delta t\right)\ [kWh]$	
	$else; DISC(t) = min\left(\frac{E_D(t)}{\eta_{discharg}}; P_{bat} * \Delta t\right)[kWh]$	(23)
		(24)
4	$if(E_C(t) > EC_{toGRID}(t)); CHAR(t) = min\left(EC_{toGRID}(t) * \eta_{charg}; P_{bat} * \Delta t\right)[kWh]$	(25)
	$else; CHAR(t) = min\left(E_C(t) * \eta_{charg}; P_{bat} * \Delta t\right)[kWh]$	
		(26)
5	$if(DISC(t) > 0); B_{level}(t) = max(B_{level}(t-1) - DISC(t); B_{min}(t))\ [kWh]$	
	$else; B_{level}(t) = min(B_{level}(t-1) + CHAR(t); B_{max}(t))[kWh]$	(27)
		(28)

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Appendix A. Battery algorithm

The algorithm in Table 7 is applied to calculate the performance of the CBESS in each timestep. It is divided in 5 steps. In step 1 and 2 is calculated the energy available in the battery in timestep *t*, considering the restrictions of being always between 10 and 95 % level of SOC. Step 3 calculates the discharge of the battery considering the restrictions of P_{bat} and the discharge efficiency. In the same line, step 4 calculates the charge of the battery considering also P_{bat} restriction and the charge efficiency. In step 5, the new state of charge for the battery is calculated depending if it is in charge or discharge mode, calculating the kWh stored in each timestep with B_{level}.

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