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Original Research Article

Design and Operational Indicators to Foster the Transition of Existing Renewable Energy Communities towards Positive Energy Districts

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ABSTRACT

Renewable energy communities occupy a critical position in catalysing the energy transition within urban areas, while simultaneously making substantial contributions towards the realization of the Sustainable Development Goals outlined in the 2030 Agenda for Sustainable Development, adopted by all United Nations Member States in 2015. Positive Energy Districts are also gaining momentum, emerging as a concept of growing interest among researchers and urban planners. Renewable energy communities and positive energy districts are both expressions of sustainable urban energy forms, yet there is the need to evaluate if a renewable energy community could be considered a positive energy district and under which conditions this transition will occur. To this end, a holistic framework examining the transition from existing renewable energy communities to positive energy districts is proposed and characterized by focused indicators, serving as critical instruments to conduct a tailored evaluation and characterization. Results demonstrate that the transition can be achieved by increasing the renewable energy installations in the area by 20 %.

KEYWORDS

Energy communities, Positive Energy Districts, Energy transition, Renewable energy, Social stakeholders, Economic assessment, Environmental aspects.

HIGHLIGHTS

- Transition from renewable energy communities to positive energy districts
- Holistic evaluation of energy communities using tailored indicators
- Promoting environmental, economic and social benefits at the urban level
- Inclusion of key elements such energy production, efficiency and flexibility

INTRODUCTION

The recent European energy strategy has established conditions to facilitate the transition towards a more sustainable and participatory energy sector, aimed at achieving global climate goals, reducing emissions, and ensuring a more competitive, secure, and affordable energy supply [1]. Over the last decade, there has been a significant empowerment of energy consumers, particularly with the proliferation of renewable-based energy production systems at the micro-scale, located in or near buildings or at least in proximity to the point of

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consumption. This shift has paved the way for the decentralization of the energy supply and a strengthening of the role of final users in the entire supply chain. Formerly known as consumers, they now participate in the energy market in their renewed role as prosumers, effectively revolutionizing traditional (and centralized) energy assets.

As a direct consequence of the local energy production and consumption, renewable energy communities (RECs) are emerging in Europe as a means for consumers to organize collectively and actively participate in the entire energy production, distribution, and storage chain, thereby gaining economic, environmental, and social advantages for the community and, consequently, for individual consumers as parts of the community itself [2]. Despite their involvement in the economic activity of electricity trading with the power grid and electricity shared among members, RECs are non-commercial entities. Moreover, they operate under a specific legal framework, as outlined by the EU Directive and the national transpositions of Member States, such as Decree No. 199 in Italy [3].

The scientific community has responded significantly to the diffusion of the RED II, focusing on various critical aspects related to RECs, from the regulatory framework design [4] to technical, operational and sustainability issues. In this direction, Masip *et al.* [5] conducted a study on energy communities that integrate electrical load with the demand for domestic hot water in a district of 150 buildings in Spain. Sudhoff *et al.* [6] studied the contribution of RECs to reduce power peaks in the distribution grid. They demonstrated that specific operation strategies of RECs permit the achievement of a peak power reduction in a range from 23% to 55%. Stefan *et al.* [7] implemented a blockchain-based REC and evaluated energy trading aspects, particularly by quantifying the total energy costs for energy community members. Other financial aspects are considered by Cielo *et al.* [8], who developed a business model to considered self-consumption and self-sufficiency of Italian RECs to quantify the internal rate of return and emissions reduction. Their study revealed a minimum internal rate of return of 11%, for Italian RECs under different scenarios. Going further, Viti *et al.* [9] compared the economic performance of RECs to that of single buildings acting as self-consumers, with a primary focus on energy bill savings. However, RECs are not the sole examples of urban forms for collective citizen participation grounded around the topic of renewable energy and sustainability principles. In particular, in this scenario, Positive Energy Districts (PED) are emerging as a new opportunity, in which the role of self-production, self-consumption, and distribution among consumers will significantly impact on the sustainable energy transition in urban areas.

As for Positive Energy Districts (PEDs), numerous studies have proposed conceptual framework that emphasize the integration of renewable energy production, energy efficiency measures, smart grid technologies, and community engagement as essential elements of the PED implementation process. In [10], the authors evaluated the effectiveness of energy retrofitting, renewable integration and energy flexibility for achieving the status of PEDs in the case of a Mediterranean district. In some cases, these analyses included considerations of the policies and regulations supporting the transition to PEDs, as seen in the work of Trevisan *et al.* [11]. Similarly, Alpagaut *et al.* [12] outline main PED-tailored phases of implementation from concept boundary identification to financial and social capabilities exploitation. Other authors deepened the available definitions of PEDs, trying to homogenize the use of diverse terms and repetitions, as done in [13]. Social aspects are tackled by Nguyen and Batel [14], proposing a critical framework for PED development and including uncertainty, risk perception, trust and justice. Gouveia *et al.* [15] emphasized the importance of energy efficiency actions, such as the retrofit of historic districts, to address energy poverty for PEDs.

Differently, a novel approach to PEDs optimization is proposed in [16], through a review about digital twins' concepts, working principles, tools, and potential applications to PEDs. Krangsås *et al.* [17] implement a Delphi process to identify challenges and interdependencies in developing Positive Energy Districts, emphasizing governance, market, and technological aspects. Finally, research gaps **[18]** and policy recommendations **[19]** are provided through a systematic review of PED's literature and real case studies in Europe, respectively.

These studies underscore the importance of supportive policies, incentives, and regulations at the local, regional, and national levels, and investigated the impact of PEDs for achieving sustainability targets. However, they do not delve into the potential diffusion of PEDs from existing RECs, especially if considering the need for identifying critical aspects, as well as defining and quantifying key performance indicators.

In light of this, there is room for discussing whether and how RECs could represent a significant step toward achieving the PED paradigm in urban areas, as advocated in **[20]**. To reach this goal, it is crucial to highlight the similarities and differences between these two energy-related urban forms. This paper aims to contribute in this sense by proposing a framework of crucial steps to foster the transition from RECs to PEDs. This can be reached by implementing strategic actions that facilitate the evolution of community energy systems towards greater autonomy and sustainability, as advocated by both RECs and PEDs definitions. In particular, the goals of this transition are:

- increase the energy self-sufficiency, maximizing the production of energy from renewables to satisfy the demand of consumers, thus reducing the dependency on national grids and external energy sources;
- reducing carbon emissions, increasing the diffusion of renewable systems will lower the emissions associated to fossil fuels;
- empowering consumers to manage their own energy needs in light of the local energy resources.

Under these premises, the framework proposed in this paper introduces a holistic approach that considers not just the technical and economic aspects, but also the social, environmental, and governance dimensions of RECs aiming to be PEDs. The contribution of this research to the field of RECs and PEDs is twofold. It establishes a set of newly and tailored indicators allowing RECs to measure not just energy production and consumption, but also the impacts of their energy practices on social equity, local governance and environmental impact. Additionally, it stands as a novel idea to bridge the gap between RECs and PEDs, proposing an effective roadmap on how existing urban energy and collective forms (such as RECs are) can be sustainably move to novel and innovative concepts (as PEDs).

DIMENSIONS AND FUNCTIONS OF RECs AND PEDs

The common framework for promoting and disseminating RECs in urban areas is derived from the Renewable Energy Directive **[1]**. Article 22 of the Directive states that "*renewable energy communities are entitled to produce, consume, store and sell renewable energy, […], share, within the renewable energy community, renewable energy that is produced by the production units owned by that renewable energy community, subject to maintaining the rights and obligations of the renewable energy community members as customers, and access all suitable energy markets […]*".

To gain a better understanding of what a REC entails, it is crucial to break down the definition above to identify who is involved, to what extent, and what the main goals are, along with how they can be achieved. This analysis leads to the identification of three main dimensions, each characterized by specific targets and functions that can serve as references for defining key performance indicators, as outlined in **Table 1**.

The membership dimension addresses the question "who is involved in a REC?", and it pertains to membership and refers to the roles undertaken by stakeholders involved in the REC constitution process. The dimension of "membership" can be better described by identifying key targets, recognized here as consumers (also in their role as producers), local authorities, and small/medium enterprises. These targets are also acknowledged as potential participants or contributors to the REC, according to normative guidelines. They can be characterized by tailored functions that are useful for measuring their impact on the constitution, design, and implementation of the REC. Specifically, in relation to the membership dimensions, participation is valuable not only for quantifying the number of participants but also for qualifying them based on their roles. Autonomy and proximity measures could be implemented to assess achieved energy independence and territorial diffusion impacts. Governance and normative functions could be measured by tracking the number of calls and acts promoted by the authorities and municipalities.

Table 1. Dimensions and functions identified in a REC

Questions	Dimensions	Targets	Functions
Who?	Membership	- Consumers/Producers - Local authorities - Small/Medium Enterprises	- Participation - Governance/Normative - Proximity
Which goals?	Sustainability assessment	- Environmental impact - Economic aspects - Social impact	- Greenhouse gas emissions - Efficiency - Energy savings - Costs - Incentives for valorisation - Energy poverty - Flexibility
How?	Technology and operation	- Renewable production - Storage systems	- Energy production - Energy stored - Self-consumption - Energy sharing - Energy import - Energy export - E-mobility

The second dimension pertains to sustainability assessment, described through environmental, economic, and social targets, advocated by the European Union as fundamental to achieving the objectives outlined in the 2030 climate plan of the European Green Deal [21]. This dimension addresses the question “what are the objective of a REC?”. To delve further, environmental aspects can be evaluated by considering targets related to greenhouse gases or, initially, CO_2 emissions, along with energy efficiency and flexibility. The economic aspect involves considering capital costs for renewable and technological installations, as well as operation and managements issues. Other functions essential for characterizing economic targets include revenues generated by the REC through the valorisation of self-consumed and shared energy within the REC, dedicated incentives, and energy savings, as defined in **Table 1**. The social target can be characterized by the impact that REC’s actions have on the community, such as reducing energy poverty or improving services and the quality of life.

Finally, the third dimension addresses the question “which technological and operation aspects should be included into the design of operation of a REC?” and concerns technological design and operation aspects, which can be linked into the three main targets: energy audits, renewable production, and storage. Here, the targets can be characterized by functions corresponding to energy demand, production and storage evaluation, including electrical mobility. Other relevant functions pertain to energy balances within the REC and between the REC and external grids. The first group includes the amount of energy that is self-consumed or shared among REC members, while the second group deals with energy import and export.

Before delving into the detail of PEDs characterization based on the mentioned dimensions, it is important to briefly contextualize their origin. Positive Energy Districts belong to Action 3.2 “Smart Cities and Communities” initiative within the European Strategic Energy Technology (SET) Plan [22]. The SET Plan comprises six domains, all contributing to achieving European goals by 2030. Each domain is further divided into Implementation Working Groups, focussing on specific aspects. PEDs fall under the second domain, labelled as “energy systems”, and their implementation is governed by IWG Action 3.2. Contributions to this action come from JPI Urban Europe, which has elaborated the “Positive Energy Districts and Neighbourhoods for Sustainable Urban Development” programme to promote the diffusion of 100 PEDs by 2025 [23], and from the DUT Partnership, proposing innovative actions to foster PEDs’ diffusion [24].

In contrast to RECs, PEDs do not have a legal entity, and there are working groups actively studying PEDs from definitional perspective to the technological design and sustainability assessment. These include the IEA EBC Annex 83 “Positive Energy Districts” [25] and the Cooperation in Science and Technology (COST) Action CA19126 “PED-EU-NET Positive Energy Districts European Network” [26]. While analysed from different perspectives, there is agreement on several key aspects that characterize PEDs.

PEDs interact with the “environment” across a boundary, which can be physical or virtual. Depending on this, three main PED typologies can be identified, according to the research conducted by Lindholm *et al.* [20]:

- autonomous PED. This typology of district has well-defined geographical boundaries and achieves complete energy self-sufficiency through the generation of renewable energy within its boundaries. It does not rely on external sources from the electricity grid or district heating/gas network for its energy needs but can export surplus renewable energy;
- dynamic PED. Characterized by well-defined geographical borders, this district annually generates more renewable energy on-site than it consumes. It has the flexibility to interact with other PEDs and access external electricity grids and district heating/gas networks;
- virtual PED. This district allows for virtual renewable energy systems and energy storage across its geographic boundary. However, the combined yearly energy output from these virtual systems and on-site renewable sources must exceed the district’s annual energy demand.

Therefore, the study of a PED should begin by defining whether its boundary is physical (as in the case of autonomous and dynamic PEDs) or virtual (e.g., virtual PED). Once the PED typology of PED is recognized, it becomes possible to evaluate energy flows within the PED or energy interactions with the external environment and assess their impact. In this context, the reference framework for PEDs identifies three main energy functions for PED implementation within the regional or national energy system [23], as illustrated in **Figure 1**. The first and most obvious characteristic of PEDs is their reliance on renewable sources, referred to as “energy production”. Additionally, PEDs commit to achieving “energy efficiency” through the conscious exploitation of energy sources. Lastly, addressing “energy flexibility” is essential to avoid social and economic discrepancies.

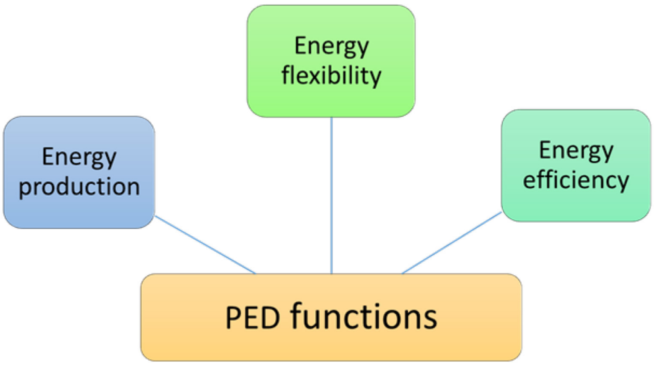

Figure 1. Functions of Positive Energy Districts, as identified in [17]

The above definitions have been intentionally kept quite general to allow for case-specific considerations and strategies. However, one of the primary challenges in realizing PEDs lies in effectively linking the introduced energy functions to existing urban agglomerates and fitting them within the regulatory framework of the recent RED II Directive. As said, this Directive places particular emphasis on the role of prosumers and their ability to participate in the entire energy supply chain, encompassing production, self-consumption, and distribution to other connected buildings.

The analysis conducted thus far highlights the main similarities and differences between RECs and PEDs. Indeed, these two paradigms share several aspects, as both:

- represent two forms of collective energy-related urban development;
- place the consumer at the centre of the project;
- co-own the renewable energy systems;
- contribute to the realization of climate-neutral cities;
- address energy poverty and inequalities by promoting fair and inclusive urban areas;
- create a new energy market in which consumers actively participate.

On the other hand, the main differences can be attributed to:

- the regulatory aspect, with RECs being legal entities while PEDs are not yet;
- the constraints of positive surplus and net-zero emissions applied to PEDs, which are not mandated for RECs. In RECs, renewable production and self-consumption are the primary activities of the community, along with sustainability criteria that are not specifically defined.

MATERIALS AND METHODS

This section delineates the framework designed to guide the transition from RECs to PEDs. Initially, the sequential steps constituting the proposed framework are detailed. Following this, a set of tailored indicators developed specifically for assessing and monitoring the progress of RECs as they evolve into PEDs are introduced and elaborated. These indicators aim to capture the essential aspects of membership and governance, sustainability assessment, as well as technology and operations. Lastly, a discussion on the practical implementation of the framework and validity of the indicators is presented.

Transition framework

As evident from the above comparison, RECs and PEDs share a significant number of common aspects, leading to the conclusion that PEDs may be viewed as a potential future evolution of existing RECs. However, it is crucial to emphasize that PEDs should not be planned solely as newly constructed areas; their effective proliferation is heavily reliant on existing neighbourhoods. In this regard, there is a consensus on the necessity of establishing a cohesive approach to promote the implementation of actions and strategies tailored to existing built environments. It is in this direction that RECs can serve as a means to address the ambitious goals forth by the SET Plan IWG Action 3.2, particularly concerning the dissemination of PEDs as a way to achieve climate neutrality by 2050 [22]. Indeed, RECs are structured as relatively independent urban organizations, and they are built upon renewable energy and storage systems, making them a solid foundation for facilitating a sustainable transition from environmental, economic and social perspectives.

To this end, this study aims to propose a comprehensive framework that guides the transition from existing RECs to the PED paradigm. It intends to be a valuable resource for urban planners, energy managers, local authorities, and all stakeholders, including REC members in their roles as consumers and producers. The framework is designed without reference to specific urban features, allowing for national adaptations and customization at any stage of the REC-to-PED process. This framework can be described as a series of steps, which are summarized in Figure 2.

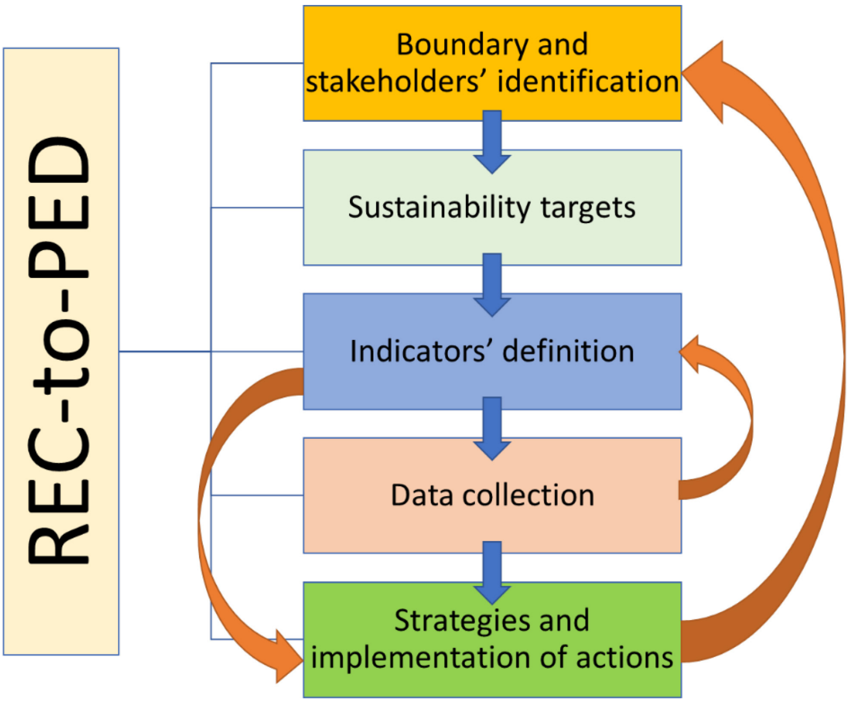

Figure 2. Framework for the REC-to-PED transition process

The first step involves identifying the boundary and stakeholders of the REC-to-PED transition. This entails contacting and involving all stakeholders in the transition process, whether it is approached from a bottom-up or top-down perspective. Examples of stakeholders include REC members, energy systems owners, local authorities, local associations, small/medium enterprises (especially those already part of the REC), and commercial partners.

The second step should define the sustainability targets of the REC-to-PED transition process. Both urban agglomerates aim to achieve environmental, economic and social benefits for their members. Although there is no clear definition of how these benefits should be achieved or measured, the way this definition is approached differs slightly between the two cases. For PEDs, there is a specific focus on carbon emissions, which should reach an annual net-zero balance. This step is crucial as it not only enable the realization of the PED paradigm but also concentrates efforts to maintain it over several years. In this stage, the role of stakeholders, incoming and outgoing energy flows, energy interactions among members, energy technologies, and equipment should be documented.

The third step involves defining indicators based on the main functions of RECs, which are then compared with the defining characteristics of PEDs, including an annual net-positive renewable energy balance and net-zero carbon emissions. These indicators should also be evaluated in the context of the functions related to energy efficiency, energy production, and energy flexibility associated with PEDs.

The fourth step consists of the data collection phase for actively elaborating the measures deriving from the established indicators.

The fifth step involves the definition of actions and recommendations to achieve the milestones referenced by the indicators, thereby establishing a consolidated strategy among members and stakeholders.

Overview of the indicators

Indicators serve as specific markers that gauge the attainment of inputs, outputs, outcomes, and the impact of your projects. Indicators are designed to measure the effectiveness of any implementation effort and offer an objective means of showcasing the PED-to-REC transition accomplishment. Additionally, indicators will play a fundamental role in monitoring progress toward achieving the Sustainable Development Goals (SDGs) at local, national, regional, and global levels. Indeed, these indicators will serve as a report card for assessing advancements in sustainable development and ensuring the accountability of all stakeholders in achieving the SDGs. Based on the preceding discussion, the purpose-built indicators stemming from the dimensions and functions delineated in **Table 1** have been formulated and presented in **Table 2**.

As mentioned earlier, both RECs and PEDs revolve around the consumers, making it essential to recognize the number of families affiliated with the REC and, eventually, the future PED. Participation is straightforwardly represented by the number of REC members, denoted as M. It is worth noting that membership can be further detailed by considering member typologies, such as families, offices, public buildings, small/medium enterprises, and so forth, depending on the specific objective of the analysis. Another critical aspect pertains to the role of municipalities and local authorities in driving the transition. In this context, it is important to assess whether the significance of public initiatives is considered crucial or whether private actions predominate. This distinction is captured by indicator (1), which can also help determine which stakeholders are actively engaged in the REC-to-PED transition process, whether they belong to public bodies/authorities or are private citizens (including small/medium enterprises).

Regarding the concept of proximity, the current regulations governing REC constitution stipulate a limit where all members must connect to the same electrical primary substation **[3]**. While energy flows are technically considered virtual, then notion of proximity persists since REC members belong to the same municipality. Hence, an indicator (3) is proposed to measure territorial expansion, comparing the average sum of distances between two REC members to their average distance. A smaller value of this indicator designates a denser district, enhancing the efficiency of energy distribution among members and community engagements. Conversely, a larger value implies a potential infrastructure development with higher costs for energy distribution.

In terms of sustainability assessment, the three primary pillars of environmental, economic and social impact are addressed through dedicated indicators. The calculation of avoided emissions for a REC is represented by indicator (4). This indicator relates emissions associated with renewable production to emissions stemming from fossil supply from the central grid. As emphasized in RED II, one of the primary objectives of RECs is to achieve environmental benefits for the urban area in which they are established. Typically, this involves reducing carbon emissions, often calculated by comparing emissions linked to satisfying the total REC demand via fossil production against those associated with renewable production. Conversely, PEDs are mandated to maintain a net-zero balance for carbon emissions. Therefore, calculating emissions associated with RECs is important to gauge the emissions balance status, especially if aiming to align with net-zero objectives of PEDs and formulate suitable strategies.

Table 2. REC-to-PED indicators

Dimensions	Functions	Indicator	U. M.	
Membership	Participation	M	[−]	(1)
	Governance	$\frac{\#number\ of\ public\ initatives}{\#number\ of\ (public\ and\ private\ initiatives)}$	[−]	(2)
	Proximity	$\frac{2}{M(M-1)}\sum_{i=1}^{M}\sum_{j=i+1}^{M} d_{ij}$	[−]	(3)
Sustainability assessment	Avoided emissions	$\frac{\sum_i (E_{\text{prod}_i} \times ef_{\text{renew}})}{\sum_i (E_{\text{dem}_i} \times ef_{\text{fossil}})}$	t CO_2 eq.	(4)
	Energy efficiency	$\frac{\sum_i E_{\text{imp}_i}}{\sum_i E_{\text{exp}_i}} \times 100$	[%]	(5)
	Energy self-sufficiency ratio	$\frac{\sum_i (E_{\text{self}_i} + \sum_j E_{\text{sharing}_j})}{\sum_i E_{\text{dem}_i}} \times 100$	[%]	(6)
	Energy savings	$1 - \left[\frac{\sum_i E_{\text{imp}_i} \times cost_{\text{imp,energy}}}{\sum_i E_{\text{dem}_i} \times cost_{\text{imp,energy}}}\right] \times 100$	[%]	(7)
	Avoided expenses	$\frac{\sum_i E_{\text{self}_i}}{\sum_i E_{\text{dem}_i}} \times cost_{\text{imp,energy}}$	[€]	(8)
	Revenues	$\sum_j E_{\text{sharing}_j} \times cost_{\text{shared,energy}} + \sum_i E_{\text{exp,grid}_i} \times cost_{\text{exp,energy}}$	[€]	(9)
	Energy poverty rate	$\frac{\#number\ of\ members\ of\ REC\ in\ EP\ conditions}{M} \times 100$	[%]	(10)
Technology and operation	Average energy Production	$\frac{\sum_i E_{\text{prod}_i}}{M}$	[kWh]	(11)
	Average energy stored	$\frac{\sum_i E_{\text{stor}_i}}{M}$	[kWh]	(12)
	Self-consumption	$\frac{\sum_i E_{\text{prod}_i}}{\sum_i E_{\text{dem}_i}} \times 100$	[%]	(13)
	Energy sharing	$\frac{\sum_i (E_{\text{prod}_i} - E_{\text{self}_i} - E_{\text{exp}_i})}{\sum_i E_{\text{prod}_i}} \times 100$	[%]	(14)
	Energy import	$\sum_i E_{\text{imp}_i}$	[kWh]	(15)
	Energy export	$\sum_i E_{\text{exp}_i}$	[kWh]	(16)
	E-mobility	$\frac{\sum_i E_{\text{dem,mobility}_i}}{\sum_i E_{\text{dem}_i}} \times 100$	[%]	(17)

Indicators (5) and (6) pertain to energy-specific aspects and can be readily linked to two of the three PEDs' functions, as illustrated in **Figure 1**. In particular, indicator (5) evaluates the energy efficiency of the REC by comparing imported energy of all members to export energy and expresses it as a percentage. The definition of this indicator can be conceived as a sort of "energy efficiency" expressed in light of REC regulation. It reflects how well RECs target the main scope of minimizing the energy imports to align with sustainability goals and reduce dependence on non-renewable sources whilst fostering local renewable supply. The key in building this indicator lies in the definition of two main concepts arising from the context of energy performance assessment of REC, i.e. energy self-sufficiency and environmental and economic benefits. Therefore, a more "efficient" REC maximizes the use of locally produced renewable energy and minimizes the import from external grids yielding cost savings and emissions reduction related to energy production and transport from outside the REC boundaries. Indicator (6) is called energy self-sufficiency ratio and considers two crucial components: the self-consumed energy by each REC member and shared energy between REC members, evaluated in relation to the total energy demand. Energy self-sufficiency ratio is a key aspect for PEDs, as it reflects the REC's ability to adapt to changing energy needs and conditions. A higher level of energy self-sufficiency ratio allows for a more responsive and adaptable energy system. This includes balancing production and demand, especially utilizing exceeding production in periods when the demand is higher. Other applications could involve the adoption of smart controllers to allow for dynamic flow management. For these reasons, these two indicators are of particular relevance when planning the transition from RECs to PEDs. The economic perspective is addressed through indicators (7), (8) and (9), which focus on energy savings, avoided expenses and revenues, respectively. Indicator (7) calculates energy savings by comparing the total cost of energy imports to the total energy demand. It provides insight into the financial benefits of the REC's energy practises, highlighting potential cost reduction achieved from reduced imports through energy-efficient measures and renewable energy generation. Indicator (8) deals with avoided expenses and quantifies the proportion of self-consumed energy relative to total energy demand. This value is then multiplied by the cost of energy imports. It is relevant in the context of financial aspects and energy expenses, since is demonstrates how much expenditure can be avoided by producing and consuming energy internally within the REC, reducing reliance on external energy sources. Finally, the REC's financial performance is assessed in terms of revenues, as calculated through indicator (9). This indicator considers shared energy and energy exports, multiplied by their respective costs. It provides a comprehensive view of the financial gains generated by the REC's activities. The social perspective is addressed through indicator (10), which focuses on energy poverty rate. This indicator compares the number of REC members experiencing energy poverty conditions to the total number of members M. During the assessment stage of REC's transition, it is important to specify the criteria used to assess whether a REC member is experiencing energy poverty. This condition can be referred to low-income families with difficulties in paying the energy bills. In Italy this value is around 14.6%, as estimated the National Institute for Statistics **[27]**. It reflects the REC's efforts to ensure that all members have access to affordable and reliable energy services. Reducing energy poverty is a critical social objective for both RECs and PEDs, contributing to inclusive urban development.

The third dimension encompasses technological and operational aspects. Indicators (11) and indicator (12) evaluate energy production and storage, respectively. They consider the total energy produced and stored by all REC members and divide these values by the total number of members M. These indicators provide insights into the REC's capacity for energy generation and storage, essential for achieving self-sufficiency and reliability. Indicator (13) assesses self-consumption by comparing the energy produced to the energy demand for all REC members. It helps gauge the extent to which the REC relies on its internally generated energy, promoting self-sufficiency and reducing dependence on external energy sources. Indicator (14) addresses energy sharing by considering the energy produced minus self-consumed and exported energy, divided by the total energy produced. This indicator reflects the REC's commitment to collaborative energy practises, which can enhance resource utilization and community engagement and can represent the starting point to evaluate the energy balance for PEDs. Indicators (15) and (16) calculate total energy imports and energy exports for all REC members, respectively. These indicators quantify the REC's interactions with external energy sources, providing insights into its energy trade initiatives and dependence on the centralized energy grid. Lastly, indicator (17) centres on electric mobility and assesses the proportion of energy demand related to e-mobility in comparison to the total energy demand for all REC members.

Overall, these indicators provide a comprehensive framework for evaluating the REC's performance across various dimensions, including energy efficiency, economic viability, social equity, and technological capabilities, all of which are essential in the transition from existing RECs to the PED paradigm.

Practical implementation and reliability

As can be observed from **Figure 2**, a crucial step for a successful transition REC-to-PED transition consists in the practical implementation strategies. In terms of data collection and application, each indicator within the framework will be measured annually, i.e. in line with the annual balances available for PED's performance evaluation. This frequency also ensures a timely feedback for corrective actions, as provided in the scheme of **Figure 2**. Data analysis techniques may be implemented from RECs analysts, such as statistical methods based on averages and growth modelling to forecast future developments based on the current and measured data. In addition, by systematically tracking these indicators, it is possible to build historical databases and link to sustainability goals, such as those outlined in the European Green Deal [28] and the Agenda 2030 of the Sustainable Development [29]. To ensure continuous improvement and reliability of the proposed framework, it is fundamental to adopt a multi-stakeholder approach, providing engagement with REC members at various stages of the REC-to-PED design, implementation and operation. In addition, also local stakeholders, such as municipalities or energy providers should be involved in the discussion, with the main idea of collecting data and pursuit scenario analysis. Regular feedback mechanisms should also be facilitated, to allow interventions when and where needed. This collaborative approach ensures the framework's effectiveness, reliability and replication across diverse urban contexts.

CASE STUDY

This case study explores a REC located in Catania, Sicily, and constituted by 10 residential buildings, as a candidate REC for PED transition.

Italian RECs operate considering four main electrical fluxes, balanced as recommended in the Italian decree n. 414 of the Ministry for Energy and Environment [30]. These are:

- self-consumption, considered as the amount of energy consumed as part of the amount directly produced by the renewable energy installations owned by the REC;
- sharing, assumed as the energy virtually shared among REC members and deriving from the production of the renewable installations owned by the REC. In this case, according to the Italian rules, electrical energy is firstly exported to the grid, which acts as a storage system, but without accounting additional transmission or distribution costs.
- import, being the energy withdrawn from the grid to satisfy residual energy demand;
- export, being the effective energy surplus produced by the REC and not used for either self-consumption or sharing.

The study leverages hourly resolution data for electrical consumption from the ARERA database, the Italian regulator for energy [31]. The input data derived from the ARERA database includes date, time, and information distinguishing weekdays from weekends and public holidays. **Figure 3** reports the hourly trends of a residential unit for four typical days in each season.

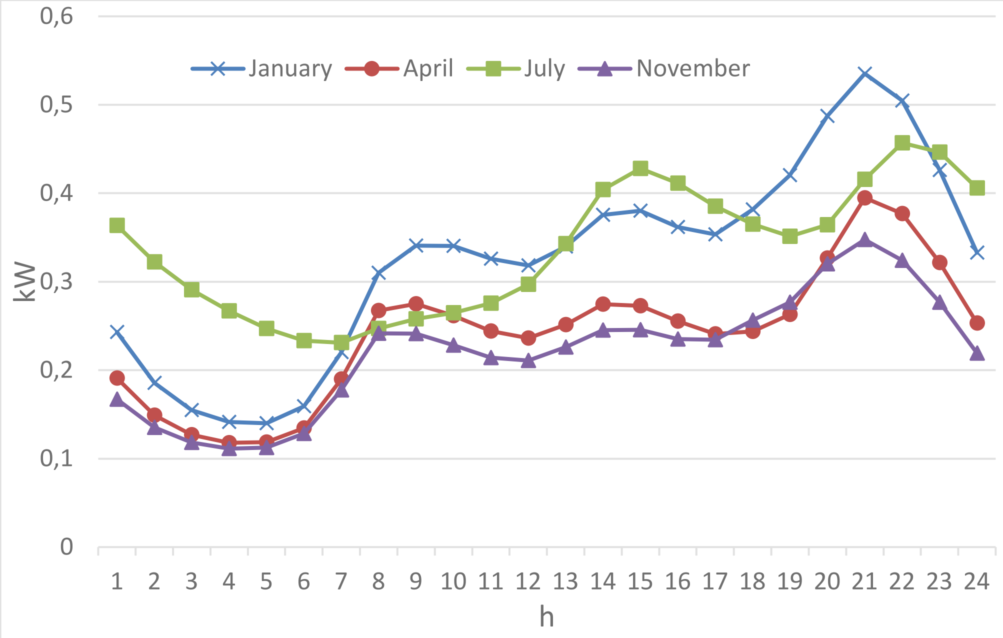

Figure 3. Typical daily electrical consumption for a residential unit

The case study considers three defined scenarios, each representing a strategic modification to the REC's configuration:

- #Sc0, baseline configuration.
  This scenario reports the actual performances of the REC, constituted by $M = 10$ members, each equipped with PV installations scaled on the available rooftop surface area per square meters and aiming to achieved an annual production of 2700 kWh per buildings, as in [32];
- #Sc1, increased PV capacity.
  In this case, the scenario takes inspiration by the need to expand the REC as a strategy for increasing self-sufficiency and achieve the sustainability targets recommended for RECs [33]. In this study, the increase of PV capacity has been set to 20 % of the initial PV size, contingent on available surface area;
- #Sc2, community expansion.
  This scenario accounts for two additional members to the REC and has been included to explore the dynamics of community scaling. PV insertion is considered for these members as well, to guarantee for equitably access to energy and benefits' sharing.

Figure 4 reports the number of families for each member of the REC, i.e. buildings or multi-apartments units, for the three scenarios. In particular, #Sc0 and #Sc1 account for the same number of families, whilst #Sc2 evaluates the impact of two additional members and related number of families and **Figure 5** reports the total electrical demand for each scenario.

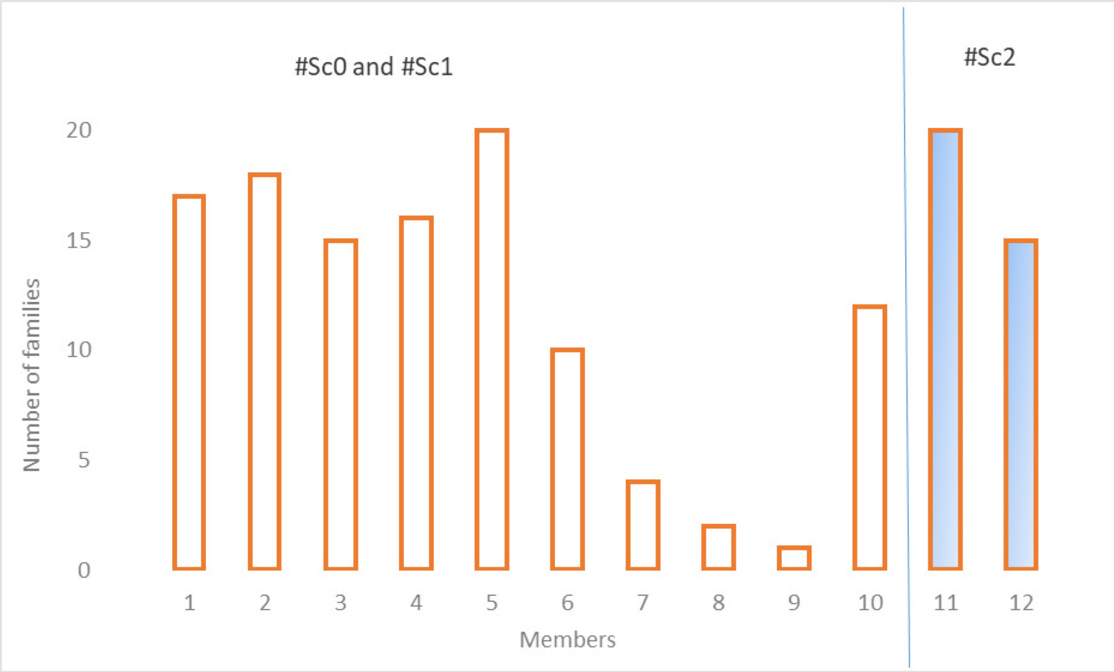

Figure 4. Number of families for each member of the REC

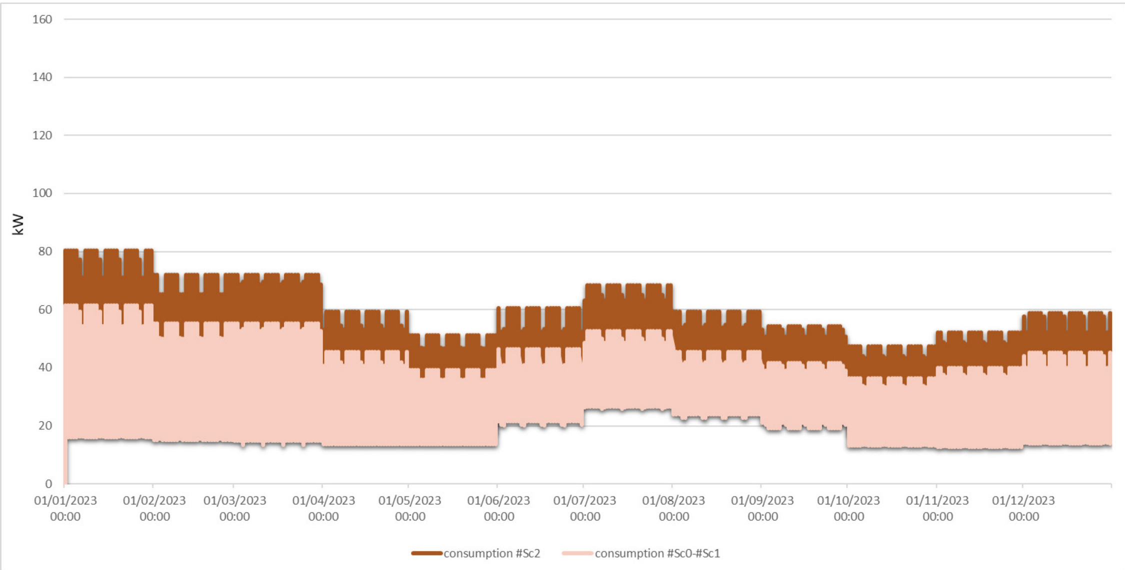

Figure 5. Energy consumption of the REC for the proposed REC configuration scenarios

Figure 6 represents the total electrical output from PV panels installed on the rooftop area of any building. With regard to the energy production, the study considers rooftop-mounted PV system, with 14% panel efficiency, and derived from the PVGIS tool [34]. It can be noticed that #Sc1 with respect to the baseline configuration of #Sc0 considers a 20% of PV size increase, whilst #Sc2 considers two additional contributions from new members, but no increase in the other member, i.e. as in the baseline configuration #Sc0.

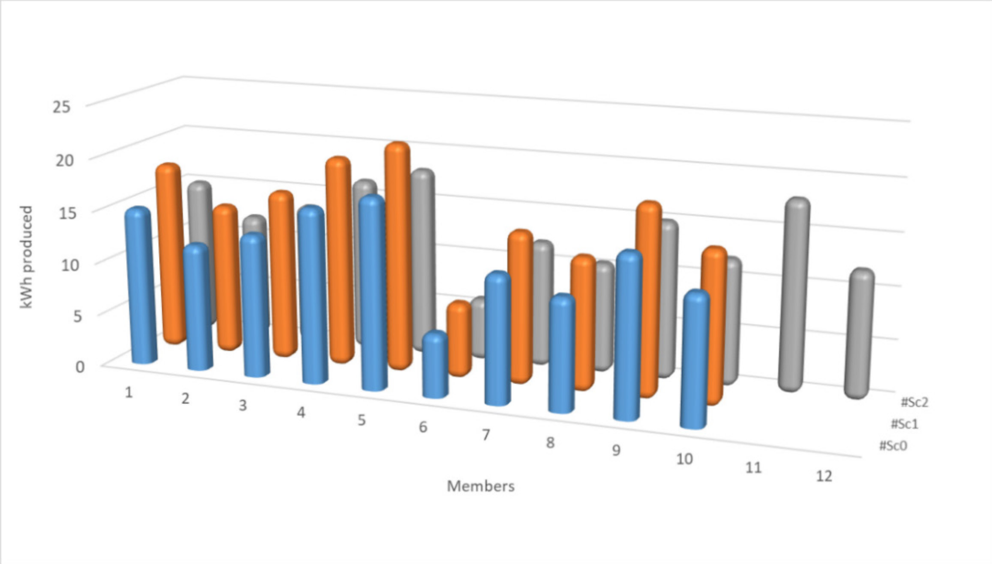

Figure 6. Typical monthly electrical production for 1 kW_p PV system

The presented scenarios are simulated using the optimization model developed in [35], specifically formulated for the Italian RECs. In this case study, PV systems typically have emission factors ranging from 15 to 50 g CO_2 eq./kWh, quantified considering manufacturing, transportation, installation, maintenance and decommissioning, and depending on the technology, location and efficiency. In this study, the average value of 30 g CO_2 eq./kWh have been chosen for calculations [36]. For fossil-based production, the average 0,278 kg CO_2 eq./kWh emission factor has been selected [37]. Regarding the costs input data, this study considered 0,15 €/kWh as the unit cost of electricity [31] and 0,12 €/kWh as the unit price of electricity in Italy [31].

RESULTS AND DISCUSSION

The results of this case study have been obtained by simulating the three different scenarios according to the regulation of the Italian normative [35]. Figure 7 shows the energy flows under the baseline configuration #Sc0, i.e. with each member of the REC utilizing rooftop PV installations. This is of fundamental importance to compare potential shift towards the PED paradigm.

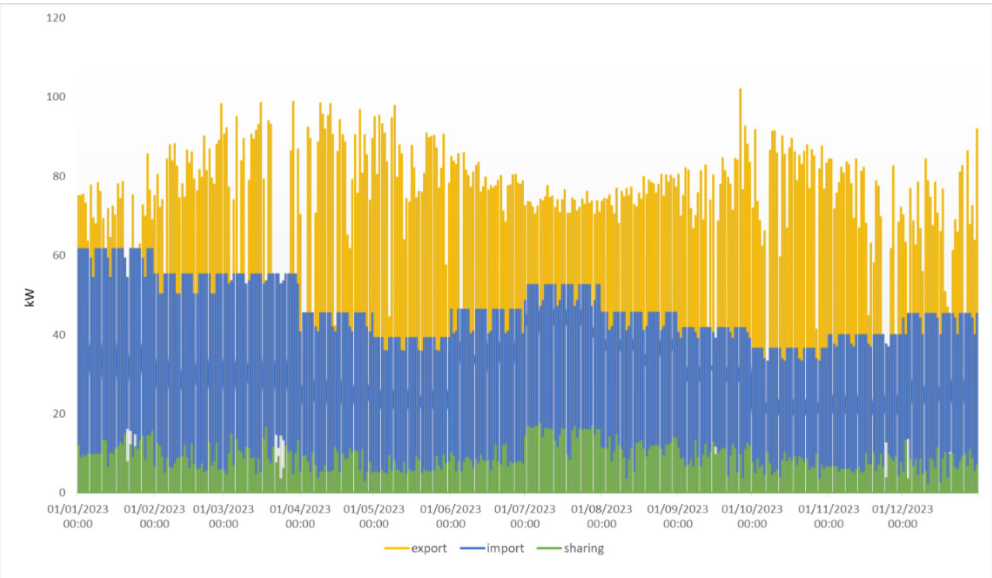

Figure 7. Export, import and sharing for #Sc0, baseline configuration

This scenario provides data on the current state of the REC performance without any enhancements, here studied either as increase of PV installation or community expansion. As can be observed, the reported values for imported energy highlights that, despite renewable production, the community is not fully self-sufficient, pointing to the need for further investments in production capacity or storage solutions if aiming to reach a higher level of energy self-sufficiency. On the other hand, the quantity of exported energy emphasizes the capability to have an energy surplus during certain periods, which can be considered as a critical aspect to evaluate the transition towards the PED paradigm. **Figure 8** details the changes of the energy export, import and sharing for #Sc1 when the PV capacity of each member is increased. This corresponds to an increase in both the energy produced and exported, suggesting improved energy production capability. Indeed, the impact of scaling up renewable energy installations within the community highlight the potential for greater autonomy and reduced grid dependence.

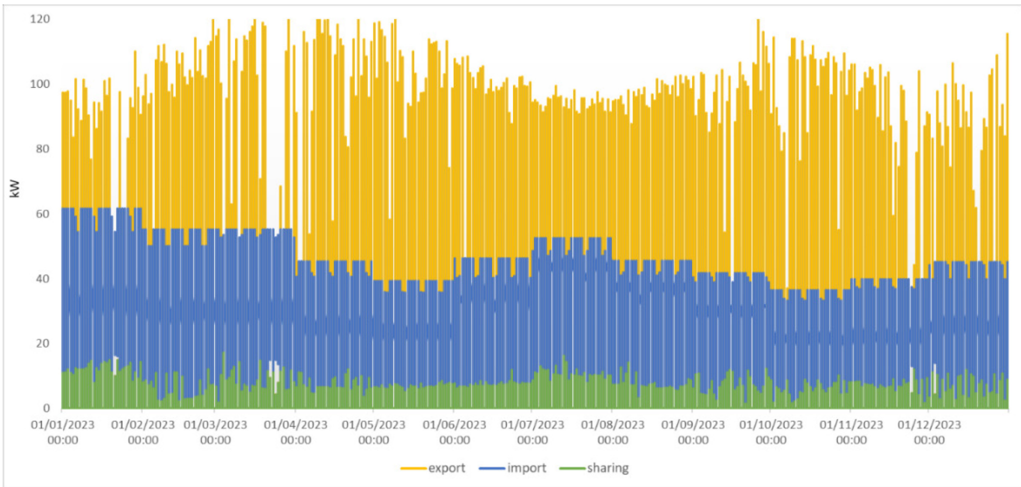

Figure 8. Export, import and sharing for #Sc1, increased PV capacity

With more energy produced locally, the energy import decreases consequently, representing a substantial step towards PED both in terms of reduced grid independence and reduced environmental impact. Indeed, the increased production capacity not only contributes to cover the internal consumption but also allows for greater export of energy surpluses, a fundamental feature of PEDs, where production exceeds consumption.

Finally, **Figure 9** explores the effect of expanding the community by adding to new members, as in the #Sc2. Adding new members significantly increases overall consumption and requires for further investments to put into place PED strategies.

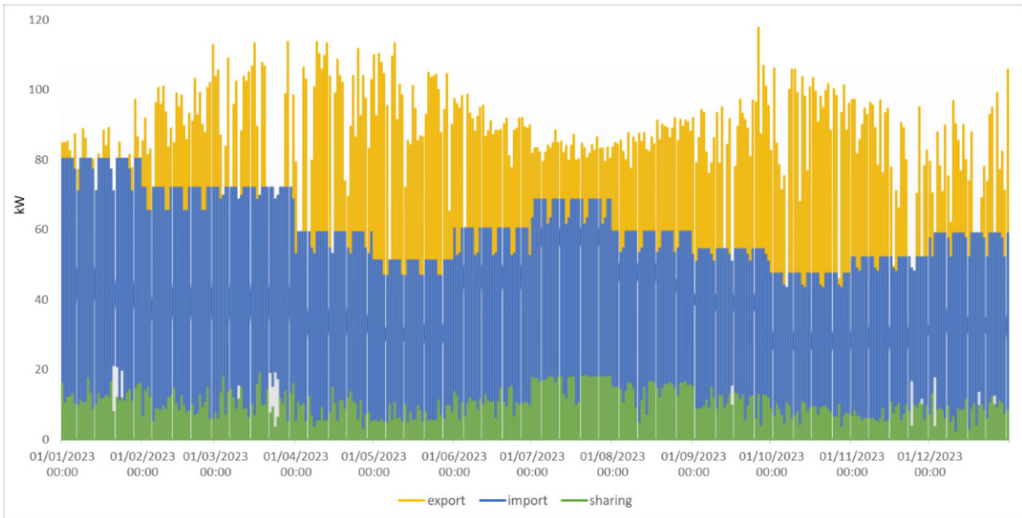

Figure 9. Export, import and sharing for #Sc2, community expansion

Table 3 reports the indicators that can be used to evaluate the transition from REC to PED, as suggested in **Table 2**. The indicators are assessed across the three different scenarios to discuss how changes in energy production capacity or community expansion can affect the feasibility of a REC to become a PED. As can be observed, the indicators are grouped in terms of membership, sustainability assessment, technology and operation, the dimensions identified in **Table 1**, being some of them belonging to energy flows and properly highlighted here.

Table 3. Calculated REC-to-PED indicators

Dimension	Indicator	#Sc0	#Sc1	#Sc2	UoM
Membership	Participation	115	115	150	[-]
	Governance	N/A	N/A	N/A	
	Proximity	N/A	N/A	N/A	
Sustainability assessment	Avoided emissions	29616.1	30374.8	38080.4	kg CO_2 eq./year
	Energy efficiency	87%	116%	74%	[%]
	Energy self-sufficiency ratio	40%	41%	39%	[%]
	Energy savings	N/A	N/A	N/A	
	Avoided expenses	14680.71	15284.21	19106.16	€/year
	Revenues	17950.99	23399.96	19956.70	€/year
	Energy poverty rate	N/A	N/A	N/A	
Technology and operation	Average energy production	2151.8	2581.68	1957.86	kWh/member
	Average energy stored	N/A	N/A	N/A	
	Self-consumptio n	43%	34%	43%	%
	Self-sufficiency	40%	41%	39%	%
	Energy sharing	3%	2%	3%	%
	Energy import	171663.30	167640.08	224190.92	kWh/year
	Energy export	149591.59	194999.70	166305.83	kWh/year
	E-mobility	N/A	N/A	N/A	
Energy flows	Annual consumed	269535.29	269535.29	351565.29	kWh/year
	Annual self-consumption	97871.45	101894.75	127374.41	kWh/year
	Annual sharing	8661.19	7367.20	9605.29	kWh/year
	Annual produced	247462.75	296894.05	293680.28	kWh/year
PED rate	Production over consumption	92%	110%	84%	%

Annual exported, imported and produced energy are reported at varying the three scenarios: as can be observed, export and import are critical for understanding the balance of local production versus grid dependency. In particular, #Sc1 has the highest annual exported energy and a significant improvement in energy self-consumption, thus indicating better self-sufficiency. Self-consumption and energy sharing, on the other hand, are critical for a REC moving towards the PED paradigm: in this regard, higher self-consumption (#Sc1) indicates an effective use of locally generated energy, reducing reliance on external sources and enhancing community resilience.

The assessment of sustainability-related indicators permits to have a multi-faceted discussion across the three scenarios. The avoided emissions increase across scenarios, being higher in #Sc2 with a value of 38080.4 kg CO_2 eq./year and therefore showing that larger communities can significantly contribute to reducing carbon emissions. On the other hand, #Sc1 achieves the highest energy efficiency, 116%, and higher energy self-sufficiency, 41%, demonstrating the benefits of increased PV capacity. Compared with #Sc0, the financial assessment for #Sc1 and #Sc2 shows that in the case of #Sc1 there are higher opportunity for revenues, whilst higher avoided expenses are achieved in #Sc2.

From the energy management viewpoint, beyond the energy flows and self-sufficiency already discusses, it can be noticed that energy sharing is similar for the three scenarios, with a decrease in #Sc2 due to the higher export (and, therefore, revenues) to the grid.

Finally, a PED rate is evidenced in the last row of **Table 3**, obtained as the production over consumption: this indicator is pivotal to assess the potential achievement of the PED status. Here, as can be noticed, only #Sc1 excesses the 100%, indicating that this REC configuration produces more energy than it consumes, one of the two fundamental criteria for a PED. Based on the variability observed for this indicator, where only increasing energy production leads to the PED status, it is worth highlighting that simply expanding the membership of the REC is not sufficient (and may even diminish the performances) in designing the optimal configuration for the REC-to-PED process. This means that effective transition to PEDs requires also a substantial infrastructure and technological investment, particularly in renewable energy installations and batteries or in different operational and management procedures, here constrained by the Italian regulation. At the same time, some indicators, like energy poverty rate, energy stored or mobility require a higher level of data availability and have not been calculated for the available case study.

Expected impact and limitations of the developed framework

The developed framework of indicators for the REC-to-PED transition shows multifaceted impacts on the consumer-based energy communities, as it integrates not only quantitative and qualitative indicators across technical, social, economic and environmental dimensions (all specified with easy-to-calculate measures), but also provides insights for future collective urban forms evolutions. The expected impacts can be highlighted for the three identified dimensions of **Table 1**:

- Membership
  The framework of indicators can influence energy policies and regulations at local and national level, being it scalable to different existing RECs and independent from the national regulations. In this perspective, it can be used to assess how RECs can be integrated into broader energy systems, or into broader energy concepts. At the same time, the REC-to-PED framework can also serve as a standard for assessing and implementing transition in diverse contexts;
- Sustainability Assessment
  The framework supports RECs in becoming economically viable by optimizing operations to reduce energy costs and maximize revenues from energy sharing and import/export. In this sense, it indicates pathways for making RECs more attractive to investors. It also fosters the role of community members as active participants, favouring the inclusion of families in energy poverty conditions thanks to the revenues originating

from sharing and export. Finally, the framework also supports the evolution of existing RECs into more environmental-friendly communities, as PEDs are characterized by net-zero carbon balances, therefore aligning with the objectives of the European Green Deal:

- Technology and operation
  The framework facilitates the management of energy flows deriving from production, consumption, and storage, promoting energy independence from national grids. This is particularly crucial for PEDs, which aim for a net-positive energy surplus.

Finally, the REC-to-PED framework can also be able to catalyse a wider adoption of the indicators, even for contexts and applications to diverse urban sustainability initiatives, being it developed to measure benefits from various perspectives.
On the other hand, limitations can be identified in the difficulty to have specific data at the local level, such as for mobility management and spatial allocations of energy production and consumption units if pointing to have a physical energy distribution infrastructure and not only virtually managed flows. In addition, further studies should be focused on assess the impact of subsidies and regulatory/policy barriers.

CONCLUSIONS

The transition from a REC to a PED requires long-term commitment, meticulous planning, collaboration among local actors and a shared vision for sustainable urban areas. In particular, this research focused on the importance of a comprehensive framework supporting stakeholders in this transition, and provided a set of indicators useful to evaluate the performance of RECs and the evolution into PEDs.

The research identified different aspects to be considered as crucial to drive this transition:

- Membership and governance, with an emphasis on understanding the size and composition of these energy communities, highlighting the diversity of stakeholders involved, and delving into the governance aspect by assessing the influence of public versus private initiatives in driving the transition;
- Proximity and territorial implications, including the geographical distribution of REC members, the territorial expansion and density, underscoring the importance of cohesive community development;
- Energetic, environmental and economic aspects, in terms of reducing its carbon footprint, achieving energy efficiency and realizing economic benefits through the evaluation of energy savings, avoided expenses, and revenues;
- Social considerations, addressing energy poverty within the community and highlighting the commitment to ensuring equitable access to affordable and reliable energy services;
- Technological and operational aspects, assessing various facets, including energy production, storage, self-consumption, energy sharing, imports, exports, and the integration of electrical mobility.

In conclusion, this research underscored the pivotal role of a comprehensive framework and dedicated indicators in evaluating and guiding the transition from RECs to PEDs. By examining membership, governance, proximity, sustainability aspects, and technological aspects, communities can make informed decisions, measure their progress, and work towards more sustainable and resilient energy systems. Additionally, these indicators offer a holistic approach to evaluating the multifaceted dimensions of energy initiative, contributing to the broader goal of achieving climate neutrality and sustainable urban development.

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NOMENCLATURE

$cost_{\mathrm{imp,energy}}$	Unitary cost for energy imported from the grid	[€/kWh]
$cost_{\mathrm{shared,energy}}$	Unitary cost for energy shared among members	[€/kWh]
$cost_{\mathrm{exp,energy}}$	Unitary cost for energy exported from the grid	[€/kWh]
d_{ij}	Distance between member i and j	[m]
ef_{fossil}	Emission factor associated to fossil sources	g CO_2 eq./kWh
ef_{renew}	Emission factor associated to renewable sources	g CO_2 eq./kWh
E_{prod_i}	Energy production of member *i*	[kWh]
E_{dem_i}	Energy demand of member *i*	[kWh]
E_{imp_i}	Energy imported from the grid for each member *i*	[kWh]
E_{exp_i}	Energy exported to the grid for each member *i*	[kWh]
E_{self_i}	Energy self-consumed for each member *i*	[kWh]
E_{sharing_i}	Energy shared by each member *i*	[kWh]
E_{stor_i}	Energy stored by each member *i*	[kWh]
$E_{\mathrm{dem,mobility}_i}$	Energy demand for mobility of each member *i*	[kWh]
$i, j \in \{1, \ldots, M\}$	Set of members of a REC	[-]

Abbreviations

EP	Energy Poverty
PED	Positive Energy District
REC	Renewable Energy Community
SDG	Sustainable Development Goal

REFERENCES

1. "Directive - 2018/2001 - EN - EUR-Lex." Accessed: Feb. 08, 2024. [Online]. Available: https://eur-lex.europa.eu/eli/dir/2018/2001/oj.
2. E. Cutore, A. Fichera, and R. Volpe, "A Roadmap for the Design, Operation and Monitoring of Renewable Energy Communities in Italy," Sustainability, vol. 15, no. 10, Art. no. 10, Jan. 2023, https://doi.org/10.3390/su15108118.
3. "Gazzetta Ufficiale." Accessed: Feb. 08, 2024. [Online]. Available: https://www.gazzettaufficiale.it/atto/serie_generale/caricaDettaglioAtto/originario?atto.dataPubblicazioneGazzetta=2021-11-30&atto.codiceRedazionale=21G00214&elenco30giorni=true.
4. C. D'Alpaos and F. Andreolli, "Renewable Energy Communities: The Challenge for New Policy and Regulatory Frameworks Design," in New Metropolitan Perspectives, C. Bevilacqua, F. Calabrò, and L. Della Spina, Eds., in Smart Innovation, Systems and Technologies. Cham: Springer International Publishing, 2021, pp. 500–509, https://doi.org/10.1007/978-3-030-48279-4_47.
5. X. Masip, E. Fuster-Palop, C. Prades-Gil, J. D. Viana-Fons, J. Payá, and E. Navarro-Peris, "Case study of electric and DHW energy communities in a Mediterranean district," Renew. Sustain. Energy Rev., vol. 178, p. 113234, May 2023, https://doi.org/10.1016/j.rser.2023.113234.
6. R. Sudhoff, S. Schreck, S. Thiem, and S. Niessen, "Operating Renewable Energy Communities to Reduce Power Peaks in the Distribution Grid: An Analysis on Grid-Friendliness, Different Shares of Participants, and Economic Benefits," Energies, vol. 15, no. 15, Art. no. 15, Jan. 2022, https://doi.org/10.3390/en15155468.
7. M. Stefan, P. Zehetbauer, S. Cejka, F. Zeilinger, and G. Taljan, "Blockchain-based self-consumption optimisation and energy trading in renewable energy communities," CIRED - Open Access Proc. J., vol. 2020, no. 1, pp. 371–374, Apr. 2021, https://doi.org/10.1049/oap-cired.2021.0061.
8. A. Cielo, P. Margiaria, P. Lazzeroni, I. Mariuzzo, and M. Repetto, "Renewable Energy Communities business models under the 2020 Italian regulation," J. Clean. Prod., vol. 316, p. 128217, Sep. 2021, https://doi.org/10.1016/j.jclepro.2021.128217.
9. S. Viti, A. Lanzini, F. D. Minuto, M. Caldera, and R. Borchiellini, "Techno-economic comparison of buildings acting as Single-Self Consumers or as energy community through multiple economic scenarios," Sustain. Cities Soc., vol. 61, p. 102342, Oct. 2020, https://doi.org/10.1016/j.scs.2020.102342.
10. I. Marotta, T. Péan, F. Guarino, S. Longo, M. Cellura, and J. Salom, "Towards Positive Energy Districts: Energy Renovation of a Mediterranean District and Activation of Energy Flexibility," Solar, vol. 3, no. 2, Art. no. 2, Jun. 2023, https://doi.org/10.3390/solar3020016.
11. R. Trevisan, E. Ghiani, and F. Pilo, "Renewable Energy Communities in Positive Energy Districts: A Governance and Realisation Framework in Compliance with the Italian Regulation," Smart Cities, vol. 6, no. 1, Art. no. 1, Feb. 2023, https://doi.org/10.3390/smartcities6010026.
12. B. Alpagut, Ö. Akyürek, and E. M. Mitre, "Positive Energy Districts Methodology and Its Replication Potential," Proceedings, vol. 20, no. 1, Art. no. 1, 2019, https://doi.org/10.3390/proceedings2019020008.
13. L. Casamassima, L. Bottecchia, A. Bruck, L. Kranzl, and R. Haas, "Economic, social, and environmental aspects of Positive Energy Districts—A review," WIREs Energy Environ., vol. 11, no. 6, p. e452, 2022, https://doi.org/10.1002/wene.452.
14. M.-T. Nguyen and S. Batel, "A Critical Framework to Develop Human-Centric Positive Energy Districts: Towards Justice, Inclusion, and Well-Being," Front. Sustain. Cities, vol. 3, 2021, Accessed: Feb. 08, 2024. [Online]. Available: https://www.frontiersin.org/articles/10.3389/frsc.2021.691236.

15. J. P. Gouveia, J. Seixas, P. Palma, H. Duarte, H. Luz, and G. B. Cavadini, "Positive Energy District: A Model for Historic Districts to Address Energy Poverty," Front. Sustain. Cities, vol. 3, 2021, Accessed: Feb. 08, 2024. [Online]. Available: https://www.frontiersin.org/articles/10.3389/frsc.2021.648473.
16. X. Zhang et al., "Digital Twin for Accelerating Sustainability in Positive Energy District: A Review of Simulation Tools and Applications," Front. Sustain. Cities, vol. 3, Jun. 2021, https://doi.org/10.3389/frsc.2021.663269.
17. S. G. Krangsås et al., "Positive Energy Districts: Identifying Challenges and Interdependencies," Sustainability, vol. 13, no. 19, Art. no. 19, Jan. 2021, https://doi.org/10.3390/su131910551.
18. J. Brozovsky, A. Gustavsen, and N. Gaitani, "Zero emission neighbourhoods and positive energy districts – A state-of-the-art review," Sustain. Cities Soc., vol. 72, p. 103013, Sep. 2021, https://doi.org/10.1016/j.scs.2021.103013.
19. E. Derkenbaeva, S. Halleck Vega, G. J. Hofstede, and E. van Leeuwen, "Positive energy districts: Mainstreaming energy transition in urban areas," Renew. Sustain. Energy Rev., vol. 153, p. 111782, Jan. 2022, https://doi.org/10.1016/j.rser.2021.111782.
20. O. Lindholm, H. ur Rehman, and F. Reda, "Positioning Positive Energy Districts in European Cities," Buildings, vol. 11, no. 1, Art. no. 1, Jan. 2021, https://doi.org/10.3390/buildings11010019.
21. "The European Green Deal - European Commission." Accessed: Feb. 08, 2024. [Online]. Available: https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en.
22. "Strategic Energy Technology Plan." Accessed: Feb. 08, 2024. [Online]. Available: https://energy.ec.europa.eu/topics/research-and-technology/strategic-energy-technology-plan_en.
23. "Positive Energy Districts (PED)," JPI Urban Europe. Accessed: Feb. 08, 2024. [Online]. Available: https://jpi-urbaneurope.eu/ped/.
24. D. Hoogenboom, "Driving Urban Transitions to a sustainable future - DUT Partnership." Accessed: Feb. 08, 2024. [Online]. Available: https://dutpartnership.eu/.
25. "IEA EBC || Annex 83 || Positive Energy Districts || IEA EBC || Annex 83." Accessed: Feb. 08, 2024. [Online]. Available: https://annex83.iea-ebc.org.
26. "PED-EU-NET | COST ACTION CA19126 – Positive Energy Districts European Network." Accessed: Feb. 08, 2024. [Online]. Available: https://pedeu.net.
27. "Istat.it." Accessed: May 03, 2024. [Online]. Available: https://www.istat.it.
28. European Commission, "Communication From The Commission, The European Green Deal", COM(2019) 640 final, Accessed: May 03, 2024. [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2019%3A640%3AFIN.
29. "The 2030 Agenda for Sustainable Development." United Nations. Accessed: May. 14, 2024. [Online]. Available: https://sustainabledevelopment.un.org/content/documents/21252030%20Agenda%20for%20Sustainable%20Development%20web.pdf.
30. "DECRETO CACER e TIAD – Regole operative per l'accesso al servizio per l'autoconsumo diffuso e al contributo PNRR", Accessed: May 03, 2024. [Online]. Available: https://www.mase.gov.it/sites/default/files/ALLEGATO%201%20Regole%20operative%20CACER%20def.pdf.
31. "Arera: Home | ARERA." Accessed: May 03, 2024. [Online]. Available: https://www.arera.it.
32. A. Fichera, R. Volpe, and M. Frasca, "Assessment of the Energy Distribution in Urban Areas by Using the Framework of Complex Network Theory," Int. J. Heat Technol., vol. 34, no. S2, pp. S430–S434, Oct. 2016, https://doi.org/10.18280/ijht.34S234.

33. E. Cutore, A. Fichera, and R. Volpe, "A Roadmap for the Design, Operation and Monitoring of Renewable Energy Communities in Italy," Sustainability, vol. 15, no. 10, Art. no. 10, Jan. 2023, https://doi.org/10.3390/su15108118.
34. "JRC Photovoltaic Geographical Information System (PVGIS) - European Commission." Accessed: May 03, 2024. [Online]. Available: https://re.jrc.ec.europa.eu/pvg_tools/en/.
35. E. Cutore, R. Volpe, R. Sgroi, and A. Fichera, "Energy management and sustainability assessment of renewable energy communities: The Italian context," Energy Convers. Manag., vol. 278, p. 116713, Feb. 2023, https://doi.org/10.1016/j.enconman.2023.116713.
36. B. Koffi, A. Cerutti, M. Duerr, A. Iancu, A. Kona, and G. Janssens-Maenhout, "CoM Default Emission Factors for the Member States of the European Union," 2017. Accessed: May 03, 2024. [Online]. Available: https://eu-mayors.ec.europa.eu/sites/default/files/2022-10/JRC-CoM-EF-CoMW-EF-2017.pdf.
37. "CO2 emissions per kWh in Italy - Nowtricity." Accessed: May 03, 2024. [Online]. Available: https://www.nowtricity.com/country/italy/.

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