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Assessment of energy sharing coefficients under the new Portuguese renewable energy communities regulation

Humberto Queiroz [a,b,*], Rui Amaral Lopes [a,b], João Martins [a,b], Filipe Neves Silva [c], Luís Fialho [d], Nuno Bilo [e]

[a] NOVA School of Science and Technology, NOVA University Lisbon, Portugal
[b] Center of Technology and Systems (UNINOVA-CTS) and Associated Lab of Intelligent Systems (LASI), Portugal
[c] EDP New, Portugal
[d] University of Évora, Renewable Energies Chair, Portugal
[e] Évora Municipality, Portugal

A R T I C L E I N F O

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A B S T R A C T

The recent published European legal framework (Directives (EU) 2018/2001 and 2019/944) on renewable energy consumption, and its Portuguese transposition (the Decree-Law 15/2022), opens the possibility for buildings to operate as energy communities. One of the objectives is to increase the use of locally generated energy from renewable sources, by sharing available surplus among participants, using sharing coefficients defined by the entire community.

Taking the actual legal framework into consideration, this paper presents an analysis of the energy sharing coefficients proposed by the newly published Portuguese legislation via the assessment of a renewable energy community, formed by public buildings, whose operation varies according to different sharing coefficient applied. Results show that time-variable energy sharing coefficients are the best option to the considered renewable energy community. Collected results also show that larger consumers can extract higher benefits from being integrated on a renewable energy community. These benefits decrease when buildings are allowed to self-consume local generated energy prior to the sharing process as demand inequalities become less important for the computation of the considered sharing coefficients. The entire community also presents better performance in this case.

1. Introduction

The European Union (EU) has been encouraging its member states to increase the share of renewable energy sources (RES) into their energy pool. This encouragement aims, among other goals, to mitigate climate changes effects, mostly caused by the emission of greenhouse gases (GHG) into the atmosphere when energy is generated using fossil fuels, and to increase energy security [1]. One of the main characteristics of the different RES technologies is the low level, or even the absence, of GHG emissions during the operation phase. However, most RES exhibit a variable generation pattern, following the availability of the respective primary energy resource, which increases the complexity of power systems management [2].

* Corresponding author. NOVA School of Science and Technology, NOVA University Lisbon, Portugal.
E-mail addresses: h.queiroz@campus.fct.unl.pt (H. Queiroz), rm.lopes@fct.unl.pt (R.A. Lopes), jf.martins@fct.unl.pt (J. Martins), filipe.nevessilva@edp.pt (F.N. Silva), lafialho@uevora.pt (L. Fialho), nuno.choraobilo@cm-evora.pt (N. Bilo).

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Nomenclatures

Acronyms

Bld	Building
CEC	Citizen energy community
CSME	Collective self-consumption entity manager
DSO	Distribution system operator
EU	European Union
EV	Electric vehicle
FEC	Fixed and equal sharing coefficient
FPC	Fixed and proportional sharing coefficient
GHG	Greenhouse gases
H2020	Horizon 2020
NOCT	Nominal operating cell temperature
P2P	Peer-to-peer
PV	Solar photovoltaic
REC	Renewable energy community
RES	Renewable energy source
STC	Standard test conditions
VSC	Variable sharing coefficient
ZCC	Zero-carbon community

Variables

P_G	PV system instant power output [W]
N	Number of modules in a PV array
A	Useful area of a PV module [m^2]
G	Instantaneous global solar irradiance on the horizontal plane [W/m^2]
η_c	Instantaneous PV module's efficiency
η_i	Efficiency considering balance-of-system losses
η_{STC}	PV module's efficiency at Standard Test Conditions
μ	PV module's temperature coefficient [$^\circ C^{-1}$]
θ_a	Ambient temperature [°C]
$T_{c,STC}$	PV cell temperature at Standard Test Conditions [°C]
$T_{c,NOCT}$	PV cell temperature at Nominal Operating Cell Temperature [°C]
$\theta_{a,NOCT}$	Ambient temperature at Nominal Operating Cell Temperature [°C]
G_{NOCT}	Global solar irradiance at Nominal Operating Cell Temperature [W/m^2]
BD	Building demand [W]

On the consumer side, the energy generated from local renewable sources is used to reduce energy import from the grid and the respective costs [3]. To enhance the local usage of RES and associated benefits related to self-consumption, the concepts of Renewable Energy Community (REC) and Citizen Energy Community (CEC) have been introduced and encouraged by the EU and national entities in the last years, as described in Section 1.1. These entities are entitled to share locally generated energy among their members at a lower cost, when compared to the price of energy imported from distribution grids. This sharing process represents the cornerstone of the referred energy communities as it offers real benefits to small consumers and contributes to the engagement of citizens in topics related to the energy sector, including renewable energy generation and self-consumption. By increasing the number of renewable energy communities and citizen energy communities, members states can increase the use of RES and ultimately decrease the GHG emissions of the energy sector, as aimed by the EU [1].

1.1. *Self-consumption regulation*

Self-consumption of RES refers to the immediate usage of energy generated from renewable sources to satisfy energy demand within the premises where the respective energy conversion systems, commonly based on photovoltaic (PV) technology, are installed. This practice can be conducted at both individual and aggregated levels and the literature shows that the second option presents better results when compared to an individual operation due to the sharing of generation surplus among residential community members and the respective reduction of energy import from distribution grids [4].

The European Commission published two important directives to foster the implementation of these activities, namely, Directive (EU) 2018/2001 [5], published on December 11th, and Directive (EU) 2019/944 [6], published on May 30th. The former set goals for the increasing of renewable energy sources usage. The latter, concerns electricity markets operation, considering common rules of internal electricity markets. Both legal instruments also incentivise the association of consumers, residential, commercial, or industrial, to trade their flexibility and self-generated energy into local markets. The REC and CEC concepts are developed to comply with this incentive. These two types of communities, despite their similarities regarding member participation and entitlement for energy trading, have some specificities that differentiate them. The main difference concerns the fact that a CEC can own, establish, purchase or lease electricity distribution networks (these possibilities are not available for a REC). The term REC is chosen in the remaining of this paper for the sake of readability given that the referred difference between CEC and REC is not addressed in this study.

Portugal, as one of the EU member states, addresses the importance of the aforementioned legal framework by the publication of the Decree-Law 15/2022 [7], which approves the applicable legal regime for renewable energy self-consumption (both individual and collective). Furthermore, Regulation 373/2021 was approved by the national Energy Services Regulatory Authority, providing further details to regulate electricity self-consumption, both individual and collective through the transposition to the REC concept to the Portuguese legal framework, and the relationship between the various stakeholders involved in this process [8].

1.2. Literature review

The collective association of consumers and/or prosumers to conduct collective self-consumption, instead of individual self-consumption, is assessed in a variety of ways in the literature. These associations are implemented and studied to achieve different objectives, such as energy savings and reduction of GHG emissions [9], higher PV self-consumption ratios [10], or improvement of wellbeing on a grid fault via energy flexibility [11]. For low-voltage grids, the deployment of energy communities can also offer real-time scheduling of flexibility [12]. Regarding energy carriers, electricity is not the only one possible to be used by REC members. Authors in Ref. [13] described the analysis of a renewable polygeneration system connected to a district heating and cooling network in Naples, Italy. The study incorporates thermodynamic, economic, and environmental factors, considering geothermal energy as the primary source.

A significant part of an energy community management framework regards the sharing of locally generated energy among the participants. In Ref. [14], a sharing model with price-based demand response was developed, by a supply and demand ratio of shared PV energy, while the respective consumption flexibility of each one of the considered prosumers is used to develop an equivalent cost model. The authors in Ref. [15] developed an entire business model for an energy community, where one of the considered aspects is the fair distribution of the reward achieved by the community members. In this case study, community members could get a significant cost reduction, mostly by energy sharing. In Ref. [16], a power sharing model was proposed, to distribute locally generated energy inside an energy community and to increase social. It is stated that the application of this model can be useful for energy communities that have renewable energy sources owned by the community's members. However, the model is based on the ability of each member to self-consume the electricity generated by the local sources and avoid the exchange of power with others. The impacts of an energy sharing management framework on distribution grids are studied in Ref. [17] by considering heterogeneous community members in terms of energy consumption. The proposed battery control algorithm, used to increase the consumption of energy generated locally, considers the constraints of the low voltage distribution grid and can be implemented on a larger scale. Furthermore, the work reported in Ref. [18] presented an energy sharing model for zero-carbon communities using a Stackelberg game approach. The model incorporated reward and punishment mechanisms to promote energy conservation and emissions reduction. It establishes a framework involving a zero-carbon community operator and multiple prosumers with energy storage systems scheduled to minimize carbon emissions. Ceglia et al. compared the benefits of a REC with alternative single end users' configurations and the current reliance on the power grid [19]. By equipping users with a photovoltaic system, the authors demonstrate increased energy self-consumption and self-sufficiency, and significant reductions in primary energy demand, carbon dioxide emissions, and operation costs. The research conducted in Ref. [20] proposed a two-stage stochastic sharing model for communities aiming to maximize the efficient utilization of PV systems. The model addressed PV power uncertainties through regulation methods, such as demand response and energy storage charging/discharging scheduling. By employing a data-driven uncertainty set, the model optimized the social cost of PV prosumers and the community energy storage, resulting in decreased energy costs according to numerical simulations. The concept of peer-to-peer (P2P) trading platform, in which a member can buy or sell energy to other members, has also been studied in the context of energy sharing. Such platforms can lead to energy cost savings and local increase of PV electricity usage [14], provide local balance between supply and demand [21], can be used for both electricity and heating [22], and increase the penetration of electric vehicles in low voltage grids [23].

Despite the growing interest in energy communities' management frameworks across Europe, to the best of our knowledge, there is a research gap regarding the assessment of possible sharing strategies based on energy sharing coefficients defined according to existing national legislation, as it is the case of Decree-Law 15/2022 [7] in Portugal, and their consequential impacts on energy bills. Therefore, to address this gap, the present work aims to assess the benefits provided to REC members by different energy sharing coefficients proposed by the Portuguese legislation. This assessment is made by simulating a REC over a year using real consumption and meteorological data while applying different sharing coefficients (fixed and variable). Furthermore, different energy management schemes are considered for REC members, namely: i) individual operation of the buildings with no association as a community; ii) REC operation by performing collective self-consumption; iii) and REC operation while also considering individual self-consumption.

1.3. Structure of the document

The paper is organized as follows. Section 2 brings the methodology used in this study, describing the data used to simulate the operation of the considered buildings, and the algorithms applied to the management of generation units and to the operation of the considered REC. Section 3 presents the collected results and the respective analysis. Lastly, Section 4 addresses the conclusions and future research directions.

2. Methodology

The assessment of the possible sharing processes described in the Portuguese regulation is made by the simulation of an energy management system for, both, individual buildings, and an association of buildings as a REC. The implementation of a collective energy management system is therefore needed according to the Portuguese legal framework [7,8] to compute the electricity consumption, generation, sharing and export, and the associated costs and revenues, if applicable. The buildings considered for the case study belong to Évora municipality, a historical city in the centre of Portugal, as described below:

- Building 1 (*Bld#1*) – a multipurpose pavilion, used for concerts, sports tournaments, and other events;
- Building 2 (*Bld#2*) – the City Hall building;
- Building 3 (*Bld#3*) – a public market;
- Building 4 (*Bld#4*) – a public school.

2.1. Electricity demand profile

To assess the impacts of the association of buildings as a REC, real data regarding the buildings' electricity consumption were collected. The time frame of data gathering is the whole year of 2019, and the data resolution is 15 min since the data were collected directly from the Distribution System Operator (DSO) via a specific request by the buildings' owner and the following acquirement on the DSO database, which is a common procedure for buildings equipped with smart meters in Portugal. The buildings selected for the case study, which are part of one of the Lighthouse Pilots of the H2020 POCITYF project [24], have different electricity consumption profiles due to the following factors: size, usage type, and year of construction. For instance, since *Bld#4* is a school, there is a significant decrease of electricity consumption from the end of July to the second week of September, corresponding to the summer holiday period for students and most school workers. On a daily perspective, *Bld#1* is used for concerts, and other events, and has a demand peak during the night (around 08:00 p.m.), while in *Bld#3*, as a market, the demand peak occurs early in the morning. Despite the holiday period mentioned for *Bld#4*, its demand peak occurs around noon, almost at the same time in which it occurs for *Bld#2*. These particularities can affect PV self-consumption and the impact on the performance of the considered REC. Fig. 1 shows the normalised daily average electricity demand profile for each building, and Table 1 shows their respective contracted power (i.e., the maximum power capacity contracted for each building).

2.2. Electricity generation profile

PV systems are used to generate electricity on-site in each building. The electricity generated by each equipment is calculated based on the generation model described by Ref. [25]. For a PV system, the instant power output ($P_G(n)$) is described by Equation (1), where N is the number of modules, A is the useful area of one of each PV module, $G(n)$ is the instantaneous global solar irradiance on the horizontal plane, at the considered local, $\eta_c(n)$ is the instantaneous PV module's efficiency, given by Equation (2), and η_i is the efficiency considering balance-of-system losses from, for instance, power electronics equipment (e.g., DC/AC inverter), cables, or soiling in the modules (i.e., losses not related with η_c). For the purpose of this study, a constant value of 0.8 is considered for η_i as in Ref. [25]. Since this study considers a single year of operation, the yearly degradation of PV modules' production, often assumed to be 0.5–1.0%

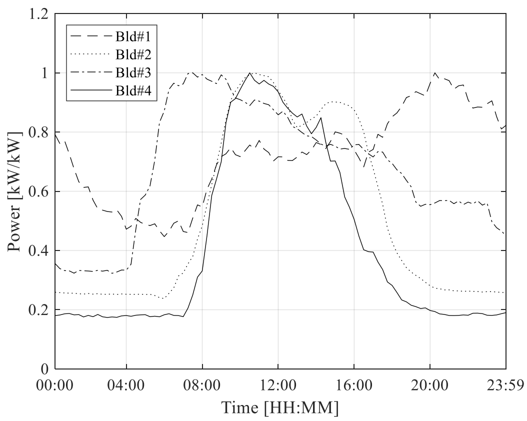

Fig. 1. Normalised buildings' daily average demand profile.

Table 1
Buildings' contracted power.

Bld	Contracted power [kVA]
1	63.00
2	135.00
3	41.41
4	43.00

per year [3], was not considered.

$$P_G(n) = N \times A \times G(n) \times \eta_c(n) \times \eta_i \quad (1)$$

$$\eta_c(n) = \eta_{STC} \times \left\{1 + \mu \times \left[\theta_a(n) - T_{c,STC} + G(n) \times \left(\frac{T_{c,NOCT} - \theta_{a,NOCT}}{G_{NOCT}}\right) \times (1 - \eta_{STC})\right]\right\} \quad (2)$$

In Equation (2), η_{STC} is the PV module's efficiency at Standard Test Conditions (STC), μ is the temperature coefficient, $\theta_a(n)$ is the ambient temperature, in degree Celsius, $T_{c,STC}$ is the PV cell temperature at STC, $T_{c,NOCT}$ is the cell temperature at Nominal Operating Cell Temperature (NOCT), $\theta_{a,NOCT}$ is the ambient temperature at NOCT and G_{NOCT} is the global irradiance at NOCT. The module parameters used in this study are presented in Table 2. The number of modules for each building (*N*), used to calculate the PV system output power in Equation (1), results from a survey conducted during the POCITYF project [24], and are presented in Table 3, together with the total installed power and annual generation considering the meteorological data described below in this section. PV modules are assumed to be installed with azimuth ant tilt angles of 0° and 38°, respectively, to maximize annual generation, and achieve a specific production of approximately 1,350 kWh/kWp. The considered buildings are located inside an architecturally sensitive area (i.e., Évora city centre) and discussions with local authorities are still ongoing to make sure that the final PV system designs will not impact the existing cultural heritage. Therefore, the final PV systems design, including installed capacity, might present some changes when compared to the values shown in Table 3. However, eventual future modifications are believed to not impact the main findings of this study as these will not change the considered types of energy sharing coefficients.

Regarding meteorological data, the solar irradiance was collected throughout 2019, with 1-min resolution, by a meteorological station installed locally. This station is equipped with a two-axis fully automatic sun tracker SOLYS2, with two CMP11 pyranometers to monitor global horizontal and diffuse solar irradiance, and one CHP1 pyrheliometer to measure direct solar irradiance. The method described in Ref. [26] was used to convert solar irradiance values from the horizontal plan to the considered inclination of the PV modules. Due to lack of real ambient temperature data for the considered period (2019), a historic dataset with 1-h resolution was acquired from the Photovoltaic Geographical Information System (PVGIS), which is an online tool and database developed by the Joint Research Centre (JRC) of the European Commission [27].

Both irradiance and ambient temperature data were treated to present a 15-min resolution in accordance with the electricity consumption data referred in Section 2.1. Fig. 2 presents the considered meteorological data with 15-min resolution for 2019 (ambient temperature in Fig. 2a and solar irradiance in Fig. 2b), together with the respective daily average values.

The installation of storage devices is not considered in this case study. Therefore, surplus electricity is entirely exported to the low voltage distribution grid. Despite the operation framework chosen for the buildings' generation units, Fig. 3 shows the algorithm for the PV electricity management, in which *P(n)* represents the PV system production at a given instant *n*, *D(n)* refers to a specific building's demand at the same instant, while *ND(n)* and *M(n)* are used to model the building demand after the PV self-consumption and the exported power after considering the PV self-consumption, respectively. Depending on the chosen operation, the amount of surplus will change (e.g., if the REC manager allows the members to self-consume part of the locally generated electricity, there will be less surplus to be shared among them). This rule-based algorithm considers only the local conditions to determine the share of electricity to be self-consumed or to be exported to the electricity grid. The variable *M(n)* considers the power readings at the buildings' energy meter level. Positive values of *M(n)* indicate that the PV system was able to provide all the instant electricity needs of the building and at the same time there is surplus electricity to be exported to the grid. In this case, the building needs after the self-consumption process, indicated by the variable *ND(n)*, are equal to zero. On the other hand, if *M(n)* is equal to zero, the PV system was

Table 2
PV module parameters.

Parameter	Value	Unit
Rated power	300	W
A	1.63	m^2
η_i	0.8	–
η_{STC}	0.184	–
μ	−0.0038	$°C^{-1}$
$T_{c,STC}$	25	°C
$T_{c,NOCT}$	45	°C
$\theta_{a,NOCT}$	20	°C
G_{NOCT}	800	$W.m^{-2}$

Table 3
Buildings' installed power and PV generation.

Building	Number of modules	Installed PV power	Annual generation
Bld#1	24 modules	7.2 kWp	9.74 MWh
Bld#2	285 modules	85.5 kWp	115.67 MWh
Bld#3	52 modules	15.6 kWp	21.2 MWh
Bld#4	135 modules	40.5 kWp	54.9 MWh

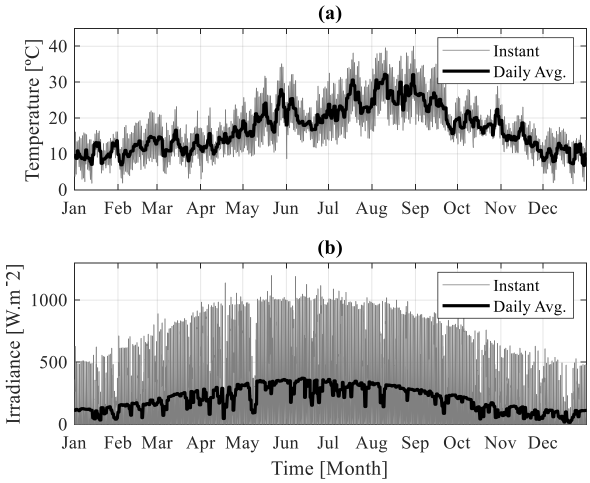

Fig. 2. Meteorological data: (a) Ambient temperature; (b) Solar irradiance.

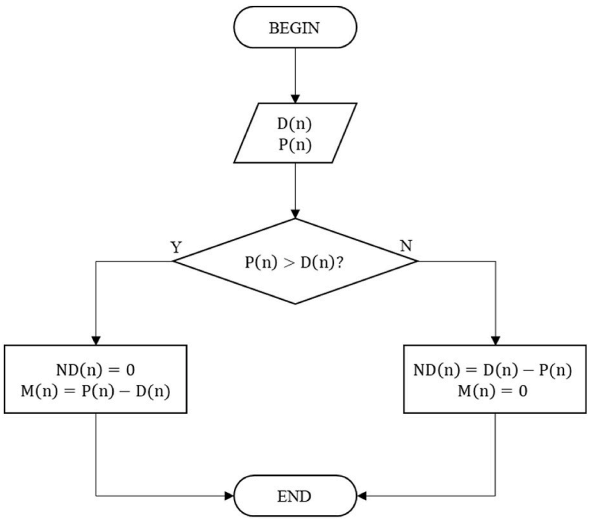

Fig. 3. PV electricity management algorithm.

not able to generate all the needs for the building, and *ND(n)* indicates that need in terms of demand, as the difference between the original demand and the local production *P(n)*, which is satisfied by energy import from the grid.

2.3. Renewable Energy Community

According to Ref. [8], a Collective Self-consumption Manager Entity (CSME) must be chosen to form a REC. This entity is responsible for the commercial relationships between the REC and the remaining stakeholders, such as the DSO and local markets. The main responsibility of the CSME refers to the electricity sharing among the community members. The CSME is also responsible to inform the DSO about the energy sharing process chosen by the REC. This sharing process is made by applying energy sharing coefficients, which are related to the percentage of the locally generated energy that is due to each member. The sharing coefficients can be freely assigned, or calculated, by the rules agreed upon by all REC members [7,8]. The current possibilities, according to the most recent Portuguese legislation, are the following [8]:

- Fixed coefficients for each member during a considered time frame, being the values freely decided by the REC members (they can be equal for each member or different among them).
- Variable coefficients computed by any valid criteria (e.g., measured consumption) as long as agreed by all REC members and using the time interval defined on the Portuguese regulation, namely 15 min [28].

While fixed coefficients are easier to apply, the variable ones offer the ability to adapt the sharing process according to specific needs of the REC under consideration, such as situations in which some of the buildings do not need to import electricity due to its prior self-consumption or to avoid sharing excessive electricity to a given building, compromising the operation of the REC as a whole. A general formulation for the calculation of this sharing coefficient *(ShCoeff)* during a given timestep *n* is described by Equation (3), where A, B, and C represent the considered parameters for the sharing coefficient calculation (e.g., energy demand or generation), while α, β, and γ are the respective ponderation factors.

$$\text{ShCoeff}(n) = 100 \times \left[\alpha \times \left(\frac{A_i(n)}{\sum_{i=1}^{N\_BLD} A_i(n)} \right) + \beta \times \left(\frac{B_i(n)}{\sum_{i=1}^{N\_BLD} B_i(n)} \right) + \gamma \times \left(\frac{C_i(n)}{\sum_{i=1}^{N\_BLD} C_i(n)} \right) + \ldots \right] \tag{3}$$

This study only considers the REC member electricity needs, regardless the permission to individual self-consumption. However, other parameters can be defined to calculate *ShCoeff*, such as the share of each member to the RES generated energy, the contribution of each member to the CAPEX/OPEX of equipment to allow the REC operation etc. Also, subjective parameters can be considered, such as, the level of energy poverty of each member.

Fig. 4 shows the REC configuration used in this work, which will considered both fixed and variable energy sharing coefficients (see Section 3.1 for more information on the considered scenarios). The renewable energy project mentioned by Decree-Law 15/2022 [7] is satisfied in this study by the PV systems installed inside the limits of each member of the considered REC, connected to the distribution grid approximately at the energy meter location. This REC is also defined under the scope of the POCITYF project [24].

It is important to highlight that the shared electricity is part of the total electricity generated within the REC, being assigned to a given member after the application of the energy sharing coefficient. However, the energy sharing process among the members is made by the DSO after the billing period, by analysing the respective energy meters' data and proceeding to a financial operation to share the electricity, based on the coefficients informed by the CSME, due to the physical impossibility to drive the electricity instantly to whichever building that has an energy share assigned. Regarding the variable sharing coefficients, they are only informed after the billing period, being calculated at each 15-min interval of energy generation and consumption. This operation is made by the addition or subtraction of the measured power, considering the available power to be shared at each instant. After the sharing process, the electricity for billing is calculated considering the modified load diagram [8]. However, despite the sharing process being a financial

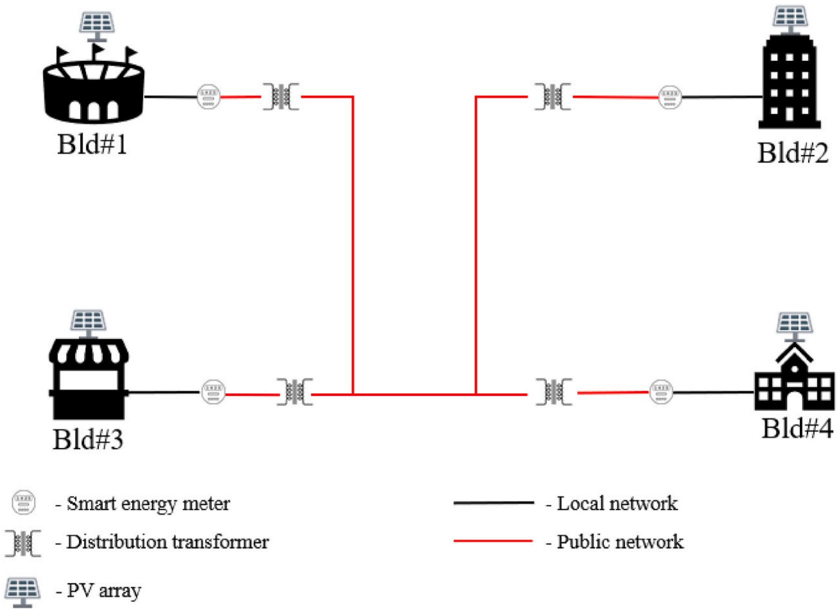

Fig. 4. REC configuration.

operation conducted after the real consumption and generation of electricity, there may be an actual alleviation of the power grid during the operation of the local PV systems, either when the buildings are self-consuming, or when electricity surplus exports occur. This procedure is in line with the ambitions of the European Commission regarding the increase of the usage of renewable energy sources close to the consumption site [5]. The designed algorithm for the electricity sharing for the REC member is shown on Fig. 5, being the input and output parameters described in Table 4.

It is important to note that in some cases REC members can self-consume part of the locally generated electricity, which can lead to possible net-zero power balances. This situation may allow a greater share of electricity for the remaining buildings which are not capable to achieve a net-zero power balance during a specific time-step. Despite the same algorithm being used on both REC configurations (i.e., REC operation with and without individual self-consumption), the input values are different. $BD_i(n)$ refers to the building demand after the individual self-consumption procedure takes place if this procedure is permitted. When only the collective self-consumption is allowed, the consumption needs are represented by the sum of all the electric operating loads and the power available to be shared is the total power production of the locally installed PV systems. Similarly, $BP_i(n)$ refers to the power available for sharing at each time instant. When the prior individual self-consumption is allowed by the REC members, $BP_i(n)$ represents the power surplus after this process. If the REC operation is based on collective self-consumption, $BP_i(n)$ represents the power locally produced by all members. This framework leads to a difference on the amount of energy available for sharing among the REC members, which depends on how they decide to manage the locally generated electricity. If the decision is to proceed to an individual self-consumption before the sharing process, the available amount of electricity to be shared is lower, since part of the generated electricity is consumed by the building users.

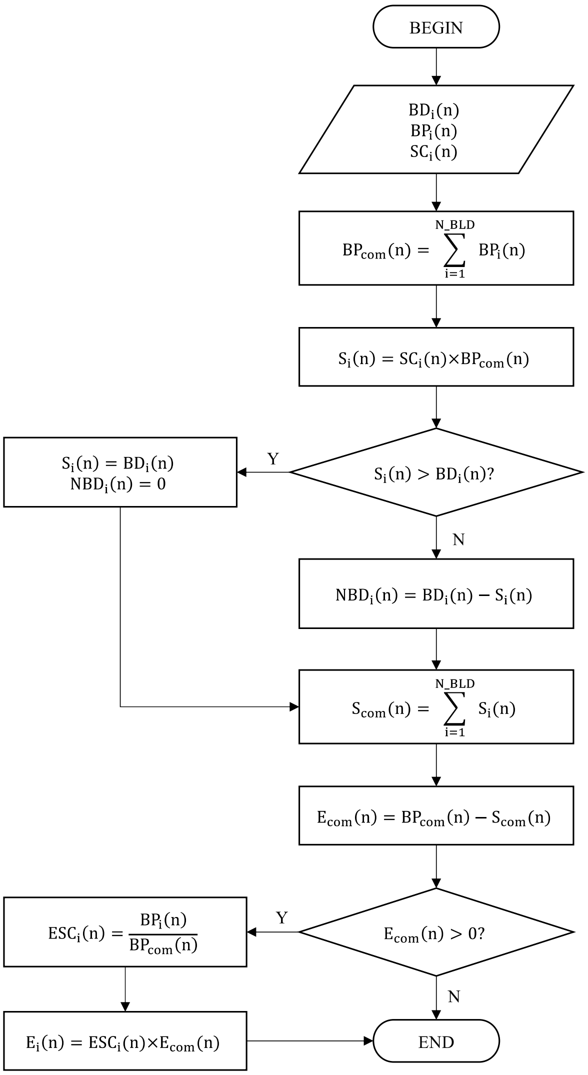

Fig. 5. REC energy sharing algorithm.

Table 4
Inputs and outputs for the REC sharing algorithm.

Parameter	Description	Unit
i	Reference to each REC member	–
com	Reference to the REC as a whole	
n	Any given time-step considered for the operation	–
N_BLD	Total of REC members	–
Inputs		
BD	Building demand in REC operation	kW
BP	Building production available for sharing	kW
SC	Energy sharing coefficient	%
Mid-Process		
ESC	REC Export sharing coefficient	%
Outputs		
S	Power to share to each REC member	kW
NBD	Building demand after sharing process	kW
E	Power exported attributed to each REC member	kW

3. Results and analysis

The REC performance for the different scenarios is compared considering the annual cost with electricity import (C_{imp}), the amount of electricity imported (E_{imp}), the total of electricity shared among the members (E_{sh}), and the amount of electricity exported to the distribution grid (E_{exp}). All simulations were carried out using MATLAB™ software tool.

3.1. Considered scenarios

This study considers the following scenarios: i) baseline operation, representing the current individual energy consumption of the buildings (no PV systems installed); ii) individual operation with PV systems installed at each building according to the information provided in Section 2.2; iii) REC operation with buildings able to perform individual self-consumption and sharing only the surplus of the locally generated energy; and iv) REC operation with buildings performing collective self-consumption of the total electricity generated by the considered PV systems.

Additionally, to assess the impacts introduced by different energy sharing options on the performance of the referred REC, this study considers three types of energy sharing coefficients in Scenarios 3 and 4, which covered the possibilities offered under the Portuguese legislation described in Section 2.3. The first one refers to a 25% fixed and equal coefficient (FEC), so all members receive the same amount of energy surplus. The second type refers to a fixed and proportional coefficient (FPC). In this case, the amount of energy surplus received by each member is proportional to its relative annual energy consumption (comparing to the annual consumption of the four buildings). The last one refers to a variable sharing coefficient (VSC), defined at each 15-min time-step *n*, according to the relative energy consumption of each member, as described by Equation (4), where $VSC_i(n)$ refers to the variable sharing coefficient attributed to building *i*, while $BD_i(n)$ represents the individual power demand of each building and N_BLD is the number of REC members. Equation (4) is therefore a particular case of the sharing coefficient described by Equation (3), with a single ponderation factor to be considered. Table 5 presents a summary of the considered scenarios.

$$\mathrm{VSC_i(n)} = \frac{\mathrm{BD_i(n)}}{\sum_{j=1}^{N\_BLD} \mathrm{BD_j(n)}} \tag{4}$$

3.2. Individual operation without PV systems

In this baseline scenario there is no local electricity generation, thus no sharing is available. For the calculation of the associated costs, the data gathered, and rules described in Ref. [28] are used. All the considered buildings have the following characteristics:

Table 5
Scenarios summary.

3.2) Scenario 1: Individual operation (without PV systems).	3.3) Scenario 2: Individual PV Self-consumption (without REC association).
3.4) Scenario 3: REC operation with individual PV self-consumption and sharing of energy surplus.	3.5) Scenario 4: REC operation with collective PV self-consumption.
Energy Sharing Coefficients for REC scenarios: • Fixed and equal (FEC) • Fixed and proportional to the annual building consumption (FPC) • Variable for each measured 15-min. time-step, proportional to each building consumption (VSC)	

- The voltage level for electricity supply at the energy meter level, considered for the tariff application, is 400 V (line-to-line voltage);
- The daily billing cycle is applied, which means that the instants of the application of each tariff are constant during the entire week (there is no difference between the tariffs on weekdays and weekends);
- There are four different tariffs to be applied during each daily cycle, namely: peak, half-peak, normal off-peak and super off-peak.

Table 6 shows the periods of each tariff, and the corresponding values.

Additionally, for the calculation of the electricity costs, a fixed tariff (24.64 €/month) was considered, and a contracted power tariff (0.69 €/kW.month) applied, together with a value for the power demand in peak hours, calculated as the average of the demand power during peak hours (15.64 €/kW.month). These values were obtained by the analysis of an electricity bill from one of the buildings and applied to all of them. The considered metrics for the assessment of Scenario 1 are presented in Table 7.

3.3. Individual operation with PV systems

In this scenario, there is energy export ($E_{\exp}$) due to the mismatch between consumption needs and energy locally generated by the PV systems described in Section 2.2. The power export is calculated by using the algorithm showed in Fig. 3. Table 8 shows the indicators for this scenario. The amount of energy self-consumed by each building (E_{sc}) is also presented. There is a natural decreasing on the imported energy and associated costs, due to the energy generated by the PV systems, which is partially used to fulfil the building user's needs. The referred mismatch results in the total export of 34% of all electricity generated by the local sources. The remaining 66% refers to the generation self-consumed by the buildings.

3.4. – REC operation with sharing of individual generation surplus

This configuration implies that buildings prioritize individual self-consumption of local generation, being the eventual surplus shared among the members that, on a given time-step, were not able to fulfil their electricity needs with the respective PV systems. Therefore, the amount of available energy to the REC sharing must be calculated at every time-step, by subtracting, from the generated energy, the energy self-consumed by the building.

As aforementioned, three different sharing coefficients are considered for each one of the REC configurations. Table 9 shows the calculated values for the considered fixed sharing coefficients (values for the variable sharing coefficient (VSC) are not depicted here given that a different value is defined for each one of the 35,040 (96 × 365) time-steps).

The operation results are shown in Table 10, in which, for each indicator and energy sharing coefficient for a specific building, values marked in a dark grey indicate the worst performance, light grey indicate the best performance and the remaining grey values indicate a performance between the previous ones. Note that the amount of energy self-consumed (E_{sc}) in this scenario is the same as in Scenario 2, due to the individual self-consumption occurring prior to the sharing process. The values of self-consumed energy can be seen in Table 8.

3.5. – REC operation with collective self-consumption

The main characteristic of this scenario is that the PV systems are not used for individual self-consumption before the sharing process takes place, resulting in more energy to be shared among REC members. The remaining process regarding the energy sharing is the same as in the previous scenario, including the value of both fixed coefficients. Table 11 summarizes the performance indicators and the same colour pattern of Table 10 is applied.

3.6. Discussion

The collected results show that the operation as a REC (Scenarios 3 and 4) conducts to lower energy costs and less imported energy, when compared to their individual operation (Scenario 2). This results from energy sharing among REC members, when considering the possibility of individual self-consumption (Scenarios 3) or collective self-consumption (Scenarios 4), which also leads to less energy exported to the distribution grid. Scenario 1, where no PV systems are available, is the one with the worst performance in terms of costs

Table 6
Daily cycle tariff intervals and values.

Winter legal hours		Summer legal hours	
Peak	09h00 – 10h30	*Peak*	10h30 – 13h00
(0.21 €/kWh)	18h00 – 20h30	(0.21 €/kWh)	19h30 – 21h00
Half-peak	08h00 – 09h00	*Half-peak*	08h00 – 10h30
(0.13 €/kWh)	10h30 – 18h00	(0.13 €/kWh)	13h00 – 19h30
	20h30 – 22h00		21h00 – 22h00
Off-peak	06h00 – 08h00	*Off-peak*	06h00 – 08h00
(0.09 €/kWh)	22h00 – 02h00	(0.09 €/kWh)	22h00 – 02h00
Super off-peak	02h00 – 06h00	*Super off-peak*	02h00 – 06h00
(0.08 €/kWh)		(0.08 €/kWh)	

Table 7
Scenario 1 indicators.

Bld	C_{imp} [€]	E_{imp} [kWh]
1	8,353	37,904
2	53,902	258,350
3	7,446	33,289
4	8,545	36,392
Total	**78,246**	**365,935**

Table 8
Scenario 2 indicators.

Bld	C_{imp} [€]	E_{imp} [kWh]	E_{exp} [kWh]	E_{sc} [kWh]
1	6,685	30,157	1,994	7,747
2	33,673	165,900	23,225	92,450
3	4,643	21,102	9,054	12,187
4	4,149	16,781	35,224	20,154
Total	**49,150**	**233,940**	**69,497**	**132,538**

Table 9
Fixed sharing coefficients.

Bld	FEC (%)	FPC (%)
1	25	10.35
2	25	70.58
3	25	9.10
4	25	9.97

and imported energy. To support this analysis, Fig. 6 shows the daily average demand profile for all buildings, scenarios, and sharing coefficients (fixed and equal sharing coefficients in Fig. 6a, fixed and proportional sharing coefficients in Fig. 6b, and variable sharing coefficients in Fig. 6c). In this figure, Scenario 2 is added for the sake of comparation with the REC operation (since no energy sharing coefficients are applied), while Scenario 1 is not considered given the inexistence of local generation.

Regarding the energy sharing coefficients, one can conclude from Tables 10 and 11 that selecting the best option depends on the considered scenario and demand profile of each building. However, it is observed that the VSC leads to a better REC performance, from a collective point of view, with lower energy costs and less energy imported. Nevertheless, when individual self-consumption is allowed for the REC members (Scenario 3), there is a lower advantage from choosing the VSC, due to the individual benefit already achieved by the individual self-consumption and less energy needs when the sharing process happens. This leads to an improved sharing process, specifically when the VSC is applied. Additionally, Scenario 4 presents the downside of inhibiting individual self-consumption from the PV systems installed on each building, which, considering investment costs, can bring challenges to engage members in selecting a REC operation with collective self-consumption over a REC operation where individual self-consumption is allowed (Scenario 3). In this case, considering a VSC according to other factors besides the buildings' demand (e.g., investment costs) might benefit the engagement process (see Equation (3)).

Other important aspect to consider is the difference on the buildings' energy needs and local generation. Table 12 shows the annual generation and demand for each building, together with the ratio between these two values, for each building. The weight of *Bld#*2 on the sharing process is higher in any REC configuration due to its larger energy needs and therefore it benefits the most from the VSC, as can it be seen in Fig. 7, which presents the individual performance of each building per scenario (*Bld#1* in Fig. 7a, *Bld#2* in Fig. 7b, *Bld#3* in Fig. 7c, and *Bld#4* in Fig. 7d). *Bld#*1 and *Bld#*3, with the lowest energy demand, show the best results when the FEC is applied as the amount of energy to be shared is not impacted by the energy needs of other members. However, even with this energy demand unbalance, the variable sharing coefficient can improve the performance of the whole REC comparing with the other possibilities of energy sharing (see Fig. 6a–c).

It is important to note that the operation framework described here refers only to financial operations, conducted by the DSO, after each monthly billing period throughout the year. Regardless the energy sharing framework, in every scenario of REC operation there is the same amount of energy involved. The main difference is the way the sharing is carried out, which impact the performance in terms of energy costs.

4. – Conclusions and future work

The study reported in this paper focus the assessment of different energy sharing strategies to be applied in Renewable Energy Communities (RECs) across Europe based on energy sharing coefficients defined according to existing national legislation, as it is the case of Decree-Law 15/2022 in Portugal. This involves simulating a REC over a year, utilizing real consumption and meteorological

Table 10
Scenario 3 indicators.

Bld	C_{imp} [€]	E_{imp} [kWh]	E_{sh} [kWh]	E_{exp} [kWh]
	(a) Fixed and equal sharing coefficients (25%)			
1	6,300	28,118	2,039	1,830
2	32,780	161,454	4,446	22,720
3	4,513	20,375	727	7,900
4	4,138	16,715	67	29,769
Total	**47,731**	**226,662**	**7,279**	**62,219**
	(b) Fixed and proportional sharing coefficients			
1	6,446	28,913	1,244	1,657
2	31,684	155,677	10,223	22,871
3	4,580	20,752	351	6,999
4	4,145	16,754	28	26,125
Total	**46,855**	**222,095**	**11,846**	**57,652**
	(c) Variable sharing coefficients			
1	6,275	28,005	2,152	1,594
2	31,347	153,876	12,024	22,545
3	4,527	20,454	649	6,570
4	4,145	16,756	26	23,937
Total	**46,294**	**219,091**	**14,851**	**54,646**

data, and implementing various sharing coefficients, both fixed and variable. Additionally, this study considers two distinct models for the REC operation to further understand the benefits offered to all members. The first model allows buildings to conduct individual self-consumption, while only sharing generation surplus. The second model refers to a scenario where only collective self-consumption is allowed.

The collected results show that the benefits offered to each member depend on the considered model for the REC operation and on the individual energy needs. Fixed energy sharing coefficients tend to be more interesting to buildings with lower energy needs, while larger consumers take more advantage from the variable energy sharing coefficient. However, it can be concluded that this last coefficient leads to the best performance when considering the entire REC for both models of operation. This study also shows that the benefits for buildings operating as a REC are evident when comparing to their individual operation without generation surplus sharing, with savings reaching 44% for the building with the highest energy demand.

Further research on different case studies, such as mixed-purpose or net-zero energy buildings joining the same REC, or the impact of energy storage equipment on the community's performance, is needed. Additionally, new formulations for the variable energy sharing coefficients should be studied. On a scenario of renewable energy communities' significant market growth, further investigation is needed on how to mitigate possible challenges imposed by RECs on distributions grids, such as power congestion or voltage rising problems, due to the integration local energy generation units.

Author contribution statement

Humberto Queiroz: conceived and designed the experiments; performed the experiments; analysed and interpreted the data; contributed reagents, materials, analysis tools or data; wrote the paper. ui Amaral Lopes: conceived and designed the experiments; analysed and interpreted the data; wrote the paper. João Martins, Luís Fialho: analysed and interpreted the data; contributed reagents, materials, analysis tools or data; wrote the paper. Filipe Neves Silva: analysed and interpreted the data; wrote the paper. Nuno Bilo: contributed reagents, materials, analysis tools or data; wrote the paper.

Table 11
Scenario 4 indicators.

Bld	C_{imp} [€]	E_{imp} [kWh]	E_{sh} [kWh]	E_{exp} [kWh]
	(a) Fixed and equal sharing coefficients (25%)			
1	5,491	24,056	13,848	5,126
2	43,448	211,161	47,189	60,844
3	4,014	17,883	15,406	11,178
4	4,291	17,429	19,057	28,906
Total	**57,244**	**270,529**	**95,500**	**106,084**
	(b) Fixed and proportional sharing coefficients			
1	6,045	26,888	11,015	2,968
2	31,006	152,580	105,770	35,249
3	4,777	21,765	11,524	6,473
4	5,900	24,638	11,848	16,738
Total	**47,728**	**225,871**	**140,157**	**61,428**
	(c) Variable sharing coefficients			
1	6,157	27,344	10,560	2,641
2	30,201	148,328	110,022	31,358
3	4,828	21,848	11,441	5,758
4	5,121	21,571	14,915	14,891
Total	**46,307**	**219,091**	**146,938**	**54,648**

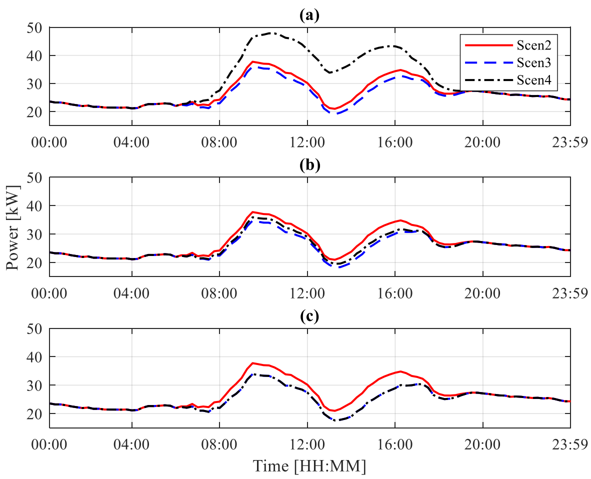

Fig. 6. Normalised REC average load diagram: (a) FEC; (b) FPC; (c) VSC.

Table 12
Annual generation and demand, together with the ratio between these metrics.

Bld	Generation [kWh]	Demand [kWh]	Generation to demand ratio [%]
1	9,741.03	37,903.75	25.70%
2	115,674.68	258,350.00	44.77%
3	21,240.85	33,289.00	63.81%
4	54,928.56	36,392.25	150.93%
Total	**201,585.12**	**365,935.00**	**55.09%**

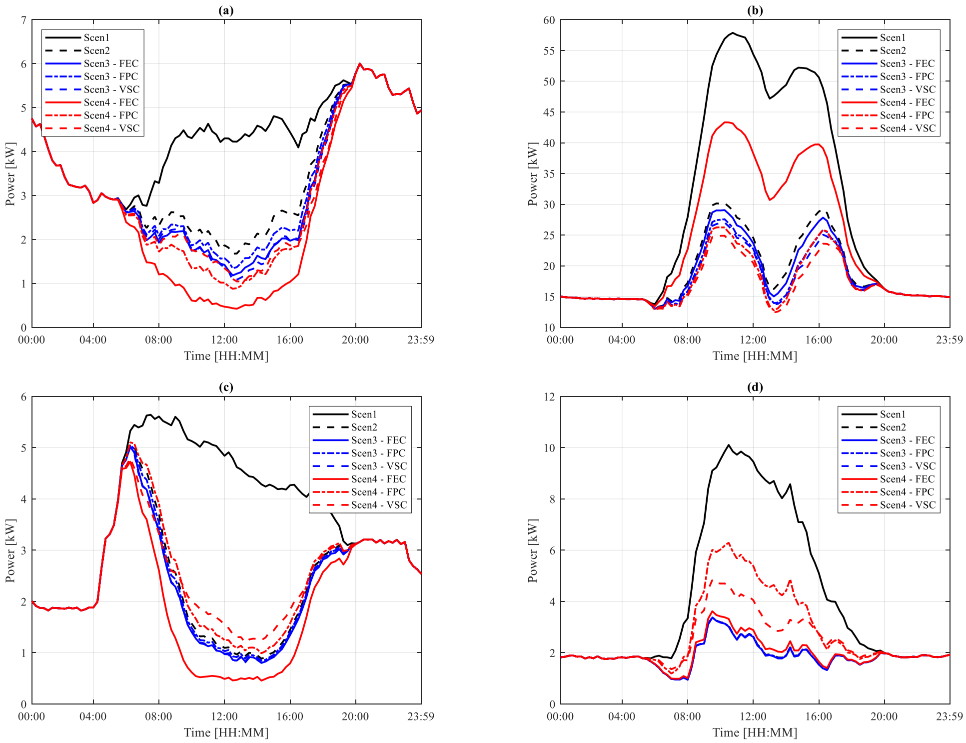

Fig. 7. Buildings' daily average demand profile per scenario: (a) Bld#1; (b) Bld#2; (c) Bld#3; (d) Bld#4.

Data availability statement

The data that has been used is confidential.

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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