Energy Reports 8 (2022) 10395–10408

Contents lists available at ScienceDirect

Energy Reports

journal homepage: www.elsevier.com/locate/egyr

Local energy communities modelling and optimisation considering storage, demand configuration and sharing strategies: A case study in Valencia (Spain)

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ARTICLE INFO

Article history:
Received 18 January 2022
Received in revised form 1 August 2022
Accepted 7 August 2022
Available online xxxx

Keywords:
Local energy community
Photovoltaic
Self-consumption
Mathematical modelling
Sharing coefficients
BESS

ABSTRACT

Local energy communities require tools to select their most fitting community members, power-sharing strategy and technologies for their goals. This work aims to develop a model and a methodology to optimise local energy communities. We evaluate the presence of a battery energy storage system with different capacities and ownership options. Besides, we test two different sharing strategies like static and variable coefficients. Finally, we characterise local energy communities' demand by comparing residential and commercial loads and varying the number of consumption points. We apply the method to a case study consisting of a 100 kWp photovoltaic installation in Valencia simulated with an hourly resolution for a whole year. We use real consumption data from households and commercial buildings and the current administrative requirements, obtaining the flows and status of each component within the local energy community at every moment. We assess each alternative's economic performance, autarchy degree, and the amount of avoided greenhouse gasses emissions. Results indicate that a local energy community well optimised can fulfil economic, environmental or self-consumption goals. Results only advise installing a storage to increase the degree of self-consumption. Moreover, we obtain the best financial and environmental results in large communities with a 75% residential consumption.

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1. Introduction

Local Energy Communities (LECs) are legal entities that effectively control their members, are locally rooted and whose goals must be to provide environmental, economic and social benefits rather than financial profits. LECs can be simulated and optimised considering energy storage, different participants typology and sharing strategies. This article develops a mathematical model to simulate a LEC and a methodology to optimise them. This work glimpses LECs' impact on the Energy Transition (ET).

LECs offer several benefits to the success of the ET (Lowitzsch et al., 2020) involving all the pillars of sustainability. On the economic side, LECs allow the members to reduce their energy expenses (Roldán Fernández et al., 2021) to the point of fighting against energy poverty (Gjorgievski et al., 2021; Hewitt et al., 2019; Heras-Saizarbitoria et al., 2018). Besides, LECs represent a new source of funding for renewable energy projects (Brummer, 2018; Soeiro and Dias, 2020) to increase the share of clean energy technologies in the system. On the technical side, LECs bring power generation closer to the consumption points, reducing power losses on the electricity system (Roldán Fernández et al., 2021) and increasing competition (Ribó-Pérez et al., 2019). It also leverages the potential flexibility of the end-users of energy (Ribó-Pérez et al., 2021). Moreover, it increases the resilience of the grid, and the users without over-investing in grid expansions (Gui and MacGill, 2018; Vibrant Clean Energy, LLC, 2020; Perez-DeLaMora et al., 2021). On the social side, LECs promote participation and democratic control of the electricity system (Brummer, 2018; Hewitt et al., 2019; Capellán-Pérez et al., 2018; Perez-DeLaMora et al., 2021) for social sectors that currently do not have the space or funding needed for an individual installation (Stewart, 2021). Therefore, LECs have great potential in urban environments as cities consume two-thirds of the energy supply and reduce 70% of CO_2 emissions (C40, 2020; UN Habitat, 2020). Moreover, LECs increase awareness of sustainable issues (Brummer, 2018; Heras-Saizarbitoria et al., 2018) and build community cohesiveness and energy-related knowledge among the members of the community (Brummer, 2018; Soeiro and Dias, 2020).

Although all their benefits, there are still many challenges to creating and operating a LEC. First, it is uncertain how to design

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https://doi.org/10.1016/j.egyr.2022.08.181
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Nomenclature

Indices

c	Allocation coefficients set index
t	Time index [h]
j	Load curve index
s	Seasons of the year index
e	Simulation scenarios index
n	Year of operation index [yr]

Sets

C	Set of all sets of allocation coefficients
E	Set of all simulation scenarios
J	Set of all points of consumption
N	Set of years of operations
S	Set of all seasons of the year
T	Set of all time periods

Parameters

C^G	Annual cost of electricity purchased from the grid [€/yr]
C^{POW}	Annual cost of power term of electricity of the grid [€/yr]
d	Market discount rate
E^B_{CAP}	Energy storage capacity of the BESS [kWh]
EF^B	Emission factor of BESS [gCO_2/kWh]
EF^{GRID}	Emission factor of electricity from the grid [gCO_2/kWh]
EF^{PV}	Emission factor of PV generation [gCO_2/kWh]
i_{elec}	Electricity inflation index
L^C	Number of commercial load curves
L^R	Number of residential load curves
OM	Operation and maintenance annual expenses [€/yr]
$P^{B,C}_{MAX}$	Maximum charging power of the BESS [kW]
$P^{B,D}_{MAX}$	Maximum discharging power of the BESS [kW]
$P^{D,C}_j$	Annual total demand of the commercial load curve j [kWh/yr]
$P^{D,R}_j$	Annual total demand of the residential load curve j [kWh/yr]
POW_j	Contracted power in the load j [kW]
P^{PV}_{NOM}	Nominal power of the PV system [kW]
PT^C	Number of commercial points of consumption
PT^R	Number of residential points of consumption
PT^T	Number of total points of consumption
$RATIO^R$	Portion of the total demand coming from residential loads
Π^{POW}	Price of contracted power [€/kW]

Variables

CF_t	PV capacity factor at moment t
C^{PUR}_t	Cost of electricity purchased from the grid at moment t [€]
C^{SELL}_t	Cost of electricity sold to the grid at moment t [€]
C^V_t	Cost of variable term of electricity from the grid at moment t [€]
E^B_t	Energy stored at BESS at moment t [kWh]
LT	Lower price threshold [€/kWh]
P^Aj, t	Power allocated to curve j at moment t [kW]
$P^{B,C}_t$	Power charged to BESS at moment t [kW]
$P^{B,D}_t$	Power discharged to BESS at moment t [kW]
$P^{B,PUR}_t$	Power charged to BESS purchased from the grid at moment t [kW]
$P^D_{j,t}$	Power demand by curve j at moment t [kW]
P^D_t	Power demand by the LEC at moment t [kW]
P^{PUR}_t	Power purchased from grid at moment t
P^{PV}_t	Power generated by the PV system at moment t [kW]
$P^{PV}_{j,t}$	Power consumed by curve j directly from the PV system at moment t [kW]
p_s	Price percentile at season s
P^{SELL}_t	Power sold to the grid at moment t [kW]
UT	Upper price threshold [€/kWh]
$\eta^{B,C}_t$	BESS charging efficiency
$\eta^{B,D}_t$	BESS discharging efficiency
Π^{PUR}_t	Price of purchased electricity at moment t [€/kWh]
Π^{SELL}_t	Price of sold electricity at moment t [€/kWh]

Metrics

GHG^{AV}	GHG emissions avoided by the LEC during its lifetime [tCO_2]
GHG^B	GHG emissions associated to the BESS use annually [tCO_2/yr]
GHG^{GRID}	GHG emissions associated to the purchases from the grid annually [tCO_2/yr]
GHG^{PV}	GHG emissions associated to the PV generation annually [tCO_2/yr]
NPV^{INV}_n	NPV of investment at year n [€]
NPV^{LEC}_n	NPV of LEC at year n [€]
NPV^{OM}_n	NPV of OM at year n [€]
NPV^{SAV}_n	NPV of savings at year n [€]
SV	Annual billing savings generated by the LEC [€]
SC	Degree of self-consumption of the LEC

Acronyms

BESS	Battery Energy Storage System
CEC	Citizen Energy community
ET	Energy Transition
EU	European Union
GHG	Greenhouse Gases
IRR	Internal Rate of Return
LEC	Local Energy Communities

NPV	Net Present Value
PV	Photovoltaic
REC	Renewable Energy Communities
RES	Renewable Energy Sources
Subscripts	
0	Original situation
LEC	After LEC implementation

a LEC to achieve economic, self-dependence or environmental goals. Besides, LECs do not know which composition of users is more suitable for their interests. Moreover, regulations are constantly changing, arising different energy allocation strategies that need evaluation to optimise the LEC performance. In this work, we answer the following research objectives:

(1) How can we model a LEC mathematically to optimise them considering current regulatory requirements and technology options.

(2) Which is the best demand configuration regarding the number of participants and the residential or commercial consumption.

(3) What are the best energy allocation strategies among the users taking into account the use of static and variable *ex-post* coefficients.

For this purpose, we have developed a mathematical model to define and simulate LECs and a methodology to optimise them economically using a single-solution-based meta-heuristic method. Afterwards, we have identified various design variables to analyse the possible LEC configurations. These variables comprise different allocation strategies, residential and commercial demand profiles, numbers of LEC members and the presence or not of a Battery Energy Storage System (BESS). We have applied this method to a case study of a LEC organised around a photovoltaic (PV) installation of 100 kW in an urban area of València, Spain.

We have organised the rest of the paper as follows, Section 2 discusses the current literature around energy communities and their modelling, Section 3 presents the methodology and the mathematical formulation to optimise and assess the community performance. Section 4 describes the Case Study analysed. Section 5 shows the results from the different simulations and discusses them and their implications. Finally, Section 6 concludes by summarising the main findings of the paper.

2. Related work

2.1. LEC concept and regulation

Until recently, the concept of LEC embraced projects of a very different nature because LECs were being developed with no specific regulation for them (Hewitt et al., 2019). After the completion in 2019 of the Clean Energy for all Europeans Package, the concept of energy communities got introduced in two different Directives. "Citizen Energy Community" (CEC) from the recast Electricity Market Directive and "Renewable Energy Community" (REC) from the Renewable Energy Directive are similar concepts but have some key differences (Council of European Energy Regulators, 2019). Their members must effectively control the community, and their main objective must be to provide environmental, economic and social benefits rather than financial profits. However, while CECs work under no geographical limitation, the members of a REC must be located in the proximity of the renewable energy project owned by the community. On the other hand, CECs are limited to the electricity sector, but RECs can be active in all energy sectors, provided that they use only RES.

In Spain, transposition took place by the Royal Decrees 244/2019 and 23/2020 (BOE, 2019, 2020). Under this framework, the distance between the power generation system and LEC members must be less than 500 m. LECs can share their generated power using static or variable allocation coefficients. LECs using static coefficients allocate their generated power every hour with the same sharing ratios. In turn, LECs using variable coefficients can assign different percentages to each user on each hour. It is also relevant to consider that renewable installation will have access to a net metering surplus compensation while the installed nominal power is lower than 100 kW.

2.2. LEC modelling

Previous work has modelled each of the components involved in the LEC model and has served as a basis for developing our mathematical model. Some previous works have model PV installations to achieve exact results (Vinod et al., 2018; Ma et al., 2014; Luo et al., 2020), others used simulation software to obtain PV results (O'Shaughnessy et al., 2018; Maturo et al., 2021) or collected data directly from a PV installation (Olaszi and Ladanyi, 2017).

Regarding stationary batteries, various publications study how batteries work alongside a PV installation (Olaszi and Ladanyi, 2017; Angenendt et al., 2018; Zhang et al., 2017; O'Shaughnessy et al., 2018). Other publications have researched the communal use of batteries (Lokeshgupta and Sivasubramani, 2019; Parra et al., 2017; Barbour et al., 2018; Koskela et al., 2019; Roberts et al., 2019).

About collective self-generation, there is also interest in the scientific literature to model and optimise its operation (Ye et al., 2017; Leithon et al., 2018, 2019). Besides, energy communities are the focus of numerous works. Some research has focused on developing tools to design LEC (Lyden et al., 2018; Dorotić et al., 2019), others have studied the impact of different regulations for the LEC (Chakraborty et al., 2018; Manso-Burgos et al., 2021) or the effect of LECs on a national grid (Fina et al., 2020). On top of that, many studied LECs by modelling and simulating them. Awad and Gül (Awad and Gül, 2018) developed a model to simulate the energy demand of a community and a method to design a LEC that maximises self-consumption and minimises cost. They applied this model to homes of different energy efficiencies to study how buildings affect the design of sustainable communities. Then, they compared the LEC with the deployment of PV installations in each household. They conclude that collective self-consumption is more cost-effective than individual self-consumption. Lilla et al. (2019) studied the power-sharing process in a LEC. They modelled day-ahead scheduling of a LEC to minimise grid cost. They evaluated centralised and distributed programming processes, obtaining similar results. Grzanić et al. (2021) developed a method and mathematical model to allocate and bill energy among users of a LEC in two stages. The first step is a commonly used method in the literature, but it is sometimes detrimental to some users. The second step serves to compensate these users fairly. Maturo et al. (2021) investigated the performance of several schemes for energy-independent communities considering technologies such as anaerobic digestion, cogeneration or district heating and cooling.

However, to the best of our knowledge, no other work has modelled and optimised a LEC considering as many variables as we do. First, we compare the impact of different sharing strategies. Besides, we evaluate the different number of members and demand characterisations. Moreover, in this work, we also consider the integration of BESS in the LEC. Combining these

Table 1
Cases in which scenarios are classified.

Case	Grid-connected	PV installation	BESS	Allocation strategy
Only P	Yes	Yes	No	
PV + BESS Static coeff.	Yes	Yes	Yes	Static coefficients
PV + BESS Variable coeff.	Yes	Yes	Yes	Variable coefficients

variables allows us to compare each alternative's benefits and impacts. We believe these questions are relevant, need to be addressed together, and have not been adequately studied enough by previous work. On top of that, we will apply the model and the methodology to a case study in Valencia, Spain. Being Spain one of the countries with more solar potential in Europe, it is relevant to study a solar-based LEC there and evaluate the potential benefits for the region.

3. Methods

3.1. Methodology

We have developed a method, as shown in Fig. 1, to find the best configuration of a LEC. The method follows a meta-heuristic approach as it consists of trial and error until it finds the best single solution. Nonetheless, we define the parameters and the values to try beforehand. Hence, the method starts by defining the case study and the scenarios. For the case study, we need to know various specifications developed in Section 4.

We consider several design variables regarding the allocation strategy, the LEC consumption characterisation, and the BESS specifications to define the scenarios. We obtain the different scenarios to evaluate by combining all the possible values for these design variables. Afterwards, we divide the scenarios into three groups (see Table 1) based on the allocation coefficients employed and the availability of a BESS.

A set of coefficients c is needed to allocate the generated power among LEC members each hour. A set of coefficients are values that add up to 1 and establish the energy sharing among the community. For instance, the LEC with five loads can equally assign 0.2 for each load or 0.1, 0.3, 0.4, 0.1 and 0.1; both are valid sets of coefficients. For static coefficients, this set c will be the constant for all the hours of the year. Therefore, we apply each set c in each hour before trying the next set. Once all sets c are tested, we identify the set that generates the most significant bill savings as optimal. In turn, the set of coefficients c can be different on each hour of the year for variable coefficients. Therefore, on each hour, all the sets c are applied. Thus, we select an optimal set of coefficients for each hour.

Moreover, we determine a threshold p_s to limit BESS discharge to the hours when the grid is more expensive (more on this in Section 3.2). This threshold is a percentile that ranges from 0 to 100, in steps of 25. We optimise this threshold for each season to adapt to the stationary solar resource and electricity consumption.

The optimisation problem changes depending on the scenario's case. Fig. 2 shows how we solve each hour of a scenario with no BESS available. The generated power is allocated based on the corresponding coefficients to each energy user. Comparing the allocated power with the demand, we determine how much energy is self-consumed and whether there is a power surplus or a deficit. As there is no BESS, the grid balances these mismatches by buying or selling the corresponding electricity.

On the other side, Fig. 3 shows how we solve each hour of a scenario with a BESS available and variable allocation coefficients. The method is identical to the previous one with no BESS system until we determine the power surplus or deficit. We store surpluses in the BESS, and if the BESS is full, we sell it to the grid.

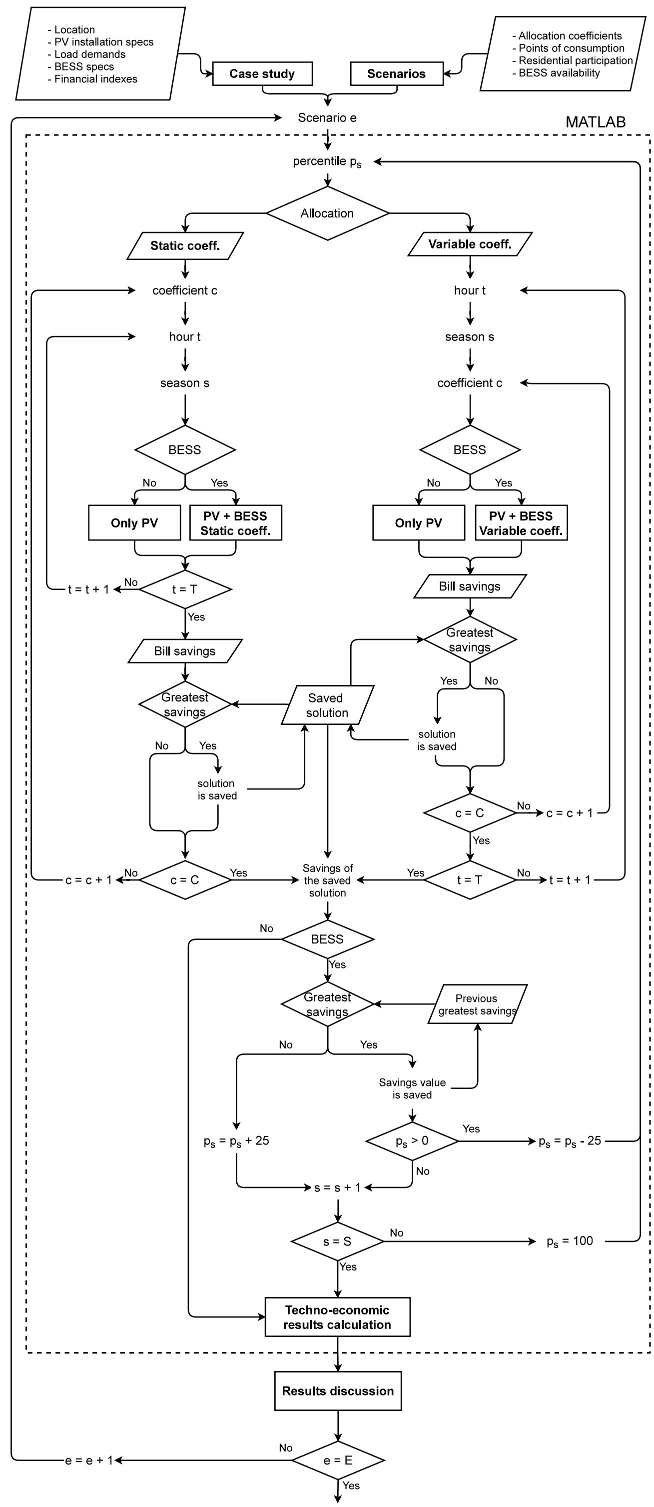


Fig. 1. Methodology employed to optimise a LEC.

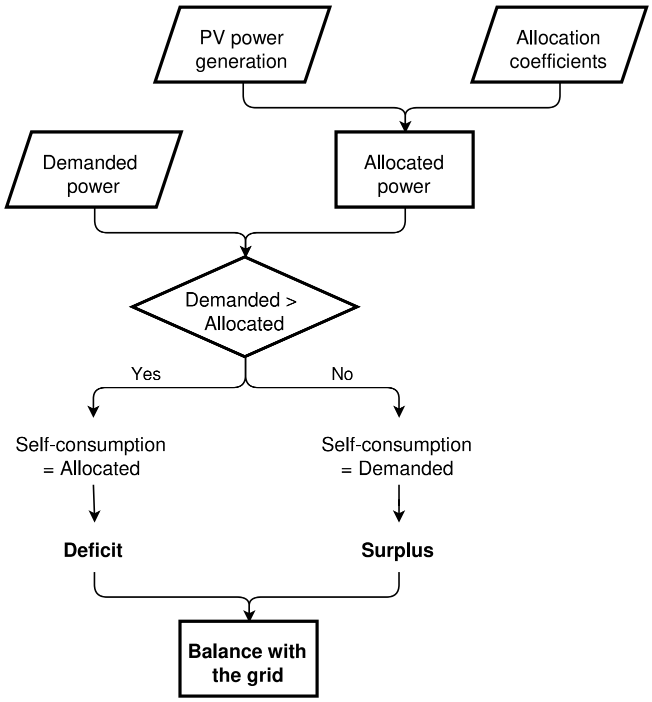


Fig. 2. LEC power allocation for case with only PV.

When there is a power deficit, the options are discharging the BESS or purchasing power from the grid. To make this decision, we compare the grid price to the upper threshold (UT), and when the price is higher, we cover the deficit by discharging the BESS. This upper threshold is renewed daily, based on the grid prices of the day and the percentile p_s (see Section 3.2). Afterwards, we compare the grid price with the lower threshold (LT). We use this threshold to establish which price is low enough to charge the BESS directly from the grid (see Section 3.2). Finally, we balance deficits and surpluses with the grid.

In turn, Fig. 4 shows how we solve each hour of a scenario with a BESS available and static allocation coefficients. The main difference with the previous method is that the BESS gets charged from the PV system by an allocation coefficient of its own. The share of the PV system generation to the different elements (loads and BESS) is not allowed to vary over time using static coefficients, and the LEC needs to consider a coefficient for the BESS. Therefore, the LEC sells the surplus energy to the grid. On the other hand, dealing with a power deficit is similar to that employed with variable coefficients, but the sharing is proportional to the allocation coefficients established for the LEC. Thus, we discharge the maximum power that does not generate a surplus.

3.2. Energy management strategy

When a BESS is available, we do not discharge the stored energy at any instant with an energy deficit. However, we follow a strategy to maximise economic savings and thus increase BESS's value. This strategy aims to discharge the storage system when higher electricity prices. We consider retail prices for this arbitrage strategy, as it is the price consumers of the LEC will have to pay. To this end, we define an upper price threshold UT above which the BESS is allowed to discharge. We define UT in Eq. (1) as the p_s percentile of the day's prices; thus, it changes daily. Moreover, p_s can change every season to adjust the stored energy to the price peaks. Thus, the discharge will be more restricted in winter than in summer because of the lower solar resource.

$$UT = \Pi_{PUR,t} \cdot P_{p_s} \qquad \forall t \in [t, t+24], s \in S \tag{1}$$

On the other hand, we define a lower price threshold, LT, to detect low electricity prices. We obtain LT as the 25th percentile of the last 15 days' electricity prices, Eq. (2). If the grid price is lower than this threshold, we charge the BESS from the grid.

$$LT = \Pi_{PUR,t} \cdot P_{25} \qquad \forall t \in [t-168, t] \tag{2}$$

3.3. Mathematical model

We include the mathematical model of a LEC in this section, starting by defining the different components participating in the LEC. Then, we describe the constraints of the system. Finally, we explain the optimisation problem.

The objective function of the optimisation, Eq. (3), is to maximise the energy bill savings of the members of the LEC.

$$max \ \ SV = C^G|_0 - C^G|_{LEC} \tag{3}$$

3.3.1. Modelling of components

- LEC electric load
  LEC's electric demand at any moment, P_t^D, corresponds to the sum of the electric demand of each point of consumption j, Eq. (4).

$$P_t^D = \sum_{j=1}^{J} P_{j,t}^D \qquad \forall t \in T \tag{4}$$

  We apply the model to residential and commercial demands. We use Eqs. (5) and (6) to obtain the number of residential and commercial consumption points. We obtain them using the annual demand of each load curve ($P_j^{D,R}$, $P_j^{D,C}$), the residential consumption ratio ($RATIO^R$) and the number of residential and commercial load curves used (L^R, L^C). To obtain Eq. (6), we simplified from a system of equations considering all these variables.

$$PT^T = PT^R + PT^C \tag{5}$$

$$PT^R = \frac{PT^T \sum_{j=1}^{L^C} P_j^{D,C}}{\frac{L^C}{L^R} \sum_{j=1}^{L^R} P_j^{D,R}\left(\frac{100}{RATIO^R} - 1\right) + \sum_{j=1}^{L^C} P_j^{D,C}} \tag{6}$$

- PV system
  We estimate the hourly generation of the PV system, Eq. (7), from the capacity factors and the nominal power.

$$P_t^{PV} = P_{nom}^{PV} CF_t \qquad \forall t \in T \tag{7}$$

- BESS
  Eq. (8) defines the energy stored at the BESS at any moment. It is the energy stored previously plus the change that occurred during the moment t:

$$E_t^B = E_{t-1}^B + P_t^{B,C} \eta^{B,C} t - \frac{P_t^{B,D}}{\eta^{B,D}} t \qquad \forall t \in T \tag{8}$$

- Grid
  The annual cost of electricity is the sum of the variable term, which depends on the amount of purchased electricity at each hour, and the price of the contracted electricity term, which depends on the contracted power of each consumption point. The cost of the contracted power is the sum of the cost for each consumer, Eq. (9). The variable term, Eq. (10), is the price difference between the purchased and the sold energy at each hour.

$$C^G = \sum_{t=1}^{T} C_t^V + C^{POW} = \sum_{t=1}^{T} C_t^V + \Pi^{POW} \sum_{j=1}^{J} POW_j \tag{9}$$

$$C_t^V = C_t^{PUR} - C_t^{SELL} = P_t^{PUR} \Delta t \Pi_t^{PUR} - P_t^{SELL} \Delta t \Pi_t^{SELL} \qquad \forall t \in T \tag{10}$$

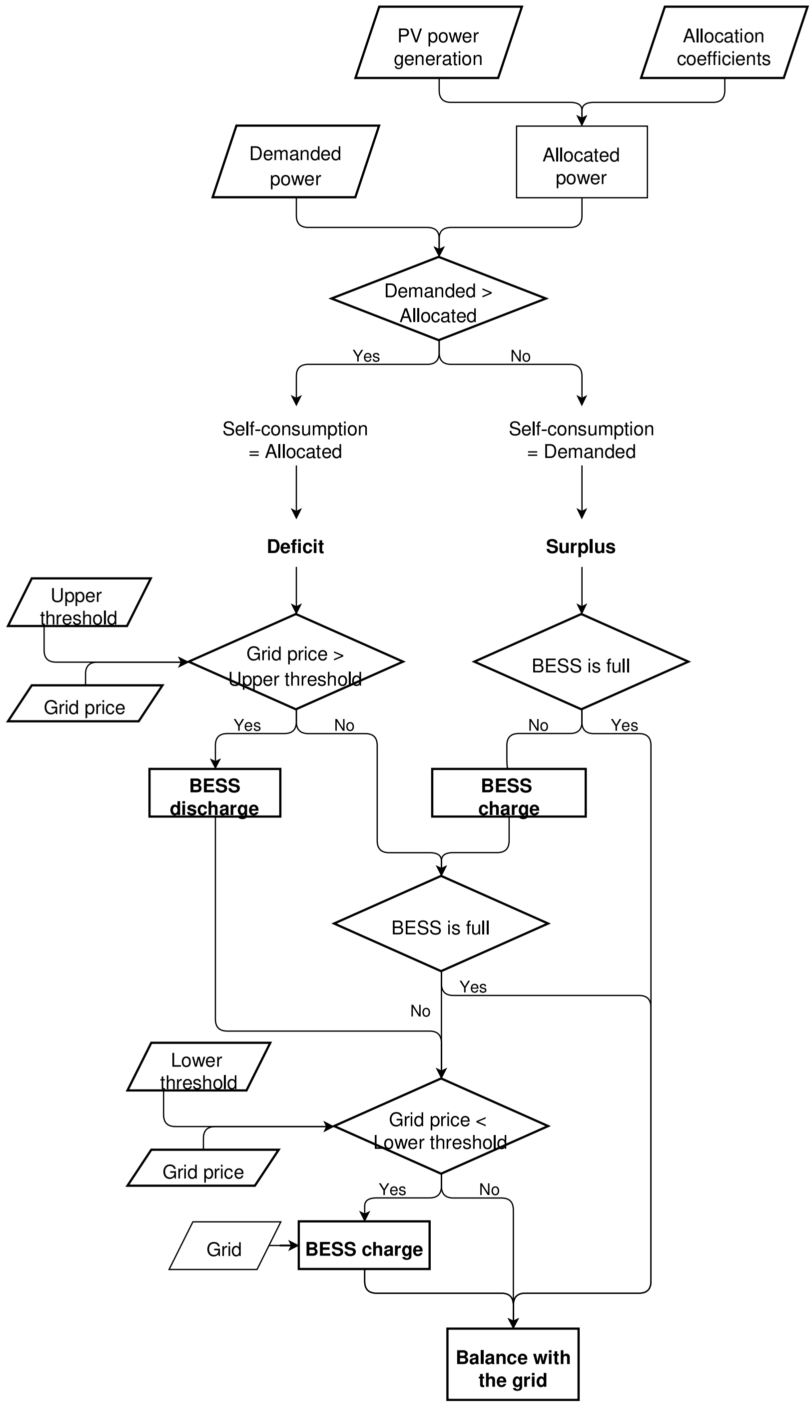


Fig. 3. LEC power allocation for case with BESS and variable coefficients.

3.3.2. Constraints

- System energy balance

  The energy sources of energy must match at any moment the energy sinks, Eq. (11). Additionally, Eq. (12) forces a net balance over the year for the BESS.

$$(P_t^{PV} + P_t^{B,D} + P_t^{PUR})\Delta t = (P_t^{D} + P_t^{B,C} + P_t^{SELL})\Delta t \qquad \forall t \in T \quad (11)$$

$$E_0^B = E_T^B \quad (12)$$

- Energy sharing

Eq. (13) establishes that the power allocated, P^A, to each curve j is equal to the corresponding share, c_j, of the generated power, P^{PV}. c_j are the allocation coefficients. Eq. (14) indicates that, at each moment, the allocation coefficients add up to the unity. Depending on the values of these allocation coefficients, the LEC will face more or fewer power surpluses, affecting the final results. We have added Eq. (15) to simplify the optimisation. According to this constraint, individual coefficients can only take positive values multiples of 0.1 (as 0.1, 0.2, 0.3...). This constraint acceptably limits the optimised result's accuracy but dramatically reduces the

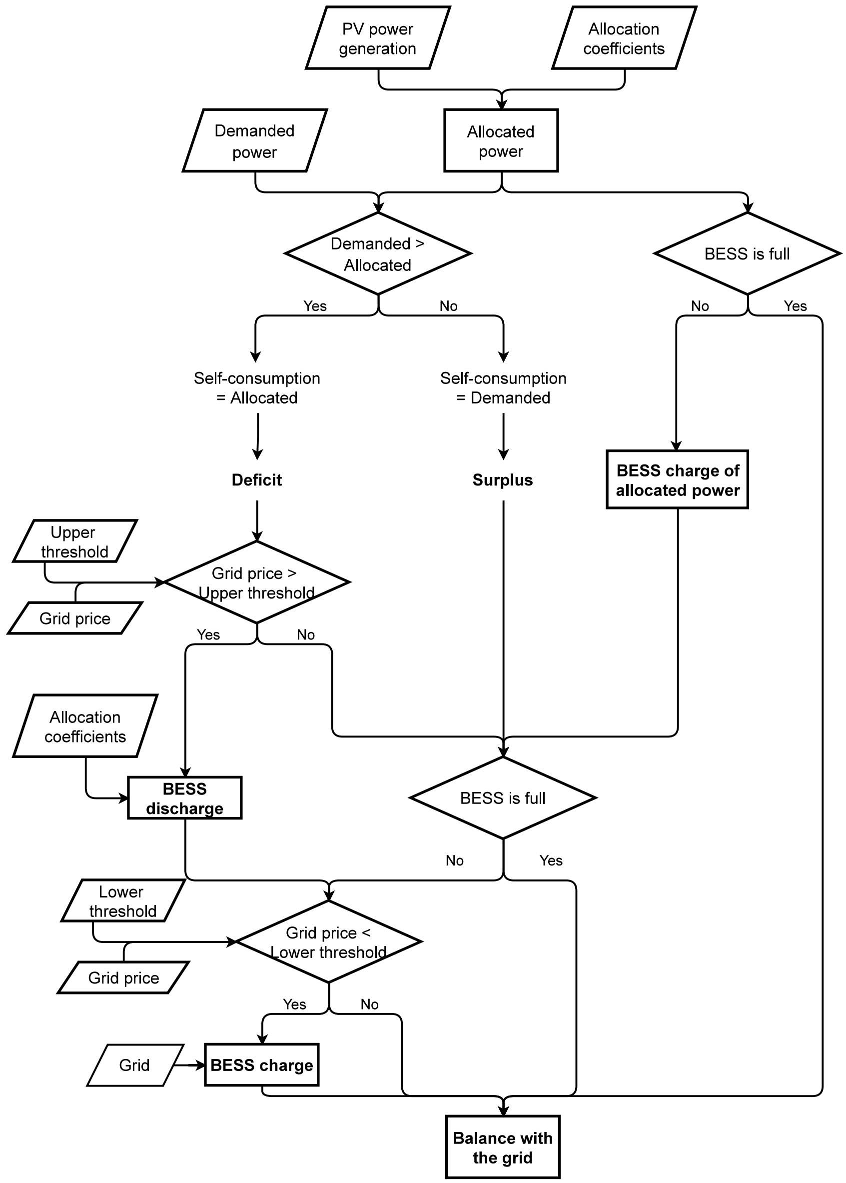


Fig. 4. LEC power allocation for case with BESS and static coefficients.

computational requirements.

$$P^{A}_{j,t} = P^{PV}_{t} c_{j,t} \qquad \forall t \in T, j \in J, c \in C \tag{13}$$

$$\sum_{j=1}^{J} c_{j,t} = 1 \qquad \forall t \in T, c \in C \tag{14}$$

$$c_j = 0.1\mathbb{N}^* \qquad \forall c \in C, j \in J \tag{15}$$

The power self-consumed for each curve j at any moment is the lower value between the demanded and the allocated power, Eq. (16).

$$P^{PV}_{j,t} = min(P^{A}_{j,t}, P^{D}_{j,t}) \qquad \forall t \in T, j \in J \tag{16}$$

- BESS constraints
  Eq. (17) prevents the simultaneous charging and discharging of the BESS. Meanwhile, Eqs. (18)–(20) set constraints for the charging power, discharging power and the energy storage capacity of the BESS.

$$P^{B,D}_{t} P^{B,C}_{t} = 0 \qquad \forall t \in T \tag{17}$$

$$0 \le P^{B,C}_{t} \le P^{B,C}_{MAX} \qquad \forall t \in T \tag{18}$$

$$0 \le P^{B,D}_{t} \le P^{B,D}_{MAX} \qquad \forall t \in T \tag{19}$$

$$0 \le E^{B}_{t} \le E^{B}_{CAP} \qquad \forall t \in T \tag{20}$$

Eq. (21) constrains the BESS discharge to the periods when grid price is higher than the upper threshold UT and batteries have energy stored. Similarly, Eq. (22) constrains the BESS charge purchasing electricity from the grid for the periods when grid prices are lower than the lower threshold LT and batteries are not fully charged.

$$\begin{cases} P^{B,D}_{t} = 0 & \Pi^{PUR}_{t} < UT \\ P^{B,D}_{t} \ge 0 & \Pi^{PUR}_{t} \ge UT \end{cases} \qquad \forall t \in T \tag{21}$$

$$\begin{cases} P^{B,PUR}_{t} = 0 & \Pi^{PUR}_{t} > LT \\ P^{B,PUR}_{t} \ge 0 & \Pi^{PUR}_{t} \le LT \end{cases} \qquad \forall t \in T \tag{22}$$

- Billing constraints
  Eq. (23) establishes that the contracted power of LEC members does not change. This approach is conservative and simplifies the assessment of results.

$$C^{POW}|_0 = C^{POW}|_{LEC} \tag{23}$$

  In turn, Eq. (24) indicates that, in the present situation, consumers do not sell any renewable electricity surplus to the grid.

$$C_t^{SELL}|_0 = 0 \qquad \forall t \in T \tag{24}$$

3.4. Metrics

We have evaluated the results of this work according to the three pillars of sustainability. We employ different metrics to evaluate economic sustainability. We use the Internal Rate of Return (IRR) to compare different alternatives regardless of their investment difference. The Net Present Value (NPV) serves to reflect the economic progression of the LEC over the years. We employ the annual savings (SV) for cases with BESS available due to the impact of battery replacement on LEC's economic performance. To evaluate social sustainability, we have used the degree of self-consumption to measure social participation in the electricity system. Besides, we measure the greenhouse gas (GHG) emissions avoided by the LEC for environmental sustainability.

- Financial evaluation
  We calculate the NPV of the LEC as indicated in Eq. (25). We evaluate the different components of the LEC's NPV following Eqs. (26)–(28).

$$NPV_n^{LEC} = NPV_n^{SAV} - NPV_n^{OM} - NPV_n^{INV} \tag{25}$$

$$NPV_n^{SAV} = \frac{SV}{d - i_{elec}}\left[1 - \left(\frac{1+i_{elec}}{1+d}\right)^n\right] \qquad \forall n \in N \tag{26}$$

$$NPV_n^{OM} = \frac{OM}{d}\left[1 - \left(\frac{1}{1+d}\right)^n\right] \qquad \forall n \in N \tag{27}$$

$$NPV_n^{INV} = NPV_{n-1}^{INV} + \frac{INV_n}{(1+d)^n} \qquad \forall n \in N \tag{28}$$

  We obtain the IRR as the market discount rate, d, that makes the NPV of the LEC at the need of the project lifetime, Eq. (29).

$$IRR = d \iff NPV_N^{LEC} = 0 \tag{29}$$

- Degree of self-consumption
  To know the degree of self-consumption, we consider the expression Eq. (30). The degree of self-consumption measures the amount of energy covered by the LEC out of the total energy demand.

$$SC = \frac{\sum_{t=1}^{T}\left(\sum_{j=1}^{J} P_{j,t}^{PV} + P_t^{B,D} - P_t^{B,PUR}\right)}{\sum_{t=1}^{T} P_t^D} \tag{30}$$

- GHG emissions avoided
  Eq. (31) is employed to account for GHG emissions avoided by the LEC. The avoided emissions are evaluated based on the current situation. We use Eqs. (32)–(34) to calculate the emissions corresponding to the different technologies.

$$GHG^{AV} = \left(GHG^{GRID}|_0 - GHG^{GRID}|_{LEC} - GHG^{PV} - GHG^{B}\right) N \tag{31}$$

$$GHG^{GRID} = \sum_{t=1}^{T}\left(P_t^{PUR}\Delta t\right) EF^{GRID} \tag{32}$$

Table 2
Scenarios variables and their possible values.

Variable	Values
Allocation coefficient	Static or variable
Points of consumption	50, 100 or 150 points
Residential consumption	25%, 50%, 75% or 100%
BESS	Available or not available
BESS capacity	100 or 300 kWh
BESS Ownership	Private or communal
BESS Static Coefficient	0.1, 0.2 or 0.3

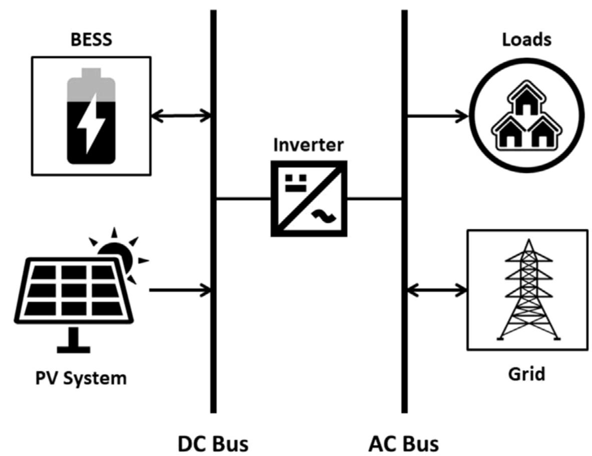


Fig. 5. LEC simplified layout.

$$GHG^{PV} = \sum_{t=1}^{T}\left(P_t^{PV}\Delta t\right) EF^{PV} \tag{33}$$

$$GHG^{B} = \sum_{t=1}^{T}\left(P_t^{B,C}\Delta t\right) EF^{B} \tag{34}$$

4. Case study

4.1. Studied scenarios

We have defined seven design variables and their possible values to evaluate the best LEC configuration (Table 2). We consider using static or variable coefficients as allocation strategies. We characterise the demand possibilities with sizes of the LEC from 50 to 150 points of consumption and residential consumption ratios from 25% to 100% of the total energy demand.

The BESS is optional, and where it is available, the capacity can be 100 or 300 kWh, in line with the results of Parra et al. (2017). Besides, the ownership of the BESS can be private or communal. Private ownership means that each point of consumption installs a BESS in his household, whilst communal ownership implies that only the required batteries for the LEC get installed in a centralised facility. Besides, we compare generation shares of 0.1, 0.2 and 0.3 to charge the BESS when using static coefficients.

In the end, combining all these values, we obtain 144 scenarios that allow us to study the relative impact of each variable.

4.2. LEC specifications

We locate the LEC over a public building in the city of Valencia, Spain and present its simplified layout in Fig. 5. It comprises a PV system, loads of the electricity end-users and the grid as backup. Besides, it can count with a BESS depending on the scenario.

We display PV system constant parameters for all scenarios in the Table 3. LEC can compensate for renewable surplus

Table 3
PV system characteristics.

PV system parameter	Unit	Value
Nominal power (P_t^{PV})	kW_p	100
Annual generation	kWh	124,186
Installation cost	e	132,822
Inverter cost	e/u	3,654
Inverter lifespan	yr	10
PV O&M	e/kW_p/yr	20
Project lifespan (N)	yr	20

Table 4
BESS system characteristics.

PV system parameter	Unit	Communal	Individual
Total energy capacity (E^B_{CAP})	kWh	13.1	3.3
Depth of discharge	%	94.7	87.9
Round-trip efficiency (η^B)	%	95	95
Life cycles	#	6,000	6,000
Battery price	e/u.	5,589	2,524
BESS O&M	%/e/yr.	1.5	1.5

by the simplified method as nominal power is 100 kW (BOE, 2019). The installation cost accounts for the entire initial investment for the PV system; we use the inverter cost only for the device replacement. We used the software PVSyst (PV Syst Photovoltaic Software, 2021) to generate the hourly capacity factors of the PV installation. Then, we obtain the solar generation by applying Eq. (7).

We use Li-ion batteries as the storage technology because it is the technology most widely used (IEA, 2021). Depending on the scenario, the BESS can have communal or individual ownership. Individual BESS should be more modular than communal BESS. Thus, we display BESS's main parameters for both alternatives in the Table 4. LEC replaces batteries at the year in which the life cycles are exhausted. The operation and maintenance costs (BESS O&M) are directly proportional to the investment cost in the BESS.

As the billing regulation has changed in 2021 and 2020 was an extraordinary year in terms of energy consumption due to the health emergency of COVID-19, we decided to use 2019 as the case study year to obtain more representative results. Nevertheless, the feed-in tariff began in April 2019. Hence, we had to extrapolate the hourly purchase prices for January, February and March. We obtained them using a linear correlation between the grid price and feed-in tariff for the rest of the year with a coefficient of determination (R^2) of 97%.

LEC loads are composed of residential and commercial consumers. We based consumers' data on historical data from real consumers obtained at the Distribution System Operator webpage, Iberdrola's i-DE (i-DE, 0000), which is the distributor in the region. As in the case of the grid prices, the hourly demand corresponds to 2019. We have considered three residential and two commercial hourly demand profiles. Each of the points of consumption corresponds to one of the five demand profiles following Eqs. (5) and (6).

4.3. Metrics rates

We need to define economic and environmental rates to evaluate the LEC's performance. Regarding the financial metrics (Table 5), as it is hard to predict accurately, we have defined different rates to obtain different scenarios. This way, we perform a sensibility analysis of the financial results. The main result uses the reference rates, and we use the optimistic and pessimistic rates to obtain the range of possible outcomes.

In turn, we use emission factors from the Spanish or the European context, Table 6.

Table 5
Financial rates under reference, optimistic and pessimistic perspectives.

Rate	Reference	Optimistic	Pessimistic
Electricity inflation index (i_{elec})	0.000	0.020	−0.020
Discount rate (d)	0.020	0.010	0.060

Table 6
Emission factors of the different technologies employed.

Technology	Emission factor (gCO_2/kWh)
Spanish Electric Grid (EF^{GRID}) (REE, 2020)	190
PV System (EF^{PV}) (Victoria and Gallego-Castillo, 2019)	20
BESS (EF^B) (Le Varlet et al., 2020)	60

Table 7
Hours with surplus production per year on average according to residential consumption with no BESS available.

Residential consumption	25%	50%	75%	100%
Hours	3,582	3,173	3,082	4,234

5. Results

We group the results by the presence or lack of a BESS in the LEC. For each group, we present the results of the three metrics focusing first on the economic impact of the allocation coefficients and demand configuration. Then, we assess the impact of different variables on the degree of self-consumption and the volume of GHG emissions avoided. Finally, we compare the metrics depending on the technologies that generate the most significant LEC investment differences.

5.1. Only PV cases

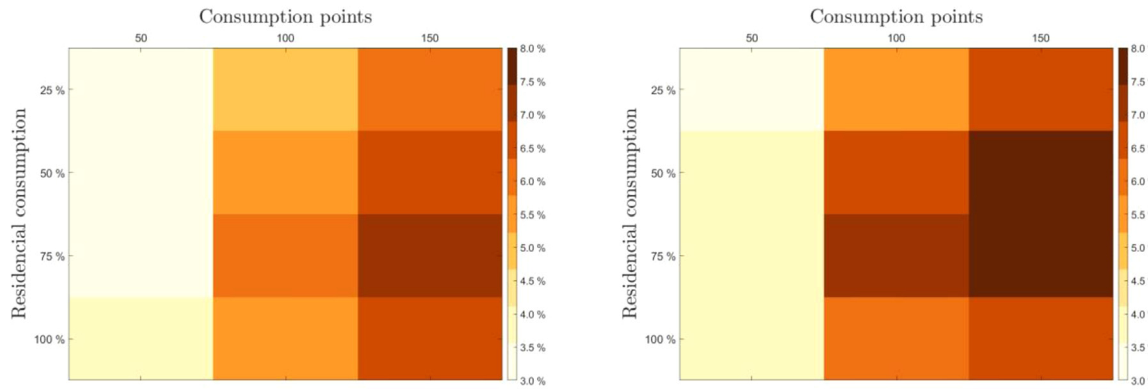
The initial investment for the only PV cases is the PV installation cost and the replacement of the inverters. Besides, the design variables that affect the economic outcome of the scenario are the number of consumption points supplied, the residential participation and the type of allocation coefficient used. Thus, we show the results for static and variable coefficients in Fig. 6.

LEC obtains its best economic performance in large communities (150 points) because as the demand increases, the surpluses reduce. Avoiding surpluses improves LEC's economy because the compensation price is lower than the purchase price. Therefore, it could be interesting to know the number of consumption points required to avoid surpluses. Nonetheless, as the community grows, it can generate disaffection as the savings for each individual get reduced, and the number of people involved hinders participation. Thus, energy communities can benefit from growing, but the LEC must consider the possible threats.

On the other hand, LEC obtained its best financial results with a 75% residential participation in energy consumption because this aggregation ratio of residential and commercial demands generates fewer surpluses than the rest of the possibilities (Table 7).

Fig. 7 presents the NPV evolution outlook under the different rates of electricity inflation and market discount for the scenario with variable coefficients, 150 points of consumption and a 75% residential participation. This Figure indicates that, for an optimised configuration, the LEC is profitable even in the worst scenario. The central value corresponds to the reference rates, and the best and worst values correspond to the optimistic and pessimistic rates.

Regarding the degree of self-consumption, Fig. 8 shows that the degree of autarchy increases in smaller LECs. This result is sensible as smaller LECs share the generated electricity among fewer users and, therefore, each consumer receives more energy



(a) Using static coefficients.　**(b)** Using variable coefficients.

Fig. 6. IRR heat map in scenarios with only PV.

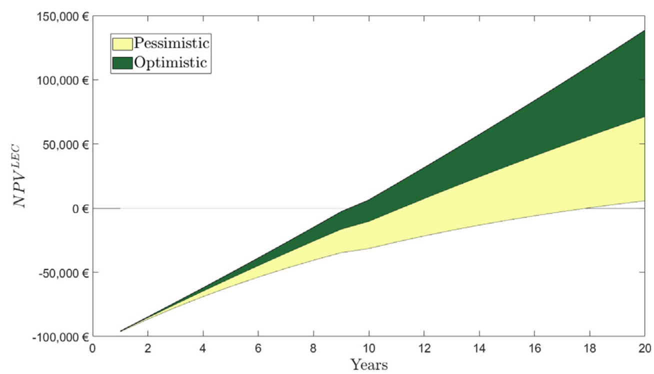


Fig. 7. NPV^{LEC} evolution outlook for a case with only PV.

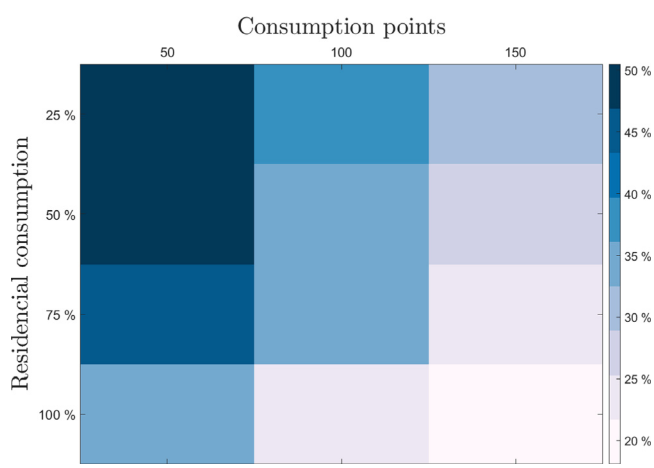


Fig. 8. Average self-consumption degree heat map in scenarios with only PV.

than in bigger LECs. Besides, self-consumption increases with low residential participation because their demand meets generation less often than commerces (namely because of weekdays).

Nevertheless, to improve the carbon footprint of the LEC, Fig. 9 indicates that it is better to go for a high number of members with relatively high residential participation. This result concurs with the financial results. The electricity consumed from the power grid is the most expensive and polluting; therefore, reducing electricity purchases reduces the GHG emissions associated with energy use.

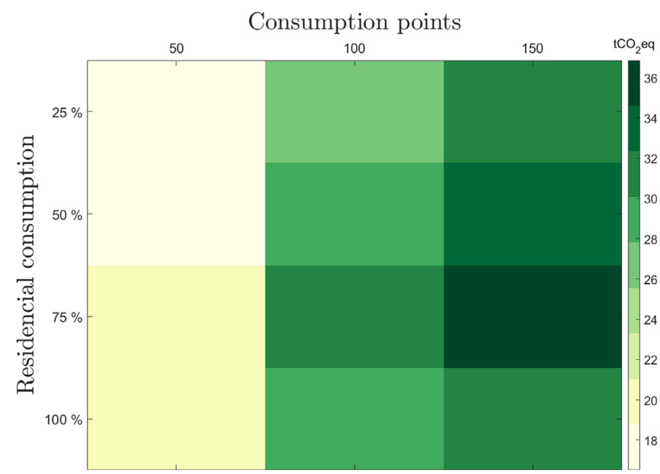


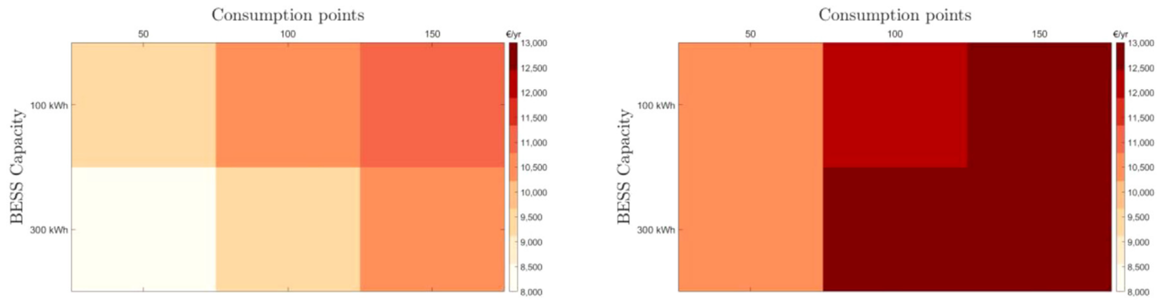
Fig. 9. Average GHG emissions avoided heat map in scenarios with only PV.

5.2. PV + BESS cases

Cases with PV and BESS are affected by the variables that already affected the previous case (allocation coefficients, size of community and residential consumption) and, on top of that, by the BESS capacity, ownership and its static coefficients when applicable.

Considering the financial results, the alternatives with private BESS present higher investment costs than communal BESS (Table 8). An improvement in the economic performance does not compensate for this investment increment, and thus, there is no scenario in which a private BESS is cost-effective. Nonetheless, communal BESS only in 1 out of 96 scenarios has an IRR higher than 1%. Therefore, BESS are not advisable from an economic standpoint; nonetheless, the rapid prices decline of batteries (Ritchie, 2021) and the new regulations of the Spanish electric system (Manso-Burgos et al., 2021) is expected to make BESS economically feasible.

Taking a look into the annual savings, Fig. 10 indicate that large communities obtain the best results. The results displayed in this section are averages for the different domestic consumption rates to evaluate the variables regardless of the community composition. The 100 kWh BESS performs better with static coefficients while, with variable coefficients, the best results are obtained with 300 kWh BESS. The flexibility that variable coefficients offer to the LEC is essential to understanding this outcome.



(a) Using static coefficients.   **(b)** Using variable coefficients.

Fig. 10. Average annual savings heat map in scenarios with PV and communal BESS.

Table 8
Total investment (NPV^{INV} 20 yr.) increment of BESS options compared to the configuration with no BESS available in average.

Case	Investment increment
Only PV	–
Communal BESS (100 kWh)	64%
Communal BESS (300 kWh)	158%
Private BESS (100 kWh)	268%
Private BESS (300 kWh)	453%

Table 9
Average results obtained in scenarios with PV and BESS.

Allocation	IRR	Annual cycles	BESS lifespan (yr.)
Static coefficients	−4.3%	47.1	25.1
Variable coefficients	−54.8%	102.5	12.3

Variable coefficients can profit from the full potential of the extra energy storage capacity and compensate for the increase in the investment.

As in the previous case, variable coefficients improve LEC's annual billing saves, Eq. (3), in all cases. Small LECs benefit more from the variable coefficients because their surplus generation is more significant than large LECs surpluses. Therefore, large LECs have less storage capacity to profit from variable coefficient flexibility.

However, we have employed the annual billing savings because IRR results get distorted by the battery replacement and do not offer consistent results. When evaluating the obtained IRR, the allocation coefficients employed impact significantly the results. As the optimisation objective is to maximise the annual savings, using variable coefficients implies a more intensive use of the BESS, thus reducing its lifespan and worsening the project's economic performance at the end (see Table 9).

We offer Fig. 11 to illustrate the impact of employing static or variable coefficients. These Figures represent identical scenarios in everything but the allocation coefficients employed. Notice that each NPV drop corresponds to an investment carried out by the LEC, pointing at the battery replacement year. LEC does not replace the batteries when using static coefficients, and it may be profitable in an optimistic scenario. However, using variable coefficients, LEC battery replacements in years 9 and 18 sink the LEC profitability. Therefore, the LEC should develop a BESS conservation strategy to profit from the potential of using variable coefficients.

When using static coefficients, LEC decides how much energy diverts to the BESS. We have tested values ranging from 10 to 30%, obtaining the best results by allocating only 10%. Besides, IRR results are best with 75% residential consumption.

Concerning the degree of self-consumption, Fig. 12 indicates that it does not increase with the increase in the BESS capacity considering individual ownership. Each point of consumption counts with its storage facility resulting in the users counting with the same number of batteries for a 100 kWh or a 300 kWh BESS requirement. In turn, increasing collective BESS capacity increases the degree of self-consumption as more generation surplus can be stored.

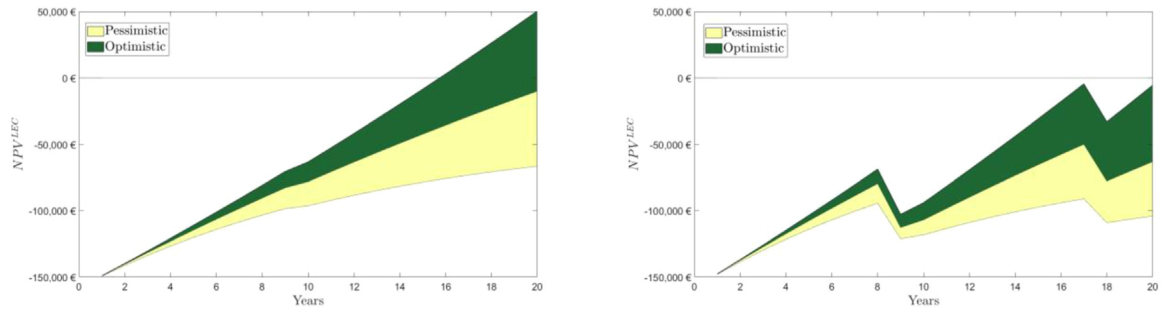
The employment of variable coefficients instead of static coefficients increases the degree of self-consumption sensibly. Besides, communal BESS provides higher levels of autarchy than individual BESS, even if it is oversized. This trend is because some users saturate their private BESS and sell the surplus to the grid while other users' BESS is not complete yet.

Considering the avoided GHG emissions on each configuration, Fig. 13 shows that static coefficients significantly reduce the potential of LECs to improve their environmental impact. Both configurations with individual BESS and variable coefficients are free to charge and discharge their BESS. This capacity reduces the use of electricity from the grid and, consequently, increases the reduction of GHG emissions. On the other hand, evaluating the impact of residential participation, the best results are obtained with a 75% residential consumption as it is the configuration that better matches demand with generation.

However, the BESS would have a more significant environmental impact if we restrict the charging of the BESS to the storage of surpluses, avoiding charging the BESS from the grid. Charging the BESS from the grid increases the energy purchased and, therefore, the carbon footprint. First, in the current configuration, there are many moments (on average, 2,894 h for static coefficients and 983 h for variable coefficients per year) in which the BESS does not store the surplus because it is already full. Second, the purchased energy from the grid to charge the BESS will suffer losses due to BESS efficiency. Hence, if LEC's primary goal is to reduce its carbon footprint, it should not charge the BESS using electricity from the grid, assuming the worsening of its economic performance.

5.3. Cases comparison

The best alternative for each variable will depend on the goal pursued. Table 10 shows which is the best option for each variable depending on the community goal. The best alternative is the same for economic and environmental objectives because the electricity purchased from the power grid is the most expensive and polluting. Therefore, the optimum LEC configuration is a large community with high residential participation and no BESS. On the other hand, when the goal is to increase LEC self-consumption, small communities with low residential participation increase the degree of self-consumption; also, we only advise a BESS for achieving autarchy.



(a) Using static coefficients.   **(b)** Using variable coefficients.

Fig. 11. NPV^{LEC} evolution outlook for a case with PV and BESS.

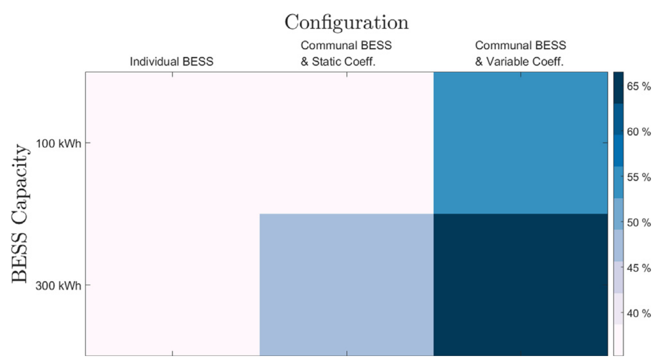


Fig. 12. Self-consumption degree heat map in scenarios with PV and BESS.

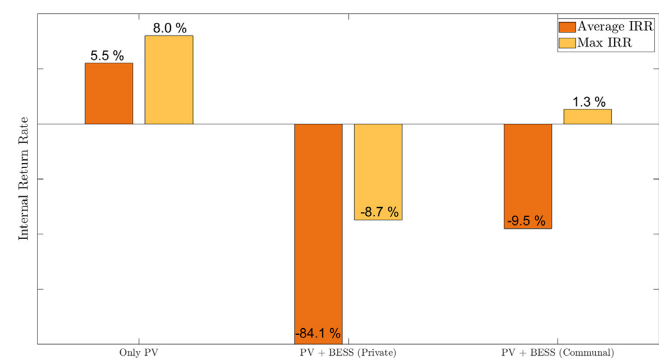


Fig. 14. IRR results comparison.

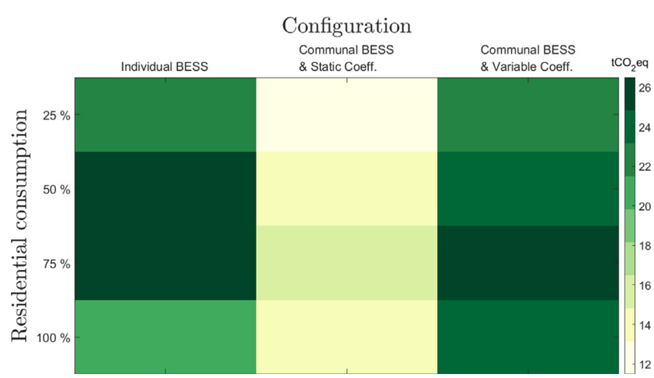


Fig. 13. Self-consumption degree heat map in scenarios with PV and BESS.

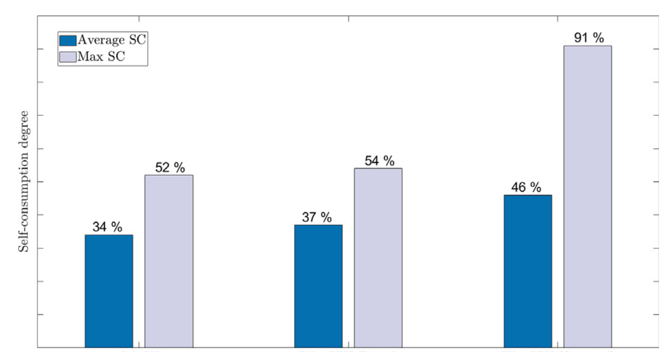


Fig. 15. Self-consumption degrees comparison.

Table 10
Best alternative for each variable depending on the LEC's goal.

Variable	Economic	Self-consumption	GHG avoided
Allocation coefficients	Variable	Variable	Variable
Points of consumption	150	50	150
Residential participation	75%	25%	75%
BESS	Not available	Available	Not available
BESS Ownership	Communal	Communal	Communal
BESS Capacity	100 kWh	300 kWh	100 kWh

Fig. 14 compares the average IRR obtained in the case of installing just the PV installation, PV with individual BESS or PV with a communal BESS. We decided to divide the scenarios into these cases because these variables significantly impact the LEC investment. This Figure shows that BESS are not profitable under these circumstances and, thus, it is not advisable for the LEC from an economic perspective.

Following, Fig. 15 compares the self-consumption degree of the different situations. BESS increases LEC's autarchy, especially under communal ownership, because the LEC centralises the management of BESS storage capacity. At the same time, each point of consumption depends on its available capacity using private BESS.

Finally, Fig. 16 compares the amount of avoided emissions through the LEC lifespan under each configuration. BESS does not improve the environmental performance of the LEC, probably due to the electricity bought from the grid at low prices. That electricity has the combined environmental impacts of the grid and the BESS, increasing the carbon footprint of the energy. Moreover, the electricity purchased from the grid increases with communal BESS. To increase the avoided emissions using a BESS, the LEC could not charge the BESS using electricity from the grid, assuming the worsening of its economic performance.

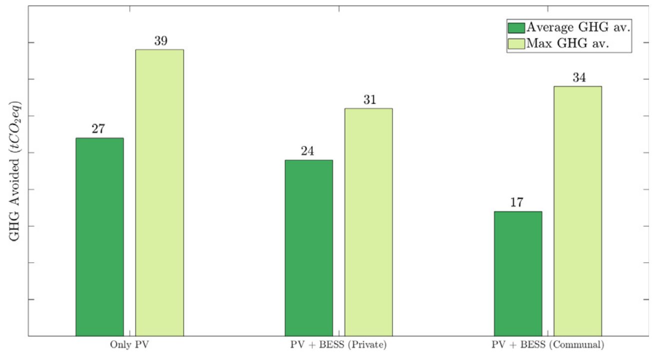


Fig. 16. Total GHG emissions avoided comparison.

6. Conclusions

LECs require tools to select their most fitting community members, power-sharing strategies and technologies for their goals. Consequently, this work develops a model and a methodology to optimise LECs. In it, we evaluate the presence of a BESS with different capacities and ownership options. Besides, we have tested two different sharing strategies, static and variable coefficients. Finally, we have characterised LECs' demand by comparing residential and commercial loads, varying the number of consumption points and the participation of the loads in the consumption. Previous literature has modelled LECs, but none considered as many variables and scenarios.

We applied the method to a case study in Valencia, Spain, resolving 144 scenarios with an hourly resolution for a whole year. We used actual consumption data from households and commercial users, obtaining the flows and status of each component within the LEC at every moment. We assessed the results using three metrics to evaluate each alternative's economic performance, autarchy degree, and the amount of avoided GHG emissions.

Even in the most pessimistic scenarios, an optimised LEC can fulfil economic, environmental, and self-consumption goals. Variable coefficients improved LEC performance regardless of the goal. However, LEC needs to develop a management strategy to ensure an optimal BESS performance with variable coefficients. Besides, as electricity purchased from the grid is the most expensive and polluting, we obtain the same optimal configuration regarding LEC's economic and environmental performance. In this sense, the results only advise installing a BESS to increase the degree of self-consumption as they are not cost-effective nor reduce the carbon footprint of the LEC. Moreover, we obtain the best financial and environmental results in large-sized LECs with a 75% residential consumption. Nonetheless, the best configuration for increasing autarchy is a small LEC with reduced residential participation.

LECs allow the participation of a broader population as the physical and economic constraints are less restrictive than in the individual self-generation. Moreover, LECs profit from the full potential of the available space for RES generation. Nonetheless, energy communities' growth is slower than in particular generation installations. This work shows that LECs are feasible and profitable when properly optimised. Furthermore, new simulations can be performed around the best values of the variables to obtain more precise results. However, there is still room for improvement as the results obtained in this work are optimised to improve the economic performance of the LEC. We could aim to maximise autarky or reduce GHG emissions, obtaining better results in those indicators. There is also the possibility of reaching a compromise solution to ensure economic performance while maximising environmental or self-consumption results. Other areas of improvement include research on demand-side response programmes, different storage systems, strategies to manage them, and the electrification of thermal loads and private transport. Hence, this research alone is not enough to explore all options of LECs and the mathematical model developed here. Future research should tackle some of the barriers that LECs face, such as sharing costs and benefits, the human organisation within the community, or the impact of regulations and administrative procedures. Researchers need to observe this topic from all perspectives to unlock the full potential of LECs.

CRediT authorship contribution statement

Á. Manso-Burgos: Conceptualization, Software, Methodology, Data curation, Visualization, Writing – original draft. **D. Ribó-Pérez:** Conceptualization, Software, Methodology, Writing – review & editing, Supervision. **T. Gómez-Navarro:** Writing – review & editing, Supervision. **M. Alcázar-Ortega:** Writing – review & editing, Supervision.

Declaration of competing interest

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

Data availability

Data will be made available on request.

Acknowledgements

This is an extended and updated version of a paper originally presented at the 16th Conference on Sustainable Development of Energy, Water and Environment Systems (SDEWES 2021) held in Dubrovnik, Croatia over the period 10th to 15th October 2021 (denoted then as paper SDEWES2021.00668 Evaluation of the participation of residential and commercial consumers in Energy Communities, a case study in València, Spain). This work was supported in part by the Spanish public administration under grant FPU2016/00962, by the PURPOSED project (ref: PID2021-128822OB-I00), financed by the Spanish State Investigation Agency. And by the Cátedra de Transición Energética Urbana (Las Naves-VCiE-UPV).

Appendix

All case studies have been solved by a stochastic method using MATLAB. The data treatment was also carried out in MATLAB. We have used an AMD Ryzen 7 5800H computer at 3.20 GHz and 16 GB of RAM. Each simulation takes from a couple of minutes to around 20 min, depending on the number of optimised variables.

References

Angenendt, G., Zurmühlen, S., Axelsen, H., Sauer, D.U., 2018. Comparison of different operation strategies for PV battery home storage systems including forecast-based operation strategies. Appl. Energy 229, 884–899.
Awad, H., Gül, M., 2018. Optimisation of community shared solar application in energy efficient communities. Sustainable Cities Soc. 43, 221–237.
Barbour, E., Parra, D., Awwad, Z., González, M.C., 2018. Community energy storage: A smart choice for the smart grid? Appl. Energy 212, 489–497.
BOE, 2019. Real Decreto 244/2019, de 5 de abril, por el que se regulan las condiciones administrativas, técnicas y económicas del autoconsumo de energía eléctrica. Report, Spanish Official Gazette.

BOE, 2020. Real Decreto-ley 23/2020, de 23 de junio, por el que se aprueban medidas en materia de energía y en otros ámbitos para la reactivación económica. Report, Spanish Official Gazette.
Brummer, V., 2018. Community energy – benefits and barriers: A comparative literature review of Community Energy in the UK, Germany and the USA, the benefits it provides for society and the barriers it faces. Renew. Sustain. Energy Rev. 94, 187–196.
C40, 2020. Why cities? URL: www.c40.org/why_cities.
Capellán-Pérez, I., Campos-Celador, A., Terés-Zubiaga, J., 2018. Renewable energy cooperatives as an instrument towards the energy transition in Spain. Energy Policy 123, 215–229.
Chakraborty, P., Baeyens, E., Khargonekar, P., Poolla, K., Varaiya, P., 2018. Analysis of solar energy aggregation under various billing mechanisms. IEEE Trans. Smart Grid 10.
Council of European Energy Regulators, 2019. Regulatory Aspects of Self-Consumption and Citizen Energy Communities. Report, CEER.
Dorotić, H., Doračić, B., Dobravec, V., Pukšec, T., Krajačić, G., Duić, N., 2019. Integration of transport and energy sectors in island communities with 100% intermittent renewable energy sources. Renew. Sustain. Energy Rev. 99, 109–124.
Fina, B., Auer, H., Friedl, W., 2020. Cost-optimal economic potential of shared rooftop PV in energy communities: Evidence from Austria. Renew. Energy 152, 217–228.
Gjorgievski, V.Z., Cundeva, S., Georghiou, G.E., 2021. Social arrangements, technical designs and impacts of energy communities: A review. Renew. Energy 169, 1138–1156.
Grzanić, M., Morales, J.M., Pineda, S., Capuder, T., 2021. Electricity cost-sharing in energy communities under dynamic pricing and uncertainty. IEEE Access 9, 30225–30241.
Gui, E.M., MacGill, I., 2018. Typology of future clean energy communities: An exploratory structure, opportunities, and challenges. Energy Res. Soc. Sci. 35, 94–107, Energy and the Future.
Heras-Saizarbitoria, I., Sáez, L., Allur, E., Morandeira, J., 2018. The emergence of renewable energy cooperatives in Spain: A review. Renew. Sustain. Energy Rev. 94, 1036–1043.
Hewitt, R.J., Bradley, N., Baggio Compagnucci, A., Barlagne, C., Ceglarz, A., Cremades, R., McKeen, M., Otto, I.M., Slee, B., 2019. Social innovation in community energy in Europe: A review of the evidence. Front. Energy Res. 7, 31.
i-DE, 0000. i-DE. URL: https://www.i-de.es/.
IEA, 2021. Energy storage. URL: https://www.iea.org/reports/energy-storage.
Koskela, J., Rautiainen, A., Järventausta, P., 2019. Using electrical energy storage in residential buildings – Sizing of battery and photovoltaic panels based on electricity cost optimization. Appl. Energy 239, 1175–1189.
Le Varlet, T., Schmidt, O., Gambhir, A., Few, S., Staffell, I., 2020. Comparative life cycle assessment of lithium-ion battery chemistries for residential storage. J. Energy Storage.
Leithon, J., Werner, S., Koivunen, V., 2018. Cooperative renewable energy management with distributed generation. In: 2018 26th European Signal Processing Conference. EUSIPCO. pp. 191–195.
Leithon, J., Werner, S., Koivunen, V., 2019. Storage management in a shared solar environment with time-varying electricity prices. IEEE Internet Things J. 6 (5), 7420–7436.
Lilla, S., Orozco, C., Borghetti, A., Napolitano, F., Tossani, F., 2019. Day-ahead scheduling of a local energy community: An alternating direction method of multipliers approach. IEEE Trans. Power Syst. PP, 1.
Lokeshgupta, B., Sivasubramani, S., 2019. Multi-objective home energy management with battery energy storage systems. Sustainable Cities Soc. 47, 101458.
Lowitzsch, J., Hoicka, C., van Tulder, F., 2020. Renewable energy communities under the 2019 European Clean Energy Package – Governance model for the energy clusters of the future? Renew. Sustain. Energy Rev. 122, 109489.
Luo, L., Abdulkareem, S.S., Rezvani, A., Miveh, M.R., Samad, S., Aljojo, N., Pazhoohesh, M., 2020. Optimal scheduling of a renewable based microgrid considering photovoltaic system and battery energy storage under uncertainty. J. Energy Storage 28, 101306.
Lyden, A., Pepper, R., Tuohy, P.G., 2018. A modelling tool selection process for planning of community scale energy systems including storage and demand side management. Sustainable Cities Soc. 39, 674–688.
Ma, T., Yang, H., Lu, L., 2014. Solar photovoltaic system modeling and performance prediction. Renew. Sustain. Energy Rev. 36, 304–315.
Manso-Burgos, A., Ribó-Pérez, D., Alcázar-Ortega, M., Gómez-Navarro, T., 2021. Local energy communities in Spain: Economic implications of the new tariff and variable coefficients. Sustainability 13 (19).
Maturo, A., Petrucci, A., Forzano, C., Giuzio, G.F., Buonomano, A., Athienitis, A., 2021. Design and environmental sustainability assessment of energy-independent communities: The case study of a livestock farm in the North of Italy. Energy Rep. 7, 8091–8107.
Olaszi, B.D., Ladanyi, J., 2017. Comparison of different discharge strategies of grid-connected residential PV systems with energy storage in perspective of optimal battery energy storage system sizing. Renew. Sustain. Energy Rev. 75, 710–718.
O'Shaughnessy, E., Cutler, D., Ardani, K., Margolis, R., 2018. Solar plus: Optimization of distributed solar PV through battery storage and dispatchable load in residential buildings. Appl. Energy 213, 11–21.
Parra, D., Norman, S.A., Walker, G.S., Gillott, M., 2017. Optimum community energy storage for renewable energy and demand load management. Appl. Energy 200, 358–369.
Perez-DeLaMora, D., Quiroz-Ibarra, J.E., Fernandez-Anaya, G., Hernandez-Martinez, E., 2021. Roadmap on community-based microgrids deployment: An extensive review. Energy Rep. 7, 2883–2898.
PV Syst Photovoltaic Software, 2021. PVSYST, URL: www.pvsyst.com.
REE, 2020. Emisiones de CO2 asociadas a la generación de electricidad en España. Report, Red Eléctrica de España.
Ribó-Pérez, D., Heleno, M., Álvarez-Bel, C., 2021. The flexibility gap: Socioeconomic and geographical factors driving residential flexibility. Energy Policy 153, 112282.
Ribó-Pérez, D., der Weijde, A.H.V., Álvarez-Bel, C., 2019. Effects of self-generation in imperfectly competitive electricity markets: The case of Spain. Energy Policy 133, 110920.
Ritchie, H., 2021. The price of batteries has declined by 97% in the last three decades - Our World in Data. URL: https://ourworldindata.org/battery-price-decline.
Roberts, M.B., Bruce, A., MacGill, I., 2019. Impact of shared battery energy storage systems on photovoltaic self-consumption and electricity bills in apartment buildings. Appl. Energy 245, 78–95.
Roldán Fernández, J.M., Burgos Payán, M., Riquelme Santos, J.M., 2021. Profitability of household photovoltaic self-consumption in Spain. J. Cleaner Prod. 279, 123439.
Soeiro, S., Dias, M.F., 2020. Community renewable energy: Benefits and drivers. In: The 7th International Conference on Energy and Environment Research—"Driving Energy and Environment in 2020 Towards A Sustainable Future". Energy Rep. 6, 134–140.
Stewart, F., 2021. All for sun, sun for all: Can community energy help to overcome socioeconomic inequalities in low-carbon technology subsidies? Energy Policy 157, 112512.
UN Habitat, 2020. UN HABITAT Climate Change. Technical Report, UN Habitat, URL: www.unhabitat.org/topic/climate-change.
Vibrant Clean Energy, LLC, 2020. Why Local Solar For All Costs Less: A New Roadmap for the Lowest Cost Grid. Report, Vibrant Clean Energy.
Victoria, M., Gallego-Castillo, C., 2019. Hourly-resolution analysis of electricity decarbonization in Spain (2017–2030). Appl. Energy.
Vinod, Kumar, R., Singh, S., 2018. Solar photovoltaic modeling and simulation: As a renewable energy solution. Energy Rep. 4, 701–712.
Ye, G., Li, G., Wu, D., Chen, X., Zhou, Y., 2017. Towards cost minimization with renewable energy sharing in cooperative residential communities. IEEE Access 5, 11688–11699.
Zhang, Y., Lundblad, A., Campana, P.E., Benavente, F., Yan, J., 2017. Battery sizing and rule-based operation of grid-connected photovoltaic-battery system: A case study in Sweden. Energy Convers. Manage. 133, 249–263.