



Original research article

## Fair shares or smart savings? Exploring business models, justice and efficiency trade-offs in Portuguese energy communities

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### ABSTRACT

Energy communities are increasingly playing an important role in citizen engagement during energy transitions. However, the functional benefits for participants are heavily reliant on how energy and profits are shared, which are dictated by regulations. While optimizing trade-offs can prove significant in making energy community projects viable, related techno-regulatory innovations on energy-sharing mechanisms still require in-depth analysis. A key unresolved issue is how to balance justice considerations with model attractiveness by aligning members' perceptions of fair redistribution with optimal energy utilization. This study investigates the interplay between sharing and metering mechanisms and their respective advantages and disadvantages, using the Portuguese case study as an example. Four hypothetical scenarios related to the implementation of European directives into Portuguese national law are analysed to quantify trade-offs between self-consumption, self-sufficiency, and participant equity. The findings demonstrate how different energy-sharing and metering mechanisms can influence resource allocation, benefit distribution, and financial sustainability. Each of these scenarios reveals that there is no one-size-fits-all solution. The consumption-proportional sharing maximizes self-consumption and self-sufficiency indexes at the community level but fails to uphold principles of energy justice, as it disproportionately benefits high-consuming members. In contrast, the fixed coefficients sharing ensures a distribution proportional to each member's monetary investment but leads to lower efficiency. These findings underscore the socio-economic implications of techno-regulatory innovations and the need to reconcile equity and efficiency. The study offers guidance to policymakers in designing fair and effective frameworks, reducing the risk of unintentionally obstructing energy community development due to impaired economic viability.

### 1. Introduction

Renewable Energy Sources (RES) are increasingly recognized to be one of the main pillars to mitigate global climate change while decreasing the dependency on fossil fuels. The decreasing cost of RES technologies has spurred investment in decentralized energy systems, driving the evolution from traditional hierarchical electrical grid structures to more flexible and distributed models. This has facilitated the emergence of energy communities, where Peer-to-Peer (P2P) energy sharing is gaining traction to optimize resource utilization and enhance the financial viability of these projects [1,2].

P2P energy sharing enables consumers to collaborate in a

decentralized manner, potentially bypassing the control of the centralized electrical grid i.e., a traditional consumer turns into a prosumer, an entity or party which can consume the electricity they produce. By sharing their distributed energy resources, such as small-scale generation and storage, prosumers can reduce the financial costs associated with their electricity bills by maximizing local energy utilization [1]. Besides being proven effective in benefiting both prosumers and the electrical grid, P2P models offer advantages in terms of reduced complexity, and improved privacy, while simultaneously alleviating grid stress associated with the increasing penetration of distributed RES [3,4].

While offering a promising avenue for decentralized energy

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production and consumption, the successful implementation of energy communities also relies on economic feasibility, especially in the context of compensation policies for surplus energy. Besides P2P trading, other policies such as net-metering and net-billing are being explored to enhance the economic benefits of decentralized energy systems [2,5,6]. Net-metering and net-billing are electricity policies designed to allow grid-connected customers who generate energy to offset their consumption and receive compensation for excess energy injected into the grid [5]. In net-metering, surplus energy is converted to "energy credits" maintaining equal value whether consumed or exported [5]. The net-billing compensates for excess energy at a monetary value, often at a lower tariff than the grid consumption rate, which can be either fixed (fixed feed-in tariff) or variable (time-varying feed-in tariff) [2,7].

RES are intermittent resources and therefore require supplementary systems to adjust the necessary real-time balance to match generation and consumption. Net-metering, net-billing, and P2P are extremely important policies to maximize the self-consumption and the self-sufficiency indexes, not only in an individual way (prosumer installation) but also collectively (energy community). The Self-Consumption Index (SCI) is the ratio between the total energy produced locally and the portion of that energy that is consumed locally. The Self-Sufficiency Index (SSI) is the ratio between the total energy consumed and the portion of that energy that is consumed locally [8,9].

In the context of pursuing a fast and just energy transition, energy communities are highlighted for their pivotal role in addressing energy injustices and reducing energy poverty by promoting social inclusion and equity [10,11]. However, the maximization of justice with energy community members must result from a legislative framework that supports them, particularly in promoting an increase in both the SCI and SSI. In this context, the European Union (EU) is actively pursuing a legislative framework that enables renewable energy adoption, embodied by the European Green Deal, to achieve a more just and democratic low-carbon energy transition [12]. To meet such objectives, key policy frameworks are set in place, such as the EU Clean Energy Package [13], which along with other EU energy policies provides a crucial legislative framework for the two regimes of energy communities being implemented in Member States, i.e., the Citizens Energy Communities (CEC) and the Renewable Energy Communities (REC) [14].

Two European directives, the Internal Electricity Market Directive [15] and the Renewable Energy Directive [16], provide the legislative foundations for fostering the successful development of REC [14]. However, its effective transposition into national law is paramount. Member States must prioritize concrete measures that empower energy communities and facilitate their engagement in the evolving energy market [14]. Due to their participatory and locally owned model, many Member States favour cooperatives as preferred structures for creating REC, even because energy cooperatives were already popular before the European directives' implementation [17]. Grounded in the three core principles of justice -distributional, recognition, and procedural-emerging research on energy justice highlights the critical need to prioritize equity within energy communities [18,19]. This approach emphasizes the need to ensure a fair distribution of benefits, acknowledging and addressing diverse community needs, and fostering inclusive, participatory decision-making.

Portugal's strong commitment to mitigate climate change is embodied by several governmental decisions and by its ambitious "Roadmap for Carbon Neutrality 2050" [20]. This comprehensive strategy envisions a just transition to a carbon-neutral economy by 2050, prioritizing social justice aspects, economic competitiveness, and synergistic benefits for public health and environmental protection [21]. By the beginning of 2021, only Portugal and three more Member States had their National Energy and Climate Plans linking REC to energy poverty mitigation [22]. The reason for choosing the Portuguese energy community legislation as a case study is threefold: (1) Portugal has a lot of untapped potential for renewables and strong civil society mobilization towards citizens' energy community [23]; (2) Portugal has been late

in implementing energy communities, thus much of the form this rollout will take is still to be decided/experimented [24]; and (3) the transposition from the EU directives to the national legislation is currently open to the possibility for pilot projects [25,26] which represents an opportunity to explore specific energy sharing scenarios in addition to those implemented. Aligned with EU objectives, in 2019, Portugal first transposed the European directives, i.e. the Internal Electricity Market Directive [15] and the Renewable Energy Directive [16], into its own law, resulting in the legal regime of self-consumption, Decree-Law no. 162/2019 [27], followed by its Regulation no. 373/2021 [28]. This energy self-consumption regime was the first attempt of Portugal to implement energy communities and incorporate the consumers into the energy markets. In 2022, the regime governing self-consumption was incorporated into the National Electric System's legal framework through the enactment of Decree-Law no. 15/2022 [25], thereby superseding the previous one. Subsequently, in the middle of 2023, the Energy Services Regulatory Authority (ERSE) introduced the Regulation 815/2023 known as the Regulation of Self-Consumption (RoSC) [26]. These policy changes opened doors for addressing technical-economic barriers related to the implementation of new energy-sharing models. Yet several policy measures are still needed to overcome the remaining set of barriers [29].

The European Federation of Citizen Energy Cooperatives (REScoop) pointed out that these barriers should have been addressed within 2 years of implementing the legislation, and assessed the progress of the Portuguese transposition as medium/low while also emphasizing that there are no cases of "best practice" within the EU, i.e., no member state attaining a high score [30]. The incomplete and non-compliant transposition of EU directives, coupled with the absence of regulatory oversight, leaves room for potential misuse. In this study, energy communities are defined (like by the European Commission) as "collective actions of citizens coming together to participate in energy system, taking ownership of their energy consumption" [31]. To align with this definition, the Portuguese legislative framework must be significantly enhanced to uphold autonomy, local ownership, and democratic participation in energy communities. Several European countries have already transposed the EU directives to implement energy communities, however, further research is necessary to identify optimal approaches that maximize benefits for energy community members, contributing to a just energy transition. It is therefore imperative to scrutinise Portuguese legislation and identify shortcomings in its transposition process. Achieving this requires a thorough understanding of the key pillars upon which this legislation is implemented, namely the energy metering, the energy sharing models, as well as the different types of installations that integrate the Self-Consumption Activity (SCA).

This paper explores the socio-economic implications of techno-regulatory innovations in energy communities and the challenges associated with them, by comparing the Portuguese regulatory framework with other Member States. The theoretical exercise proposed aims to contribute to understanding how the new regulations impact technical possibilities and thereby translate into trade-offs between equity, justice aspects (especially distributional justice), and practical considerations for the success of energy communities in Portugal. Following this introductory section, the literature review (Section 2) examines technical, social, and economic challenges related to energy justice in energy communities. The Portuguese regulatory framework for energy communities emerging from the transposition of EU directives is presented throughout Section 3 and four hypothetical REC scenarios are analysed under Section 4. Section 5 discusses the socio-economic implications derived from the techno-regulatory innovations of each model, as well as the limitations and opportunities within Portuguese policies for energy sharing, comparing Portugal with other Member States. Section 6 is the conclusion and evaluates how energy communities' pilot projects could leverage policy advancements by managing these trade-offs surrounding the question of energy sharing, such as questions of regulatory flexibility, energy efficiency, reducing energy

poverty, and fostering justice in renewable energy deployment through citizen engagement.

## 2. Background: Energy communities' challenges

In the energy transition, as new ways of energy production and consumption emerge, policy interventions can prevent the entrenchment of existing inequalities and promote justice aspects along the transitions [32]. Implementing energy communities presents a range of socio-economic implications derived from techno-regulatory innovations. Addressing them is essential for the successful deployment and sustainability of energy communities within the energy transition. Several Greek islands, including Kythnos, Ikaria, and Tilos, have successfully implemented local-scale energy innovation projects, yielding positive outcomes in various energy sectors and driving social change. In [33], the authors review the energy transition in these islands, highlighting how these examples and the rise of energy communities can offer socio-economic benefits to their members and public approval of renewable energy installations.

Having the opportunity to share energy with peers in a community (P2P) empowers citizens to have control over the energy produced and consumed, however, it poses risks. As reported by Tushar et al. [4], establishing P2P energy-sharing systems requires addressing techno-regulatory challenges to determine permissible market structures and ensure system stability and efficiency. Various studies have addressed optimizing the consumption of energy produced through renewable sources by using SCI and SSI as benchmarks to improve energy systems [34,35]. Such strategies lower the levelized cost of energy by maximizing the consumption of energy generated locally. In [36] a techno-economic model was applied to compare self-consumption potential in Spain under net-billing and net-metering. Key findings reveal that optimizing facility sizing based on load curves in net-billing can enhance profitability and maintain self-sufficiency levels similar to net-metering. However, bureaucratic delays and challenges in optimizing net-billing coefficients remain significant barriers to their implementation. The regulatory requirements for transitioning to net-billing, including hourly tariffs and smart meter deployment, impose additional financial burdens, thereby slowing broader adoption. Fioriti et al. [10] proposed a business model for aggregators in energy communities that seeks fair distribution of rewards, suggesting how economic incentives can help engage different stakeholders. Nevertheless, policymakers need to ensure equitable rewards and develop supportive market solutions for energy communities to thrive.

According to a recent European Commission report [11], energy communities can offer many advantages, such as the reduction of energy costs, as well as the inclusion of citizens in the energy transition by improving energy literacy, as envisaged by the EU Clean Energy Package [13]. However, these communities face significant social challenges, including procedural deficits in public engagement, particularly regarding fairness and trust [37], as well as issues of inclusion and fair distribution of benefits [38]. As Dudka et al. [39] observed in their study of 164 French energy communities, different models – full ownership, shared ownership, crowdfunding, and civic participation – have different implications for how justice is perceived by different members, how accountability is structured between members and their engagement in the community. The importance of justice and the perception of it is also a key social challenge as it ensures satisfaction among energy community members. In [40] the authors emphasize the importance of justice and accountability between members, arguing that members with an equal share should receive benefits proportional to their investment. Yet the trade-offs of these proportionalities are not often explored in the justice literature. Gjorgievski et al. [41] attempted to address these trade-offs by introducing a virtual net-billing approach that allows real-time energy distribution based on individual contributions while balancing justice principles and computational efficiency. The study evaluated how different energy-sharing models related to

different perspectives of justice and accountability between members, discussing trade-offs and aspects of economic efficiency at the community level.

Engaging communities and establishing public trust is crucial for building a successful, non-discriminatory energy system [37,42]. Sovacool et al. [43] highlight the distributional principle in energy justice stating that “how we distribute the benefits and burdens of energy systems is pre-eminently a concern for any society that aspires to be fair” (p.15). Distributive justice in energy communities involves ensuring that the benefits and burdens of energy transitions are shared fairly, particularly among vulnerable populations [38]. However, concerns remain regarding whether, and when, these benefits materialize [22]. Recent regulatory developments and new opportunities for energy communities, as discussed in this work, underscore the need to address pragmatic justice issues, particularly the trade-offs between equity, distributional justice, and efficiency. One key unresolved issue is how to balance justice considerations with model attractiveness by aligning members' perceptions of fair redistribution with optimal energy utilization. While the literature on the social acceptance of energy projects has primarily focused on large-scale solar photovoltaic initiatives [44], a more granular approach at the energy community level is needed to determine which trade-offs between energy justice, efficiency, and practicality are most acceptable to members.

While energy communities offer the possibility of local empowerment and support the energy transition through reduced costs and reliable energy access [40,45,46], their implementation also presents significant economic challenges, including funding difficulties, market integration issues, and the need for supportive regulatory measures [17,47]. According to Felice et al. [48], REC can reduce energy costs by 10-26 % and emissions by 5-13 % compared to traditional models. While REC aims at reducing energy costs, having energy-sharing models that enable energy justice at a local level, while also being economically efficient, is important for members. Particularly in places where energy costs are high, the energy cost reductions might be one of the main reasons for participation. For instance, policy decisions influencing how distribution grid-related costs are distributed, also influence the conditions that energy community members face regarding the P2P energy sharing models. These costs are not always proportionally divided across grid users, prompting policy discussions on aligning cost and benefit redistribution within the broader energy system and the energy community itself. Băra and Oprea [49] demonstrated how modelling can be used to balance energy community interests and optimize energy sales. However, the profitability of excess energy sales and distribution grid-related costs are influenced by policy choices, such as fiscal regulations and selling permissions [50]. Delina and Sovacool [51] already emphasized that justice principles and the speed of diffusion of sustainable innovations can positively co-evolve and reinforce each other. Goforth et al. [52] emphasizes the need for methods that directly integrate energy justice and equity to ensure equitable planning and operation of power systems. The authors also conclude that power systems often prioritize cost-minimization over energy justice considerations. For instance, a study in Ghana [53], highlights that stakeholders prioritize reliable electrification over environmental concerns, indicating that efficiency may sometimes overshadow other important subjects.

As such, increasing literature has focused on efficiency and equity trade-offs in REC energy sharing, as well as their implications for justice. Jenkins et al. [19] examine these trade-offs, particularly in how energy resources are distributed, and how resulting benefits and burdens are allocated. It highlights that an exclusive focus on efficiency, optimizing resource use, and reducing costs may neglect equitable outcomes, leading to systemic injustices. To resolve these tensions, the study advocates for a comprehensive systems approach that considers the entire energy chain and emphasizes procedural justice through inclusive decision-making, thereby promoting fairer distribution without compromising efficiency. Hanke et al. [22] pointed out the need for REC to balance technical efficiency with equitable access to energy efficiency

measures for underrepresented households. Addressing these gaps is essential for advancing towards a just and inclusive energy transition.

Portuguese energy communities are in their early stages, yet they hold significant potential for growth, particularly in renewable energy deployment [24]. Several studies in Portugal underscore the importance of community engagement in energy planning [40,45,46,54]. For instance, Pacheco et al. [45] highlight the importance of a participatory diagnosis to define energy transition pillars tailored to community needs. A case study of a REC in Amadora [55], suggests that when citizens see tangible benefits, such as reduced energy costs and environmental impact, they are more likely to engage and participate. Another study that integrates qualitative socio-economic storylines with quantitative energy modelling to enhance the robustness of long-term energy scenario development in Portugal highlights the need for participatory processes involving stakeholders to better capture diverse perspectives and improve decision-making in energy policy [54].

Although the literature provides insights into the successful implementation of energy communities in Portugal, significant gaps remain. Notably, on the understanding of balancing trade-offs between different business models of energy communities with regards to the optimisation of benefits [46]. Also, in Portugal, while there is a political interest for pursuing a clean energy transition, the actual realization of this transition depends on addressing broader socio-political and economic factors [56]. While the social benefits of REC, such as enhanced energy literacy, community engagement, and social cohesion, are well recognized, systematic frameworks for ensuring inclusive participation and addressing equity concerns are underexplored [42,57]. Campos [58] examines citizens' trust and information regarding renewable energy technologies and their impact on social acceptance through documentary analysis and a survey of 500 citizens. The study emphasizes that fragmented policies are inadequate for achieving a fast and democratic energy transition. Additionally, more empirical studies are needed to explore alternative energy compensation models, such as net metering and dynamic sharing schemes, which could better balance efficiency with equitable distribution of benefits [46]. These barriers are exacerbated by a strong focus on private ownership, which discourages joint investments and common asset ownership beyond the household level [38]. Future research should focus on developing robust methodologies that integrate techno-regulatory, social, and economic dimensions to inform policy reforms aimed at a just energy transition.

### 3. Case study description

Energy poverty is a societal issue that concerns the quality of life of many citizens. In Portugal, energy poverty is especially pronounced [29,59]. The decreasing cost of modular photovoltaic systems, coupled with the advent of energy communities' legislation, has driven an increased deployment of solar energy at a national level, making REC a strategy for mitigating energy poverty and fostering sustainable energy solutions. The national legal regime for SCA –which enabled the energy community's framework– is established by Decree-Law no. 15/2022 [25] and regulated by Regulation no. 815/2023 [26]. This law introduces some concepts and models, e.g. (1) the concept of geographic proximity; (2) the concept of a CEC; and (3) the inclusion of two new energy-sharing models [25], which demonstrate the shifting of the national electric system from a centralized energy production system to a hybrid, more decentralized model based on local production. It also opens the country to active management of smart grids, ensuring the active participation of prosumers in decentralized energy markets.

Portuguese legislation states that the SCA can be performed individually, or collectively. Individual self-consumption occurs when a single energy generation unit (as a photovoltaic unit) is associated with one electricity consumption installation. On the other hand, the self-consumption of energy in a collective way takes place when the energy produced by one or more generation units is self-consumed by two or more consumption installations, as long as they cover the geographic

proximity requirements. This concept of proximity translates the maximum geographical distance in SCA between an energy generation unit and the consumption installations that it supplies, which in Portugal varies according to the voltage levels [25]. However, there are three ways to perform SCA in a collective way in Portugal: (1) via REC; (2) via CEC; or (3) via a simplified way named Collective Self-Consumption (CSC) [25,40]. In the CSC, it is mandatory to stipulate a responsible representative, known as the Collective Self-Consumption Manager Entity (CSCME), which can either be one of the prosumers or an independent entity tasked with operational functions. The rules of the CSC are applied to both types of energy communities, where differences are associated to the method of organization. REC and CEC are legal entities established through the open and voluntary participation of their members, who may be natural people or legal entities. This legal entity is also responsible for carrying out the functions of the CSCME. The main distinction between these two types of energy communities is their associated energy production sources: CEC can consume, aggregate, and store energy regardless of whether the primary source is renewable or not. In contrast, REC offer the advantage of providing environmental benefits, alongside the economic and social advantages [25,26]. Table 1 resumes the main differences highlighted by the Portuguese legislation between energy communities and CSC.

Regulatory ambiguities, combined with limited energy literacy, hinder individuals and communities from understanding the requirements and procedures needed to select the optimal model, whether a CSC, a REC, or a CEC [38,60]. Consequently, it is crucial to examine the energy-sharing models and their effects on the different installations involved in the SCA, where energy metering plays a crucial role [46]. To evaluate the socio-economic implications of techno-regulatory innovations in energy communities, it is essential to identify the gaps in the current legislation.

#### 3.1. Installations participating in the self-consumption activity (SCA)

To simplify the complex and hybrid behaviour of the installations participating in the SCA, which sometimes receives energy from the grid (consume), and other times injects energy into the grid (produce), ERSE adopted new designations [26,28], i.e.: (1) Production Installation (PI); (2) Storage Installation (SI); and (3) Consumption Installation (CI) [26]. However, a CI can be one of the four variants depending on its characteristics, i.e., a simple CI, a CI with an energy generation unit, a CI with storage, and a CI with an energy generation unit and storage [26]. Table 2 summarizes the description of the installations participating in SCA [26,61] and Fig. 1 illustrates how these installations function together.

#### 3.2. Energy metering

Smart meters play a crucial role in the implementation of SCA, as they are responsible for measuring both the energy produced and

**Table 1**  
Main differences highlighted by the Portuguese legislation between Energy Communities and Collective Self-Consumption [table made based on information from references 25, 26].

	Energy communities	CSC
Legal Nature	Legal entity (as an energy cooperative)	Organization of two or more self-consumers
Responsibility for Legal Obligations Management	Legal entity (energy community by itself)	All CSC self-consumers
Rules	Legal entity (energy community by itself)	CSCME
Open and Voluntary Membership	Legal entity's statutes, or internal regulation	CSC internal regulation
	Mandatory	Not mandatory

**Table 2**

Description of the installations participating in Self-Consumption Activity (SCA), introduced by the national Energy Services Regulatory Authority (ERSE) in the Regulation of Self-Consumption (RoSC), and depending on its use of the grid, i.e., use of internal grid and/or distribution grid.

Installation	Description
PI	Electricity production installation for SCA directly connected to the distribution grid.
SI	Electricity storage installation participating in SCA directly connected to the grid (internal or distribution).
CI	Electricity consumption installation participating in SCA.
CI with generation unit	CI with an integrated energy generation unit associated and directly connected through its internal grid.
CI with storage	CI with an integrated storage associated and directly connected through its internal grid.
CI with generation unit and storage	CI with integrated energy generation unit and storage associated and directly connected through its internal grid.

consumed. For instance, through their bidirectional features it is possible to determine the difference between the energy produced and the energy consumed and, in case of energy surplus, determine the amount of energy available to be shared, as well as the resources needed from the distribution grid. In Portugal, the match between energy production and consumption is made in quarter-hour periods by the Distribution System Operator (DSO). Any surplus energy is managed through a net-billing scheme where prosumers have several options: (1) inject into the distribution grid at zero profit; (2) store to use later through a SI; or (3) sell via bilateral contracts on the electricity market through specific vendors [62].

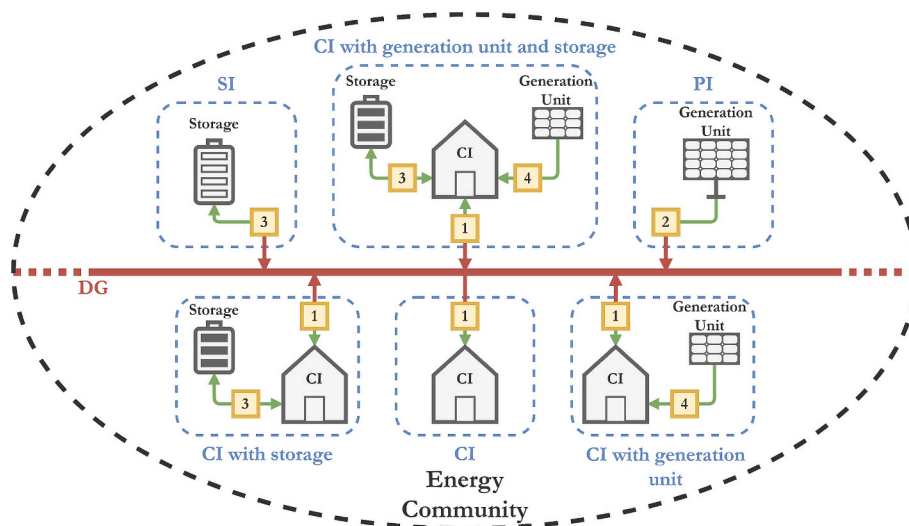
Increasing the number of smart meters, and their placement at strategic points on the distribution grid infrastructure, represents a step forward towards the digitalization of the energy system and its progress to a smart electrical grid. In this context, the RoSC establishes Mandatory Metering Points (MMP), illustrated in Fig. 1, between the following connection points: (1) the CI with the internal or distribution grid, represented by MMP 1; (2) the PI with the internal or distribution grid, represented by MMP 2; (3) the SI with the internal or distribution grid, represented by MMP 3; and (4) the generation unit with the CI whenever its power is greater than 4 kW, represented by MMP 4 [25].

During the SCA, when one or more installations are producing energy, the total energy produced (and available to share collectively) is the aggregation of the energy produced and available to share by each installation, which is accounted for by its own smart meter in an MMP. However, the energy produced (and available to share) of each installation can be accounted for by two different methods. In the first method, which prioritizes collective production (PCP), the amount of energy produced and available to share for each installation is obtained from MMP 2 and MMP 3. This means that all the energy produced by the installations (PI and/or SI) is aggregated by the energy community to be shared with all its members.

The other method prioritizes individual production (PIP) and, as such, the consumption of energy produced inside each installation. In this case, the account of energy produced and available to share is obtained from MMP 1, using the MMP 4 as a secondary meter to account for the energy produced (applied to CI with generation unit and/or storage). This means that the energy produced by each CI is only eligible for sharing and therefore aggregated by the REC if the CI produces more energy than the energy that is consumed in each quarter-hour period. That is, generated energy has to be self-consumed locally before being eligible for sharing. The Portuguese legislation regarding energy communities also limits the number of participants of REC [46]. Another important consideration in energy metering is the energy transfer across the distribution grid infrastructure, as every kWh used incurs costs related to distribution. These costs are calculated by MMP 1, 2 and 3 which are directly connected to the distribution grid [25].

### 3.3. Energy sharing models

Within an energy community, the energy produced collectively can be shared in percentages by their associated installations (usually CI) through different sharing models. It must be noted that an installation participating in SCA is only eligible to receive a portion of the energy produced collectively and available to share when its predominant behaviour is consuming. For instance, the example of a CI with a generation unit. In periods of fifteen minutes where the unit energy production (accounted for MMP 4) is greater than the CI consumption (accounted for MMP 1), that installation behaves like a production installation. As such, it is not eligible to receive the energy produced collectively [25,26]. The selection between the energy-sharing models is



**Fig. 1.** Example architecture of an Energy Community, dashed black line, constituted by one of each type of installations participating in Self-Consumption Activity (SCA). From left top to right bottom: Storage Installation (SI); Consumption Installation (CI) with energy generation unit and storage; Electricity Production Installation (PI); CI with storage; CI; and CI with energy generation unit. The yellow boxes represent the Mandatory Metering Points (MMP). The green lines represent the internal grid, and the red lines represent the distribution grid. Arrows identify possible energy flows [figure made by the authors]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

a matter of great importance in an energy community project, as the choice among these different models will define the economic viability of the project. Therefore, the goals and conditions of each project must be considered before choosing between them, as each model has its own particularities.

In Portugal, while the RoSC regulates four distinct ways to share the energy produced collectively, only two of them are used in practice, namely the fixed and consumption-proportional coefficients. The energy-sharing model based on a fixed coefficient (1) is the simplest one. It involves distributing the energy produced based on pre-determined percentages defined by the CSCME. This means that each installation participating in SCA will receive a specific percentage of the total energy produced, and available to share, during a quarter-hour period. In this case, when an installation participating in SCA behaves as a producing installation, the portion of energy that would be associated with that installation is shared by the remaining ones in proportion to their sharing coefficients [25]. The energy-sharing model with consumption-proportional coefficients (2) involves distributing the energy produced collectively based on the consumption measured at all installations, in quarter-hour periods. This implies that the CSCME lacks authority over the sharing coefficients since they are determined by the consumption levels of each installation [25].

The remaining energy-sharing models are the Hierarchical (3) and Dynamic (4). They were introduced later in the RoSC, and they can only be implemented in energy communities' pilot projects in collaboration with the DSO. However, none of them have been implemented yet due to the technical complexities required for both the DSO and the CSCME. The hierarchical energy sharing model (3) consists of defining a hierarchical structure, organized into groups (up to three [63]) of installations participating in SCA, i.e., SI, PI, and CI. The sharing of energy is performed in two interactions. In the first interaction, the energy produced is shared only with installations belonging to the same group. During the second one, the energy available for sharing, which remains after the application of the first interaction, can be shared among all the installations whose consumption demands were not fully met during the first interaction. Once the hierarchical structure is communicated to the DSO, the energy-sharing models within and between groups can be defined, i.e., can be chosen between the fixed and consumption-proportional coefficients [25]. The dynamic model (4) uses the same principle as the fixed coefficients to share energy, with the particularity that the CSCME only provides those coefficients to the DSO afterward, i.e., after energy consumption. This allows the CSCME to balance the consumption and production of each installation participating in SCA only after receiving the consumption and generation data from the DSO, defining the fixed coefficients to be applied afterwards [25].

#### 4. Analysis of the four hypothetical renewable energy community scenarios

Current regulations for REC are predominantly focused on photovoltaic systems and energy-sharing models [30]. According to the Portuguese legislative framework REC offers the potential for significant savings to its members when compared to individual self-consumption [64], where the surplus energy cannot be shared within the neighbourhood. However, designing a REC project involves deciding among several key features, including how the total energy produced and available to share is accounted for, which model is used to share that energy, and which justice and efficiency aspects to prioritize. In the national net-billing scheme, the energy surplus sale tariff is extremely lower than the consumption tariff, which means there are few economic benefits to overproducing energy when compared to a net-metering scheme [7]. This aspect underscores the critical importance of maximizing both SCI and SSI, as these indexes provide valuable insights into the efficiency and sustainability of a REC. Besides that, analysis of distributional energy justice is also needed to assess the equity of each REC member in accessing endogenous resources.

This section presents four hypothetical REC scenarios designed with representative premises to facilitate a straightforward analysis. The aim is to explore the interrelated technical, social, and economic challenges of different energy metering methods in combination with distinct energy-sharing models. The scenarios were constructed to explore the complexities and implications of P2P, offering insights into the potential impacts of various metering and sharing approaches associated with the current Portuguese legislation.

In order to carry out a balanced comparative assessment between the four hypothetical scenarios, the following premises must be considered: (1) each scenario has identical installations, i.e., four CI and two energy production systems –whether PI or generation units; (2) these installations have the same production and consumption patterns across all scenarios; (3) total energy generation matches total consumption in each scenario, which is the best condition to reach energy self-consumption and self-sufficiency; (4) scenarios are represented over a quarter-hour period; (5) each scenario is characterized by one of two energy metering methods (PCP or PIP) combined with one of two energy sharing models (fixed or consumption-proportional coefficients); and (6) each REC member invested the following percentage to buy the energy production systems: CI 1–40 %, CI 2–25 %, CI 3–25 % and CI 4–10 %. These assumptions result in the following primary data: Energy Produced Individually; Energy Consumed; Manager Entity Fixed Coefficients (only applied in the fixed coefficients model); and Investment Ratio. The remaining values, obtained from the primary data and according to the energy metering and sharing model used, are: Installation Behaviour; Energy Produced Collectively; Sharing Coefficients (depending on the model applied); Energy Allocated; Energy Self-Consumed; Energy Surplus; and Energy Supplied. Table 3 summarizes the data used to assess each scenario, presenting a description for each one.

In community initiatives, maximizing benefits for members equitably is crucial for successful adoption and enhancing the model's overall attractiveness [39]. Therefore, efficiency (e.g., maximizing SSI and SCI), fairness, and practical considerations are central to the design of energy community policies. If members incurring the costs do not

**Table 3**

Description of the data used to assess the four different practical scenarios of Renewable Energy Community (REC) implementation, and their respective units.

Data	Description	Unit
Energy Produced Individually	The total amount of energy produced individually.	kWh
Energy Consumed	The total amount of energy consumed individually.	kWh
Manager Entity Fixed Coefficients	Fixed coefficients, pre-defined by the CSCME, and communicated to the DSO. Applied to all installations.	%
Investment Ratio	Percentage of the product cost each member invested to buy the energy production system.	%
Installation Behaviour	Predominant installation behaviour. Producing when Energy Produced Individually is greater than Energy Consumed and consuming otherwise.	–
Energy Produced Collectively	The total amount of energy produced collectively, i.e., the total amount of energy produced and available to share.	kWh
Sharing Coefficients	The sharing coefficients are applied according to the sharing model defined. Applied to installations with consumption behaviour.	%
Energy Allocated	The amount of energy allocated according to the Sharing Coefficients, resulted from the Energy Produced Collectively.	kWh
Energy Self-Consumed	The amount of energy consumed from the Energy Allocated.	kWh
Energy Surplus	The amount of energy not consumed, from the Energy Allocated.	kWh
Energy Supplied	The amount of energy provided by an electricity supplier is required to satisfy the remaining consumption demand.	kWh

perceive fair benefit distribution, their willingness to participate may be adversely affected [29]. The Equity Disparity metric assesses the gap between the investment ratio – how much each member invested to buy the energy production system –, and the sharing coefficients applied according to the sharing model defined. Accordingly, each scenario’s outputs are evaluated based on three criteria: SCI, SSI, and Equity Disparity, calculated using Eqs. 1, 2 and 3, respectively.

$$\text{Self Consumption Index (\%)} = \frac{\text{Energy Self Consumed}}{\text{Energy Allocated}} \times 100 \quad (1)$$

$$\text{Self Sufficiency Index (\%)} = \frac{\text{Energy Self Consumed}}{\text{Energy Consumed}} \times 100 \quad (2)$$

$$\text{Equity Disparity (\%)} = \frac{|\text{Investment Ratio} - \text{Sharing Coefficients}|}{\frac{\text{Investment Ratio} + \text{Sharing Coefficients}}{2}} \times 100 \quad (3)$$

This exercise demonstrates the strengths and weaknesses of Portugal’s energy-sharing and metering models based on self-consumption, self-sufficiency, and equity disparity. The findings are directly derived from the modelling exercise, and although a year-long dataset with 15-min timestamps would provide more detailed insights into REC optimization (i.e. SCI, SSI and Equity Disparity), the study primary aim is to compare the four scenarios under the exact same conditions, where a period of 15 min approach, with the premises considered above, are effective to highlight the socio-economic implications derived from the techno-regulatory innovations. By portraying a 15-min interval of which conditions to achieve optimal levels of SCI and SSI are met, the study can focus on identifying gaps in the national legislation that hinder the equitable distribution of REC’ benefits.

#### 4.1. Scenario 1 (S1) - Prioritizing collective production and fixed coefficients

The first scenario (Fig. 2) illustrates a hypothetical implementation of a REC composed of two PI and four CI, where the total energy produced collectively and available to share is accounted for through the PCP method. To share the energy within the four CI is used the model of fixed coefficients. The key aspects of energy production, allocation, and consumption are outlined in Table 4, providing insights into the overall efficiency and equity of S1.

The results indicate that despite the energy produced being equal to the energy consumed at the REC level (30 kWh), the SCI and the SSI are both limited to 71.67 %. The suboptimal performance is primarily due to the inability of CI 3 and CI 4 to fully self-consume the energy allocated to them, resulting in surplus energy of 8.5 kWh. Regarding energy distributional justice, the fixed coefficients ensure that energy allocation is proportionate to the investment ratio. In this case, each CI’s investment directly corresponds to their assigned fixed coefficient, resulting in an

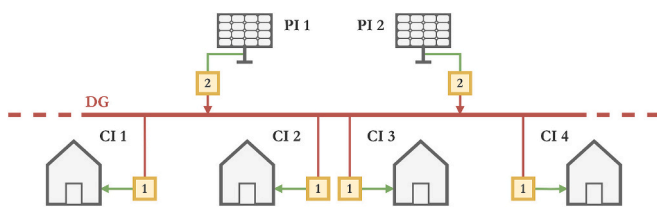


Fig. 2. Example architecture of a Renewable Energy Community, composed of two Production Installations (PI) and four Consumption Installations (CI), which prioritize collective energy production (PCP). Also represented are the Mandatory Metering Points (MMP) 1 and 2 to account for energy. The yellow boxes represent the MMP, the green lines represent the internal grid, and the red lines represent the distribution grid [figure made by the authors]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Equity Disparity of zero, indicating fair distribution based on investment. Another important consideration in S1 is that energy produced by the PI is shared among all CI via distribution grid infrastructure, which involves distribution grid usage costs for each member. However, while the equity among REC members is maintained by proportionate energy allocation, this scenario reveals efficiency challenges since the limited SCI and SSI values highlight the lack of adaptive energy allocation.

#### 4.2. Scenario 2 (S2) – Prioritizing collective production and consumption-proportional coefficients

S2 maintains an identical architecture to S1 (Fig. 2), but differs in its energy-sharing model, employing consumption-proportional coefficients. As shown in Table 5, during a quarter-hour period when energy production matches the consumption, both SCI and SSI reach 100 %. This is due to energy allocation being proportionally directed to each CI based on their individual consumption needs, thus effectively maximizing energy efficiency metrics when production and consumption are balanced.

Despite these high-efficiency metrics, there are notable issues regarding equity. The sharing model used in S2 lacks control over the energy allocated within each CI, resulting in inequity among participants. CI 1, being the largest consumer, receives the largest share of the collective production (66.6 % of the total available energy). This outcome is reflected in a considerable equity disparity among the members, as indicated by the metric, reaching 200 % in CI 4. This high disparity reveals that larger consumers disproportionately benefit from shared resources, potentially fostering inequality within the community. Thus, while the consumption-proportional coefficients excel in maximizing energy efficiency, they fail to uphold fairness among participants. As S1, S2 uses the PCP method, and therefore all the members have distribution grid-associated costs.

#### 4.3. Scenario 3 (S3) – Fixed coefficients and prioritizing individual production

The third scenario, S3, represents a hypothetical implementation of a REC with four CI, of which two (CI 1 and CI 2) are equipped with individual energy generation units (Fig. 3). In this scenario, the PIP method is used alongside fixed coefficients for energy sharing. CI 1 and 2 are both equipped with generation units, meaning the energy produced by them is primarily used to meet their own consumption, with energy surplus subsequently shared among other members. Consulting Table 6, only CI 2 produces energy for sharing (7 kWh). Therefore, during the assessed quarter-hour period, CI 2, being an energy provider, cannot receive energy, resulting in a recalculation of fixed coefficients for the remaining 3 CI.

The results indicate a higher SCI and SSI (82 %) demonstrating the efficiency advantage of the PIP method when combined with fixed coefficients. However, the increased efficiency comes with a disadvantage in terms of distributional equity. Equity Disparity is notably higher when compared to S1 which uses the same sharing coefficients. Considering the investment ratio made by each member, this scenario presents a notable issue regarding the distributional energy justice. Since CI 1 and CI 2 have integrated generation units, they consume most of the energy produced on-site, creating an imbalance in energy access for the other members.

Therefore, while the PIP method improves SCI and SSI, and reduces reliance on distribution grid infrastructure (leading to lower associated costs), it raises critical issues regarding fairness that must be addressed to ensure that all REC members equitably benefit from participation.

#### 4.4. Scenario 4 (S4) – Consumption-proportional coefficients and prioritizing individual production

The last scenario, S4, shares the same architecture depicted in Fig. 3

**Table 4**

Data of the hypothetical Renewable Energy Community Scenario 1 (S1) which prioritizes the collective energy production (PCP) and uses the sharing model based on fixed coefficients. The top four rows in light grey represent the primary data, and the bottom dark rows show the results of the evaluation criteria Self-Consumption Index, Self-Sufficiency Index and Equity Disparity for S1.

Data	PI 1	PI 2	CI 1	CI 2	CI 3	CI 4	REC
<b>E Produced Individually</b>	15	15	-	-	-	-	<b>30</b>
<b>Energy Consumed</b>	-	-	20	8	2	≈ 0	<b>30</b>
<b>ME Fixed Coefficients</b>	0	0	40	25	25	10	<b>100</b>
<b>Investment Ratio</b>	-	-	40	25	25	10	<b>100</b>
<b>Installation Behaviour</b>	Prod	Prod	Cons	Cons	Cons	Cons	-
<b>E Produced Collectively</b>	15	15	-	-	-	-	<b>30</b>
<b>Fixed Coefficient</b>	-	-	40	25	25	10	<b>100</b>
<b>Energy Allocated</b>	-	-	12	7.5	7.5	3	<b>30</b>
<b>Energy Self-Consumed</b>	-	-	12	7.5	2	0	<b>21.5</b>
<b>Energy Surplus</b>	-	-	0	0	5.5	3	<b>8.5</b>
<b>Energy Supplied</b>	-	-	8	0.5	0	0	<b>8.5</b>
<b>Self-Consumption Index</b>	-	-	100	100	26.67	0	<b>71.67</b>
<b>Self-Sufficiency Index</b>	-	-	60	93.75	100	0	<b>71.67</b>
<b>Equity Disparity</b>	-	-	0	0	0	0	-

**Table 5**

Data of the hypothetical Renewable Energy Community Scenario 2 (S2) which prioritizes collective energy production (PCP) and uses the sharing model based on consumption-proportional coefficients. The top three rows in light grey represent the primary data and the bottom dark rows show the results of the evaluation criteria Self-Consumption Index, Self-Sufficiency Index and Equity Disparity for S2.

Data	PI 1	PI 2	CI 1	CI 2	CI 3	CI 4	REC
<b>E Produced Individually</b>	15	15	-	-	-	-	<b>30</b>
<b>Energy Consumed</b>	-	-	20	8	2	≈ 0	<b>30</b>
<b>Investment Ratio</b>	-	-	40	25	25	10	<b>100</b>
<b>Installation Behaviour</b>	Prod	Prod	Cons	Cons	Cons	Cons	-
<b>E Produced Collectively</b>	15	15	-	-	-	-	<b>30</b>
<b>C-P Coefficient</b>	-	-	66.6	26.7	6.7	0	<b>100</b>
<b>Energy Allocated</b>	-	-	20	8	2	0	<b>30</b>
<b>Energy Self-Consumed</b>	-	-	20	8	2	0	<b>30</b>
<b>Energy Surplus</b>	-	-	0	0	0	0	<b>0</b>
<b>Energy Supplied</b>	-	-	0	0	0	0	<b>0</b>
<b>Self-Consumption Index</b>	-	-	100	100	100	0	<b>100</b>
<b>Self-Sufficiency Index</b>	-	-	100	100	100	0	<b>100</b>
<b>Equity Disparity</b>	-	-	49.9	6.6	115.5	200	-

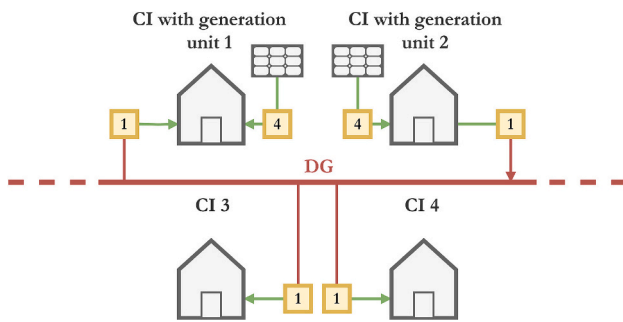
as S3, but the energy-sharing model employed is based on consumption-proportional coefficients. As evident from Table 7, the use of these coefficients successfully maximizes both the SCI and the SSI but compromises the CSCME’s ability to control the sharing coefficients. In S4 the inequitable sharing of energy becomes evident. CI 1, due to its high consumption, receives a disproportionate share of energy (71.4 %) and self-consumes all the energy produced on-site by its generation unit. While advantageous in reducing costs associated with the distribution grid, the generation unit (collectively financed by all members) is disproportionately benefitting CI 1. This outcome underscores a significant proportionality and equity issue, making S4 the least favourable from an equity standpoint.

This scenario demonstrates the trade-off between achieving optimal energy efficiency and ensuring equity among community members. While the SCI and SSI values indicate that energy production and consumption are well-matched, the distribution of benefits remains skewed, disproportionately favouring those members with higher energy

consumption, raising considerable concerns regarding equity, and potentially undermining the social objectives of the REC.

### 5. Discussion

The discussion of the four hypothetical scenarios for REC in Portugal, summarized in Table 8, provides an in-depth look at some of the interrelations of important technical, social, and economic challenges. Like Fina et al.’s [65] analysis of comparable energy-sharing models in Austria, our findings reveal how different approaches using different energy-sharing and metering mechanisms can optimize resource allocation, ensure equitable benefit distribution, and promote financial sustainability. Each of these scenarios reveals that there is no one-size-fits-all solution for optimizing REC performance. This reinforces the point made by Marcinkowski et al. [66], i.e., policies promoting different business models need a degree of recognition and adaptability to different local contexts, considering how the different scenarios have



**Fig. 3.** Example architecture of a Renewable Energy Community, composed of four Consumption Installations (CI) with energy generation units, which prioritize individual energy production (PIP). Also represented are the Mandatory Metering Points (MMP) 1 and 4 to account for energy. The yellow boxes represent the MMP, the green lines represent the internal grid, and the red lines represent the distribution grid [figure made by the authors]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

different implications, which will depend on local policy context and specific goals of REC members.

The scenarios analysed illustrate that optimizing REC performance hinges on appropriate energy metering and sharing models, while addressing social equity, ensuring fair access to RES, and maintaining economic viability through efficient management of production, allocation, and distribution costs. S1 and S2, which use the PCP method, centralize energy production but face the maximum distribution grid usage costs. In contrast, S3 and S4, employing the PIP, minimize the economic burden on community members by consuming the energy produced directly within the individual installations, reducing costs associated with distribution grid usage, and making the REC model more financially sustainable. It also has the advantage of having the energy generation unit installed directly within the CI, thereby eliminating the need for additional infrastructure while increasing both the SCI and the SSL. However, in situations where not all CI are equipped with individual generation units, the PIP may result in significant energy distribution disparities, particularly disadvantaging the CI that rely on shared production. For example, in S3 CI 1 and CI 2, which have integrated

generation units, consume most of the energy produced on-site, creating an economic imbalance for the other community members who have collectively financed the generation units but derive limited benefit from them. In S4, CI 1 benefits disproportionately from both self-consumed and shared energy, despite collective financing, leading to significant distributional justice concerns. This imbalance is especially problematic when community-owned land is used for installing the generation units, as it can obscure the uneven distribution of burdens versus benefits among members. This inequitable distribution of economic benefits highlights the need for carefully designed compensation mechanisms, and policy instruments, to ensure that all members of an REC, regardless of their consumption levels, can benefit equitably from their participation. Although these trade-offs have been acknowledged by Jenkins et al. [19] and Hanke et al. [22], they remain insufficiently explored in practical cases.

RoSC requires MMP 4 to be installed, which is placed between the CI and the generation unit and is responsible for transmitting the metering of energy produced directly to the DSO. However, this requirement has limited utility, as the energy metering under the PIP method is conducted at MMP1. In REC where generation units are collectively funded but not installed across all CI (e.g., S3 and S4), a hybrid accounting model combining PCP and PIP would be more effective. Such a hybrid model would allow the energy produced by the generation unit (through MMP 4) to be distributed directly among all participating CI, rather than primarily being consumed by the CI to which it is physically connected. This approach would thereby merge the advantages of both producing methods – a fair distribution based on investment ratio and a lower need for distribution grid usage.

In S1 and S3, the use of fixed coefficients ensures that energy allocation is proportionate to the investment made by each CI. This provides a fair approach to energy distribution based on financial contribution but fails to accommodate variations in energy consumption patterns among CI. This can lead to situations where surplus energy is produced but not consumed, undermining the overall sustainability goals of the REC. In contrast, S2 and S4, which use consumption-proportional coefficients, excel in terms of energy efficiency but fail to uphold equity-related redistributive social justice principles. Larger consumers, who are typically in more favourable socio-economic positions, benefit disproportionately, creating substantial equity disparities. In situations where not all members of the energy community can install their own

**Table 6**

Data of the hypothetical Renewable Energy Community Scenario 3 (S3) which prioritizes the individual energy production (PIP) and uses the sharing model based on fixed coefficients. The top four rows in light grey represent the primary data, and the bottom dark rows show the results of the evaluation criteria Self-Consumption Index, Self-Sufficiency Index and Equity Disparity for S3.

Data	CI with generation unit 1	CI with generation unit 2	CI 3	CI 4	REC
<b>E Produced Individually</b>	15	15	-	-	<b>30</b>
<b>Energy Consumed</b>	20	8	2	≈ 0	<b>30</b>
<b>ME Fixed Coefficients</b>	40	25	25	10	<b>100</b>
<b>Investment Ratio</b>	40	25	25	10	<b>100</b>
<b>Installation Behaviour</b>	Cons	Prod	Cons	Cons	-
<b>E Produced Collectively</b>	0	7	-	-	<b>7</b>
<b>Fixed Coefficients</b>	53.4	-	33.3	13.3	<b>100</b>
<b>Energy Allocated</b>	3.74	-	2.33	0.93	<b>7</b>
<b>Energy Self-Consumed</b>	3.74	-	2	0	<b>5.74</b>
<b>Energy Surplus</b>	0	-	0.33	0.93	<b>1.26</b>
<b>Energy Supplied</b>	1.26	-	0	0	<b>1.26</b>
<b>Self-Consumption Index</b>	100	-	85.8	0	<b>82</b>
<b>Self-Sufficiency Index</b>	93.7	-	100	0	<b>82</b>
<b>Equity Disparity</b>	28.7	-	28.5	28.3	<b>-</b>

**Table 7**

Data of the hypothetical Renewable Energy Community Scenario 4 (S4) which prioritizes individual energy production (PIP) and uses the sharing model based on consumption-proportional coefficients. The top three rows in light grey represent the primary data, and the bottom dark grey rows show the results of the evaluation criteria Self-Consumption Index, Self-Sufficiency Index and Equity Disparity for S4.

Data	CI with generation unit 1	CI with generation unit 2	CI 3	CI 4	REC
<b>E Produced Individually</b>	15	15	-	-	<b>30</b>
<b>Energy Consumed</b>	20	8	2	≈ 0	<b>30</b>
<b>Investment Ratio</b>	40	25	25	10	<b>100</b>
<b>Installation Behaviour</b>	Cons	Prod	Cons	Cons	-
<b>E Produced Collectively</b>	0	7	-	-	<b>7</b>
<b>C-P Coefficients</b>	71.4	-	28.6	0	<b>100</b>
<b>Energy Allocated</b>	5	-	2	0	<b>7</b>
<b>Energy Self-Consumed</b>	5	-	2	0	<b>7</b>
<b>Energy Surplus</b>	0	-	0	0	<b>0</b>
<b>Energy Supplied</b>	0	-	0	0	<b>0</b>
<b>Self-Consumption Index</b>	100	-	100	0	<b>100</b>
<b>Self-Sufficiency Index</b>	100	-	100	0	<b>100</b>
<b>Equity Disparity</b>	56.4	-	13.4	200	-

**Table 8**

– Summary of the analysis performed on the different energy sharing and metering mechanisms, highlighting the advantages and disadvantages of each scenario [table made by the authors].

Scenarios		Advantages	Disadvantages
Prioritizing Collective Production	<b>Scenario 1:</b> Fixed Coefficients	Fair distribution based on investment ratio.	Limited efficiency with low SCI and SSI.
	<b>Scenario 2:</b> Consumption-Proportional Coefficients	Maximum efficiency with 100 % SCI and SSI.	Significant equity disparity favouring high consumers.
Prioritizing Individual Production	<b>Scenario 3:</b> Fixed Coefficients	Improved SCI and SSI with reduced distribution grid dependency.	Unequal energy access, disadvantaging non-producing members.
	<b>Scenario 4:</b> Consumption-Proportional Coefficients	Optimal energy efficiency metrics (100 % SCI and SSI). Lower need for distribution grid usage	Severe inequity in energy distribution, favouring high-consumption installations.

production system – a scenario often seen in Portugal due to widespread energy poverty [59] – the PIP scenarios can be inequitable. This is because members without home generation units receive less benefit, as most energy is self-consumed before being shared, and still must pay for the energy allocated to them (originating from distribution grid use costs). The PIP-based S4 further exacerbates this issue, since CI 1, being a high consumer, receives an outsized benefit compared to other community members, despite the collective investment in the energy generation units.

The recently legislated dynamic sharing model presents great potential to be the best option for optimizing the energy management in a REC project, maintaining the distributional energy justice between members – as it works like fixed coefficients while maximizing the SCI and the SSI – as the coefficients can be allocated a posteriori [25,26]. However, this seems to be far from being a reality since it imposes many implementation challenges for the DSO, such as the need for dedicated algorithms and software and, in many contexts, the upgrade of infrastructures (e.g. smart meters) [29,67].

The transposition of the Clean Energy Package into national

legislation has provided Member States with significant flexibility in how to do so, thus offering the possibility for different energy community policies across Europe, each shaped by geographic, cultural, and political factors [68]. National approaches to energy communities vary significantly, with most Member States fulfilling basic EU requirements but lacking full integration into the energy market. Member States such as Greece and Croatia, have not fully distinguished between REC and CEC, unlike Italy [17]. Although Portugal has formally defined both, the definition of CEC is oversimplified and lacks clear distinctions from REC, since most of the definition criteria are very similar [25,69]. Energy communities are often idealized in a broader concept, i.e., an entity (constituted by neighbours, a community, or a council) capable of creating an autonomous production/consumption energy system and sharing energy with a network of local businesses and homes.

The Portuguese legislation lacks clarity regarding the scope of activities that an energy community can undertake. Many of the provisions appear to be largely replicated from EU directives without adaptation, resulting in an ambiguous legal framework. Also, it does not clarify their governance structure, particularly regarding ownership, which is fundamental to energy communities [69]. For instance, the current definition of REC allows installations to be owned by third parties [25,60], undermining the core objective of fostering community ownership, which may effectively reduce REC members to passive participants while ceding operational control to professional market actors such as intermediaries. While these intermediaries can enable the rapid establishment of REC through overcoming numerous barriers [29], this arrangement runs counter to the initial intentions of EU in that of empowering citizen community actors with a distinct role from that of traditional energy market players, emphasizing community-led governance and local engagement. In Portugal, the competitive costs of modular photovoltaics combined with supportive energy communities' legislation have attracted numerous intermediaries to participate in the development of these communities [29]. This led to these intermediaries offering a degree of controlled cost reduction but with limited local capacity building and energy literacy, and structuring REC internal regulations to align with their business models [60]. While this approach may benefit those solely focused on reducing energy bills without active participation, it compromises the intended autonomy and democratic governance of the energy communities, undermining the core principles of local ownership and collective decision-making from the European directives.

Additionally, administrative hurdles like complex registration and licensing procedures, as well as access to relevant data, remain barriers to progress [70]. Since the introduction of Portugal's first energy communities' legislation in 2019, many CSC projects have relied on consumption-proportional sharing coefficients. While this sharing model involves less complexities between DSO and CSCME interoperability, and at the same time optimizes SCI and SSI, it is particularly advantageous for intermediaries, as it removes the burden of managing coefficients, allowing them to ensure the profitability of their business model. However, it fails to consider other priorities of the energy community members, reducing the attractiveness of these projects due to limited distributional justice, as observed above in the analysis of the four scenarios.

While REC are at early stage of diffusion and have not yet faced significant public controversy, disputes involving larger solar power projects – such as the planned installation for Cercal, Alentejo [42] – should draw attention to the importance of community consultation, equity and energy justice for the acceptance and viability of a project. To address such issues and overcome some technical, social, and economic barriers to REC projects, the Portuguese legislation allows developing pilots to test new energy-sharing models associated with innovative technologies in partnership with the DSO [26]. However, although the recent regulation [26] accelerates the establishment of these REC pilot projects, these initiatives face significant bureaucratic challenges, particularly around licensing [29]. These challenges are mainly related to the alternative energy-sharing models, which require more robust interoperability between the DSO and the CSCME. This hinders experimentation and community learning around energy communities, such as on how to address trade-offs of energy sharing models as seen in the case study above.

Policy decisions impacting the profitability of selling surplus energy not consumed by the REC, and the level of cost for different degrees of use of the distribution grid infrastructure, impact which type of energy-sharing and metering mechanisms are most beneficial to REC members. A case study in Portugal on energy community models illustrated that such questions were central to making a REC project beneficial to its members [71]. If policymakers want to encourage REC to consume a higher amount of their produced energy, and avoid selling surplus energy, they should encourage their implementation at the low-voltage distribution grid infrastructure. This would also increase renewable energy penetration at a local level. To promote recognition justice, policymakers should put policies in place to mitigate distribution grid costs for low-voltage energy communities, making it more interesting for members, and potentially increasing the justice effect by addressing energy poverty [29]. Reduced distribution grid use costs for energy communities can be justified by cosmopolitan justice principles, as localized production benefits society by avoiding disadvantages like visual pollution and risks associated with high-voltage lines [29]. Yet not making it profitable to sell surplus energy also can risk reducing the 'return on investment' of installing intermittent RES.

Finally, cultural aspects play an important role in what is estimated as equitable and just, and which groups and principles are seen as deserving to benefit, or not, from sociotechnical change [72]. Different transition actors have different interests, and their preferred business model is based on different visions of justice and preferences in energy production concepts, such as different forms of centralized vs decentralized production and consumption models [73]. Policymakers must grasp the justice-efficiency trade-offs inherent in each energy-sharing model and align policy responses with the desired justice or efficiency outcomes [72,74]. Participation in SCA within energy communities should be accessible to all consumers, including low-income or vulnerable households. Recent modifications to Portuguese legislation introduced by Decree-Law 99/2024 [75], such as the increase of geographic proximity in low-density territories and the implementation of mechanisms to accelerate the registration of small-scale renewable energy production units, is a step in the right direction, the same legislation fails

to provide specific measures or detailed mechanisms to ensure this inclusivity as seen in this case and others [64], leaving the practical implementation ambiguous.

## 6. Conclusions

Investigating the barriers to participation and quantifying the economic and social benefits of these communities is crucial to inform effective policy development and accelerate the transition towards a decentralized and sustainable energy future. Besides creating economic models that allow the distribution of costs and income resulting from the production of renewable energy by its members, energy communities have the potential to empower direct citizen participation in the energy transition. However, barriers such as time constraints (for participation), financial limitations (for investment), and limited space (rooftop or land access) often restrict participation among resource-poor groups. In fact, the European Commission identifies that it is very difficult for people with less energy literacy and fewer possibilities to participate in this type of project [60]. The analysis of the four hypothetical scenarios highlights the technical, social, and economic challenges and trade-offs associated with implementing REC in Portugal. From a technical standpoint, the scenarios reveal the importance of selecting appropriate energy-sharing and metering mechanisms to optimize SCI and SSI. The social dimension of REC, particularly in terms of justice, presents significant challenges as it depends on the policies put in place, i.e., different energy-sharing models benefit different community members in unequal ways. Perceptions of economic efficiency, particularly the dependency on distribution grid infrastructure and its associated costs, also introduce barriers to the financial sustainability of REC.

To enhance the long-term viability of energy communities, this study recommends:

- (1) Foster local community involvement from the initial stages. This process should begin with a community participatory diagnosis to understand the socio-economic context, as seen in previous initiatives like [45], and ensure distributive energy justice, crucial for maintaining community engagement.
- (2) Simplify the licensing process, with clear and standardized guidelines. The current legislation lacks specific features to distinguish REC, CEC and CSC, as they share the same rules. As demonstrated in this study, current energy-sharing models do not perform optimally in terms of efficiency and equity. However, newly legislated mechanisms, which are currently exclusive for pilot projects, such as the dynamic sharing model, show potential for balancing these aspects in an effective way. Therefore, DSO must prioritize defining operational procedures for these new sharing models and support these pilots. Moreover, a hybrid accounting model combining PCP and PIP could be more beneficial in situations where not all energy community houses are equipped with individual generation units. Such a model would enable the energy produced by an individual generation unit to be shared among other community houses before being self-consumed by the unit owner, thereby mitigating issues related to limited land availability.
- (3) In the absence of government support mechanisms, creating an organization that consolidates all bottom-up REC – particularly those facing substantial implementation challenges – may become essential. The energy community's online platform, which was never launched [29], would serve as a valuable tool not only to publicize and share ongoing REC initiatives but also to facilitate knowledge exchange and community development, as well as to promote an open dialog with the policymakers.

Although the equity disparity metric offers a partial assessment of distributive justice within each scenario, it remains insufficient for determining the overall level of justice within an energy community,

which constitutes a limitation of this study. Given the importance of this subject, the authors plan to address this gap in future studies. Another limitation of this analysis is that it did not look at how different ownership structures impact the specific choices in terms of energy-sharing scenarios discussed above. A solution could be the application of digital twins by connecting the real and virtual worlds [35], allowing for the creation, testing and simulating of new energy-sharing scenarios. Also, virtual power plants are emerging as a promising solution for decentralized energy management systems. This technology leverages internet platforms to allow for coordination of distributed energy resources for effective market participation, which is essential for advancing social inclusivity and supporting the transition to decentralized, community-driven energy systems [76]. Such technologies, which are attracting significant academic interest, could be used to test new hierarchical and dynamic sharing schemes, making them a promising avenue for future research.

### List of acronyms

CEC	Citizens Energy Community
CI	Consumption Installation
CSC	Collective Self-Consumption
CSCME	Collective Self-Consumption Manager Entity
DSO	Distribution System Operator
EU	European Union
MMP	Mandatory Metering Point
P2P	Peer-to-Peer
PCP	Prioritize Collective Production
PI	Production Installation
PIP	Prioritize Individual Production
REC	Renewable Energy Community
RES	Renewable Energy Sources
RoSC	Regulation of Self-Consumption
SCA	Self-Consumption Activity
SCI	Self-Consumption Index
SI	Storage Installation
SSI	Self-Sufficiency Index

### CRedit authorship contribution statement

**Jóni Buchinho Santos:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Conceptualization. **Renée Scharnigg:** Writing – review & editing, Writing – original draft, Visualization, Validation, Investigation, Formal analysis. **Jânio Monteiro:** Writing – review & editing, Visualization, Validation, Supervision, Conceptualization. **André Pacheco:** Writing – review & editing, Visualization, Validation, Supervision, Conceptualization.

### 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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### Data availability

No data was used for the research described in the article.

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