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Towards the Implementation of Renewable Energy Communities in Various Application Fields in Italy

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Abstract: The European Union has introduced Renewable Energy Communities as a key component of its strategy to transform the energy sector, aiming to achieve climate neutrality by 2050. This study presents case studies of Renewable Energy Communities based on numerical and experimental investigations across various application fields in Italy, highlighting different types of stakeholders and energy configurations. The implementation of RECs is subject to a range of challenges, including diverse procedural requirements, stakeholder roles, and legal and technical constraints, which must be addressed to secure approval from national authorities. The first case study examines a photovoltaic-based energy community in Southern Italy, designed to mitigate energy poverty by supporting families unable to meet their essential energy needs. A second case study explores the benefits of a Renewable Energy Community in the industrial area of Benevento (South of Italy), which integrates a mixed-use building with an industrial wastewater treatment plant, focusing on energy sharing and environmental sustainability. The final case study investigates a Renewable Energy Community that incorporates electric vehicle charging stations, demonstrating its potential to enhance their diffusion on the territory and increase the community's self-consumption rate. Overall, the establishment of a Renewable Energy Community provides superior outcomes compared to conventional configurations of end-users regardless of the application field or the typology of members, from an energy, environmental and economic viewpoint, with additional positive outcomes possible depending on local circumstances.

Keywords: Renewable energy community; Renewable energy sources; Energy sharing; Energy transition; Energy management; Smart energy systems

1 Introduction

Climate change and global warming effects, which are affecting the whole world, make necessary tangible actions to reduce consequent natural disasters and global temperature increase. In 2015, the signatory countries of the Paris Agreement collectively committed to achieving the long-term objective of keeping the increase in global average temperature well below 2°C with respect to pre-industrial levels and pursuing efforts to limit it to 1.5°C [1].

From this perspective, the European Union (EU) put in play several directives to define the way to follow. The "*Fit for 55*" package of legislation makes all sectors of the EU economy fit to meet the ambitious target of achieving carbon neutrality by 2050. Under the European Climate Law, the EU committed to reducing its net greenhouse gas (GHG) emissions by at least 55% by 2030 [2]. Shifting from fossil fuels to renewable energy sources (RES) and improving energy efficiency are the main targets and policy objectives for the period from 2021 to 2030, established by the European 2030 Climate and Energy Framework [3].

In line with the achievement of these goals, the Clean Energy for All Europeans Package, which consists of eight laws, marks a significant step to help European citizens move towards cleaner energy [4]. In particular, through the EU 2018/2001- Renewable Energy Directive (RED II) [5] and EU 2019/944- International Market Energy Directive (IEMD) [6], for the first time, cooperation of citizens in community-shared energy projects is introduced. IEMD regulates the internal electricity market for its renewal by introducing active final customers who consume or store generated electricity.

Whereas RED II introduces in European legislation Renewable Energy Communities (RECs), a set of energy utilities (private, public, or mixed) located in a specific area in which end-users, who can be private citizens, small and medium enterprises (SMEs) or local authorities, satisfy their energy needs by adopting a cooperative approach through the use of distributed energy generation solutions promoting the use of RES and the intelligent management of energy flows in order to obtain benefits in terms of costs, sustainability and safety [7].

RECs are based on the "sharing" concept, reconsidered after the 2008 financial crisis that led to reevaluating the conventional idea of ownership [8]. Nowadays, several sectors, such as cinema, fashion and transport, offer services based on the sharing of an asset rather than on the purchase of the same. The renewed interest in a collective approach allows the energy field to efficiently operate plants that can serve multiple users, load sharing or the co-ownership of plants by several users who perhaps could not have individually. The great potential of the direct involvement of citizens makes RECs a key agent in the energy transition process [9].

Transposition of the European Directive into national laws should have been completed by June 2021 in all European states, with the aim of making possible the REC implementation in the whole European territory. Nevertheless, some states have still to align with it. The majority of EU countries introduced RECs in the national regulatory framework, even if different cultural and normative contexts already existing in each of them have led to legislative transpositions that differ state by state in some aspects [10].

In Italy, after two regional self-consumption laws, previous RED II, the transposition of the European Directive into national law has been characterized by two main phases. The first transposition started at the end of 2019 through art. 42 bis of Legislative Decree 162/2019 [11], then converted into Law No. 8/2020 [12], allowing REC members linked to the same electrical substation MV/LV, from medium (MV) to low voltage (LV), to share electric energy. The maximum power of each plant included in a REC was fixed at 200 kW. The final transposition of RED II, as part of the Legislative Decree n.199 in 2021 [13] and Ministerial Decree 414/2023 in 2024 [14], modified the previous limits, bringing the maximum power of the single plant of the REC to 1 MW and the possibility of including members that are underlying the same HV/MV electric substation, from high voltage (HV) to MV. Moreover, the chance to become a REC member has been extended to research bodies, religious and third sector bodies. The Italian regulatory framework also introduced a premium tariff for shared energy among REC members, recognized for a period of 20 years, with a value of between 60 €/MWh and 120 €/MWh, depending on the size of the plant and the energy price of the corresponding market zone [14].

Besides economic incentives for REC members, several advantages are provided to the territory where the configuration is implemented regarding environmental impact savings and additional services to the community.

Indeed, part of a REC can offer greater control of energy consumption and reduction of related GHG emissions. In order to maximize shared energy to have simultaneous production from the RES-based plant and energy consumption of members, indications about the best moments to increase or decrease consumption are given to end-users. This also depends on the sources used for the production plant. Nowadays, solar photovoltaic (PV) is the most diffused RES technology, especially due to wide market spread and national incentives, therefore low cost, and modularity of systems [15]. However, REC configurations based on RES-based plants different from PV, such as wind turbines or biomass power plants, are emerging [16, 17]. The critical acceptability of installations for RES exploitation in some areas can be contrasted through the direct involvement of citizens in the energy choices and consequent economic impact of REC.

On the basis of RED II, each REC should support the use of local RES, which are different depending on the concerned location. The use of technologies with a high rate of national component also represents an advantage in terms of foreign dependence reduction. The use of different RES systems also contributes to the development of a local short supply chain, offering employment to local citizens and economic benefits to the area. In this way, internal areas that are otherwise at risk of depopulation can become more and more attractive to citizens and businesses.

The territory where a REC is established can also offer its inhabitants electric vehicle (EV) recharging stations. Their integration as REC's point of delivery (POD) allows for the increased diffusion of these services on the territory, offering the final consumers the certainty to use energy from RES and, to the REC, the maximization of shared energy.

As the economic incentives are calculated on the latter, different optimization techniques are focused on valuing the best configuration of end-users to include in the same project. Different consumer typologies involve different energy demands and load profile trends; in addition, demand-side management (DSM) methods could be implemented.

Environmental impact reduction and primary energy savings are directly correlated to the increase in shared energy. In addition, using electric energy from RES plants of the REC can also offer members economic savings from other energy carriers' purchases. For example, if a gas-fired energy conversion system, such as a boiler, is replaced by an electric heat pump (EHP), the share of shared energy can be maximized, and gas bills can be reduced.

Power grid (PG) benefits from the flexibility services made available by RECs, whose members reduce the amount of electricity imported to hours when production is less than energy demand, and energy from RES is fed into PG when there is a surplus production.

The potential of RECs consists of offering democratic management models with direct involvement of citizens in energy transition achievement. Social purposes can be addressed by encouraging the participation of low-income citizens in these projects, offering them the opportunity to not give up on essential energy services such as heating, cooling or lighting, and reducing the so-called “energy poverty”. People who return to difficulty in paying energy bills or inability to ensure thermo-hygrometric comfort conditions within the home increased during the years, as reported by Eurostat; Europeans unable to keep their homes adequately warm grew from 9.3% in 2022 to 10.6% in 2023 [18]. This condition got worse because of the COVID-19 pandemic, geopolitical crises and ongoing conflicts.

The aim of this study is to highlight the advantages of RECs through evidence analysis from case studies based on numerical and experimental investigations that involve different actors and have implications in various application fields.

2 Implementation of a REC in Italy

The implementation of a REC is not a very smooth process, since the steps to be taken vary greatly depending on the involved parties, the approach to be taken and the objectives to be achieved by the configuration. In addition, numerous technical and legal constraints must be respected by the REC to be recognized by the national authority.

The Italian regulatory framework, according to the most recent laws in force [14], requires that specific constraints have to be respected. In particular:

- REC has to be an autonomous legal entity based on the open and voluntary participation of its members;
- RES-based plants held by the REC can have a power not exceeding 1 MW (to receive economic incentives);
- Members of the REC may be natural persons, SMEs, local authorities, including municipal administrations, religious, third sector and research bodies;
- All REC members must be connected to the same electrical substation HV/MV.

In literature, some attempts have been made to standardize the critical phases, taking into account the main stages depending on the country in which the process is applied to comply with the local regulatory framework.

Esposito et al. [19] presented a roadmap for the implementation of a REC, including four main phases. The first one is the feasibility study, which focuses on characterizing energy users, that could be carried out with a bottom-up or a top-down approach, depending on the analysis of real energy consumption data of end-users or the use of macroeconomic variables and statistical data to make energy forecasts. Sizing plants with dedicated software and assessing the project’s impact in terms of primary energy savings, reduction of environmental impact, cost avoidance and social purposes compared to conventional systems are also included in the initial step.

The second phase concerns aggregation, which involves bringing together REC members who can be producers, consumers, or prosumers. The idea of creating a REC may originate from a group of private citizens with a common purpose, as from an SME which could make its own resources available for the construction of a plant; alternatively, if the REC is initiated by a municipality, an expression of interest is conducted to gather the intentions of private citizens who wish to participate. The energy analysis, conducted during the feasibility study, allows for the aggregation of the most appropriate types of members, ensuring compliance with the legal proximity constraints and proper design of the RES-based plants. This phase also includes the legal establishment of the entity and exploring potential funding opportunities for public-driven projects or private members. Indeed, REC must be a legal entity of a collective type, with or without legal personality and without profit as its main purpose. Among the possible legal forms, the REC can be constituted as a cooperative, association (recognised or unrecognised), foundation or social enterprise.

The third phase of the roadmap is the operating phase, which encompasses the design and construction of production plants and the agreement phase between the REC and the national competent authority. During this phase, constraints are assessed, and incentives are dispensed. Including different plant typologies, sizes, ownership and RES, different REC configurations are possible. Some of the most common types of configurations are:

- Residential REC: Composed entirely of residential members, a private citizen may be the plant owner;
- Municipality-driven REC: Communities composed of private citizens, SMEs, and local authorities, who act as project promoters and may realize their plants with public funds;
- Industrial RECs: Located in industrial areas, where SMEs and factories are community members. In this case, one of the members may be the plant owner, as there are many investment opportunities to realize medium or larger plants;
- Multi-user RECs: Members can include private citizens, offices, small businesses, and religious organizations, each with different energy needs and investment capacities. In this configuration, one member can be the plant’s owner.

The final phase concerns management, which involves not only the economic aspects of the REC but also includes monitoring and maintenance of the plants and dissemination activities.

This procedure may need to be adjusted to comply with the legal framework of the country where the configuration is to be implemented. Steps may be advanced or postponed as needed. The roadmap can also be expanded if the designer determines that additional steps are necessary, or other steps can be omitted if not required by the relevant authorities or considered unnecessary.

Cutore et al. [20] proposed a structured procedure to orient stakeholders during all stages of the REC constitution process. Stakeholders' decisions, normative and regulatory issues, technological and operational aspects are some of the main factors that impact the constitution process of RECs. The roadmap can have a positive impact on all members of the REC, not only for the visualization of the steps toward the establishment of the REC but also for their temporal occurrence, as well as the practical obligations and expected outcomes. In addition, it facilitates communication among REC members and helps to assess the REC's performance in terms of deviation from its target goals, environmental, economic, and social. The presented roadmap takes inspiration from the so-called Deming cycle, or Plan-Do-Check-Act (PDCA), which is widely used by organizations and SMEs as well as large corporations to develop their strategies. The PDCA cycle comprises clearly defined processes focused on achieving the overall objective of enhancing management and operational activities, allowing a conscious approach to be adopted to direct decision-making. The developed roadmap comprises four main stages: planning, implementation, monitoring, and evaluation.

In order to evaluate the numerous benefits of REC, 3E analysis, which concerns energy, environmental and economic assessment of the innovative proposed system, in this case REC, with respect to the existing one, can be carried out.

Energy analysis concerns the evaluation of the primary energy saving (ΔE_p). This is evaluated by comparing the energy imported from the PG by the traditional system (TS) and REC configuration and the hourly efficiency for the electricity production in Italy (η), equal to 0.509 (for 2020, the most recent data available) [21], as reported in Eq. (1):

$$\Delta Ep = \frac{E_{El}^{TS} - E_{El}^{REC}}{\eta} \tag{1}$$

Environmental analysis is based on assessing the carbon dioxide (CO_2) equivalent emissions saving (ΔCO_2), which is evaluated as the difference between the CO_2 equivalent emissions of the TS and the REC, as shown in Eq. (3). Each of these terms is calculated as a product between energy imported from the PG in the correspondent configuration, TS or REC, and the CO_2 emission factor for Italy's electricity production (α), considering the production mix of technologies that include fossil fuels and RES plants, and equal to 0.287 $kgCO_2/kWh_{el}$ [21], as reported in Eq. (2):

$$CO_2^{TS(REC)} = E_{El}^{TS(REC)} * \alpha \tag{2}$$

$$\Delta \mathrm{CO}_2 = \mathrm{CO}_2^{TS} - \mathrm{CO}_2^{REC} \tag{3}$$

The economic analysis concerns Simple Payback Period (SPB) evaluation, which indicates the number of years to balance the higher renewable-based initial investment cost (IC) and the sum of the annual cash flows (F), as shown in Eq. (5). The cash flow can be defined as expressed in Eq. (4):

$$F = (R + I) - C \tag{4}$$

$$SPB = \frac{IC}{F} \tag{5}$$

where, R is the revenue from sold energy, I is the incentive provided for the electricity produced and shared by the REC members, and C includes costs for maintenance, possible fuel, and management of the proposed system.

Beyond economic benefits, primary energy and CO_2 equivalent emissions savings, RECs offer several other benefits to the territory where the system is realized, as well as contribute to the achievement of Europe's energy targets.

Moreover, two additional indexes are usually considered to evaluate the energy performance of the REC, taking into account the shared energy of the REC ($E_{El,Sh}$). Latter is calculated as the minimum between the electric energy produced ($E_{El,RES}$) by the RES plant and the energy needs of the REC members ($E_{El,US}$) on an hourly basis, as reported in Eq. (6).

$$E_{El,Sh} = \min\left(E_{El,RES}; E_{El,US}\right) \tag{6}$$

Load covered index s, also called self-sufficiency index of the REC, expresses the amount of electricity demand of all end-users covered by the RES-based plant [22], as shown in Eq. (7).

$$s = \frac{E_{El,sh}}{E_{El,US}} \tag{7}$$

The self-consumption index d, is the ratio between the electricity shared with respect to the total amount of electric energy produced by the RES-based plant [22], as shown in Eq. (8).

$$d = \frac{E_{El,sh}}{E_{El,RES}} \tag{8}$$

As previously reported, the development of a REC is a process that can have different evolutions depending on numerous factors. As a matter of fact, the concept of REC is not univocally defined, but each case may involve a different typology of members for the purpose of addressing a local goal or simply becoming part of the broader energy transition process that is taking place across Europe. In order to highlight some of the application fields that may be involved in a CER, some case studies are presented below, whose aims, advantages, and members differ case by case. Three typologies of REC are considered, as reported in Figure 1.

Figure 1. Typology of presented REC case studies

2.1 Residential REC

The fight against energy poverty is the main objective of the REC investigated by Ceglia et al. [23]. The REC presented is composed of three residential users who live in two buildings located in a small town in the South of Italy (Italian climatic zone C), and on the rooftop of one of these, a PV plant has been installed. The electric load of each residential user is based on real energy consumption data, made available by the electricity distributor. The dataset was analysed on a seasonal basis, considering weekdays and weekend days. Electricity is used to supply electric appliances, electric-based energy conversion systems to cover the cooling loads for all users and electric-based energy conversion systems to cover the heating loads only for the third user. Two configurations were investigated:

a) Traditional configuration: Each building gets from the PG the electricity needs independently;

b) REC configuration: A PV rooftop plant with a peak power of 18 kW is installed, so energy is "produced" on-site and shared with other members considering the virtual scheme. In this configuration, if energy demand is higher than the "produced" one, the additional share is supplied by the PG. While, if the production is greater than the needs, the excess energy is fed into the PG.

Dynamic simulation was carried out for one year with an hourly time step, using Homer Pro software [24] and dedicated codes in the Matlab environment [25].

For REC layout, the total electricity shared, evaluated in accordance with national regulation as reported in Eq. (6), is equal to 30.48 MWh/y, while the electric energy taken from the PG instead amounts to 8 MWh/y.

During winter months (from November to February), the amount of electricity exported to the PG decreases while the share of electricity taken from the PG increases. In the same period, the electricity production from the PV plant can cover from 64.3% of electric loads in December to 80.8% in November. From March to October, the electricity production from the PV plant is able to cover a higher share of total electric end-users demands, such as 84.7% in August and 93.8% in April. By comparing traditional configuration and REC one, a primary energy saving of 61.6% has been evaluated on a yearly basis. Furthermore, REC allows to avoid GHG emissions of 64% every year with respect to the no-sharing configuration. Finally, SPB is equal to 10 years, considering that the REC members purchase the community's plant.

Additional social analysis was conducted, proposing an evaluation of the energy poverty condition of the three residential users. Energy poverty, according to the definition provided by the European Commission, is a condition of vulnerable households who can't access essential energy services, such as heating, cooling, and lighting. When energy bills represent a high share of consumers' income or they have to reduce their energy consumption, achieving a discomfort condition at home, energy poverty occurs too [26]. The COVID-19 pandemic and conflict on Ukrainian territory have had a significant impact on the rise of electricity prices which caused an increase of people in energy poverty conditions. The considered case study focuses on the comparison between end-users as individual customers and in a REC configuration in order to evaluate the benefits of the second one. In particular, the mitigation of energy poverty has been carried out through a new social indicator. According to the literature study [27], the most widespread social index is the so-called 10% indicator, Eq. (9). It is the ratio between the global energy cost for each end-user OC and the overall family income IN, with a time step equal to 1 year. An end-user is in an energy poverty condition if he spends on energy more than 10% of his overall income.

$$10\% = \frac{OC}{IN} \tag{9}$$

10% index is upgraded by considering a more accurate income indicator, the equivalent economic situation indicator, ISEE, used in Italy to be eligible for subsidized social benefits (Eq. (10)):

$$10\%_{ISEE} = \frac{OC}{ISEE} \tag{10}$$

These two indices were evaluated in both configurations to assess the improvement in contrast to energy poverty thanks to the participation of the REC. By considering the 10% index, the results indicate that in traditional configuration only the second end-user is near to the energy poverty condition. Otherwise, if the $10\%_{ISEE}$ index is considered, both second and third end-users are in the energy poverty condition. This result highlights that the ISEE parameters could be more suitable. In the REC layout, the results of the 10% index evaluation show that no end-user is in conditions of energy poverty. Even with the $10\%_{ISEE}$ index, which is related to users' real economic situations, the energy poverty limit is not exceeded by any of the three users, demonstrating the effectiveness of the energy-sharing approach in tackling this critical problem.

2.2 Industrial REC

In 2021, the industrial sector was responsible for emitting 9.4 Gt CO2 globally, accounting for a quarter of the total emissions, excluding those from generating electricity for industrial purposes [28].

Industrial areas can take advantage of the diversity of energy demands relating to different end-use types, including those for production, services, safety, transportation, as well as lighting, heating and cooling of office buildings [29]. Thus, the development of RECs in industrial areas can merge the benefits of increased integration of RES-based plants with the advantages of combining complementary loads.

Further to this point, the study [30] aimed to investigate the constitution of a REC in the industrial area of Benevento (Italy). The proposed REC involves two different kinds of end users: a collective services center (CSC) building (Us#1) and the consortium wastewater treatment plant (WWTP) (Us#2). The CSC building is the setting of the Consortium Centre for Management, which is involved in managing the industrial area, common services, and four service sector companies. WTTP is responsible for treating the wastewater from the office building, businesses in the area, and urban wastewater from a district in a neighboring municipality. Their choice is expected to take advantage of the diversity of users' load profiles due to electric energy demand linked to different end uses in a real case study.

Information on the electricity requests of users in 2021 was collected from their electricity bills. The Italian electricity distributor provided the 2021 electric load curves with a quarter-hour time step for two PODs, one serving Us#1 and one serving Us#2. Load curves for the other seven PODs were constructed by manipulating the monthly data from the bills on a quarter-hourly basis.

Users under examination have been equipped with a PV plant, split into two parts, with each portion belonging to a different user. Us#1's PV panels have been assumed to be located on the CSC building's rooftop, unused land nearby, and PV canopies in the parking area, while Us#2's panels are on seven establishments' horizontal rooftops. Monocrystalline solar panels rated at 327 W peak power were selected for installation. The best installation conditions for the PV panels were selected to increase the PV plant's productivity by maximizing the solar radiation collected by each module and preventing shading issues between rows of panels.

In total, the PV plant peak power is equal to 466 kW, with 431 kW installed in sites pertaining to Us#1 and 35 kW to Us#2.

Software Homer Pro [24] was used to assess the electric energy generation pattern of different sections of the PV plant, categorized by their location and orientation, on a quarter-hourly basis. Simulation has been conducted dynamically for a period of one year. The software has been fed with hourly meteorological data on worldwide solar radiation and air temperature for the year 2021, gathered by a weather control unit in Benevento with ten-minute intervals. PV generation data was post-processed in Microsoft Excel [31] to assess electric consumption on-site, surplus fed into the PG, import from the PG and shared energy with a one-hour time step.

Three different scenarios, as shown in Figure 2, have been investigated:

a) Reference baseline case (BC): PG fully meets the users' electric energy demand;

b) Single end-users scenario (no REC): PV plant is split into two parts, each belonging to a different user, and there is no sharing of electric energy. Therefore, the solar panels placed on the properties of Us#1 (the CSC building rooftop, parking area, and unused land) are expected to supply only electric energy to Us#1. Similarly, PV panels located on the rooftop of the WWTP buildings belong to Us#2. Therefore, every user can utilize the renewable electricity produced by their own facility and inject any excess into the PG;

c) REC scenario (REC): PV plant is considered as one unit and provides electricity both to Us#1 and Us#2, who are REC's members. Electricity sharing is being carried out in accordance with the Italian regulation on RECs, specifically through the virtual self-consumption scheme for users connected to the same electric substation HV/MV. Electric energy supplied by the PV plant is injected into the primary substation, and then users draw energy from the substation to meet their needs since there is no physical self-consumption. Electric energy self-consumption virtually occurs when there is simultaneous absorption from and injection to the main substation. The primary substation's energy balance is assessed on an hourly basis.

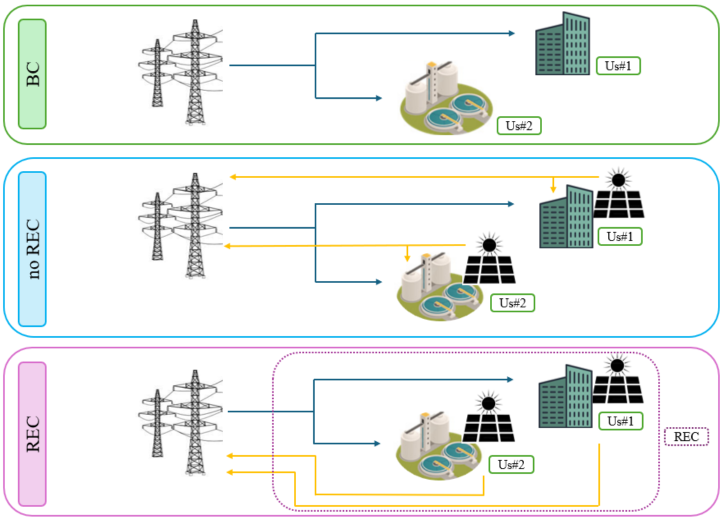

Figure 2. Layout of investigated scenarios [30]

No-REC and REC scenarios were compared with the BC from the energy, environmental and economic points of view. A monthly analysis was conducted.

The results obtained in the no REC scenario were reported by distinguishing between Us#1 and Us#2. With regard to Us#1, the d index is equal to 34.8% in December, while in the months of highest producibility, such as May and July, it amounts to 7.9% and 10.4%, respectively. On the other hand, the maximum self-sufficiency was measured in June, with the s index for Us#1 equal to 49.8%, and the minimum in December, when it is equal to 18.6%, because it is the month characterized by the highest energy demand but the minimum electricity production by PV.

Still referring to the no REC scenario in regard to Us#2, in almost all the months of 2021, the electric energy supplied by the PV plant belonging to Us#2 is fully consumed on-site. Indeed, the lowest value of the d index is detected in January and is equal to 99.5%, while the maximum value of the s index was measured in April, and it is equal to 16.1%. The under-sizing of the PV plant serving Us#2 compared to its electric load is the main cause of these results.

During the summer, there is a high self-sufficiency but a low self-consumption, like in May when the PV plant produces 70.3 MWh but only 12.2 MWh is used. In December, the highest load is recorded (22.1 MWh), while the PV plant's producibility hit its lowest point (11.8 MWh). In the REC scenario, the problems are less noticeable because the sharing of energy between Us#1 and Us#2 leads to improvements in energy self-consumption and user self-sufficiency.

The maximum value of the s index, 49.7%, is in May, and the amount of electric energy fed to the grid decreases accordingly. Similarly in July, the month with the highest total load, due to the rise in self-consumption, less electricity is taken from the grid if compared to the no REC scenario. The lowest value of the d index was in April and amounts to 29.9%, more than tripled compared to the corresponding value for Us#1.

The higher self-consumption and self-sufficiency made possible by sharing energy in the REC scenario leads to a greater decrease in primary energy demand compared to the no REC scenario. Therefore, ΔE_p is equal to 25.0

MWh and 94.5 MWh/y, respectively, for no REC and REC scenarios in July. Overall, the primary energy demand in 2021 is equal to 1.7 GWh in BC, 1.4 GWh in the no REC and 1.1 GWh in the REC scenario. As a result, the constitution of the REC allows a 34.7% primary energy saving on a yearly basis, whereas it is limited to 13.3% in the no REC scenario.

Consequently, energy sharing leads to additional reductions in CO_2 emissions due to decreased primary energy demand. Specifically, CO_2 emissions are reduced by 13.3% without energy sharing and by 34.7% with energy sharing (REC scenario) with respect to BC.

From an economic point of view, the annual 31.9% economic saving characterizing the no REC scenario increases to 42.3% in the REC scenario and cuts down the payback period to 4.9 years.

The main objective of this study is to prove the feasibility of RECs in industrial areas, expanding beyond just the specific site being studied, and encouraging others to replicate the analysis for practical use.

2.3 Offices and Integrated Vehicle REC

A share equal to 25% of global GHG emissions is attributed to the transport sector, with road transport being a major contributor, responsible for around 77% of the whole sector's emissions in Europe [32]. One of the EU's primary approaches to addressing climate change in the transport sector is through the encouragement of EV usage. EVs can further decrease emissions by exclusively using energy from RES.

In study, Ceglia et al. [33] considered a small REC composed of two office buildings located in Naples (Italian climatic zone C). The first office (Office 1) is occupied by 13 workers during weekdays while it is empty on weekends, while the second one (Office 2) is split into two office apartments, each housing up to six employees and six users during working hours, but is vacant on weekends. Both buildings have a single floor and a flat roof. The electric load for each office was calculated based on the occupancy schedule, lighting, and typical electric equipment power installed in an office. Therefore, a daily electric load was defined for a typical weekday, including heating, cooling, and transitional periods, as lighting loads may vary between seasons. Nevertheless, weekends were only assigned one category of electric load.

In the Italian climatic zone C, the heating period starts on 15 November and ends on 31 March, and the cooling period is expected to be from 1 June to 30 September. During the period between April 1 and May 31, as well as October 1 and November 14, only electricity demands need to be fulfilled with no need for space heating or cooling. Since the demand for Domestic Hot Water (DHW) is much lower than the heating and cooling needs for a tertiary building, it has not been included in the calculations. Based on these factors, Office 1 requires 3.15 MWh/y for heating and 5.21 MWh/y for cooling the space in the same building. Office 2 needs 3.62 MWh/y for heating and 5.32 MWh/y for cooling, respectively.

The schematic layout of the REC, which consists of two office buildings that can share renewable electricity, is shown in Figure 3.

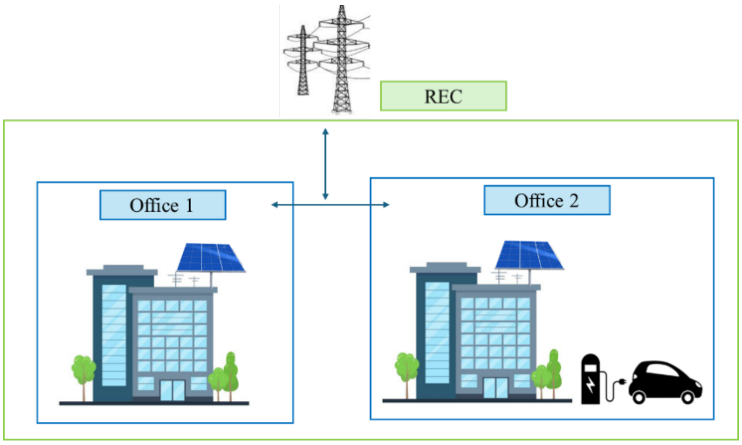

Figure 3. Schematic layout of the REC [33]

Each office is equipped with energy conversion systems that have the following key features:

- Office 1: a reversible air-to-water EHP meets the space heating and cooling load. A PV field with a peak power of 9 kWEl is installed on the roof. The panels are arranged in three arrays with 12 units facing south with a tilt angle equal to 30°;

- Office 2: an EHP with the same characteristics as Office 1 is installed. The PV field has a peak power of 14.25 kWEl. It faces south with a tilt angle of 30°. At Office 2, an EV charging station with a capacity of 3.3 kWEl is installed. It is able to provide constant charging to a selected EV with a nominal electric storage of 30 kWh [34], a specific consumption of 0.173 kWh/km in direct current [35], and a daily distance covered of 120 km. The electric energy required to charge an EV is equal to 24.41 kWh, while 7.31 h are needed to reach the full charge. Annual electricity requested by the EV amounts to 6.84 MWh/y.

Both offices' plants are connected to the PG, allowing the use of solar-generated electricity to power the EHP, equipment, lights, plant auxiliaries and EV (in Office 2), with the surplus/deficit of electricity being exchanged with the PG. In the REC layout, there is potential for sharing the electric energy generated by both PV plants. Specifically, if at times the PV system at Office 1 cannot meet in whole or in part its electricity demand, the feasibility of obtaining electricity from the PV system at Office 2 is assessed. Any remainder is balanced by importing electricity from the PG. In contrast, if the PV plant at Office 1 generates extra electricity, it checks if Office 2 needs it; if not, the surplus electricity is fed into PG. The PV plant of Office 2 follows the same control strategy for generated electricity. The TRNSYS 17 software [36] was used to simulate and model buildings and plants.

In this study, two configurations were examined to assess their energy and environmental performance:

- No sharing (no SH): Offices are not allowed to share the PV electricity with each other. More specifically, the solar power generated by each PV plant can solely be utilized to satisfy the energy demands of the building in which it is located.

- Sharing (SH): PV electricity can be shared between two offices, treating the REC as one entity that interacts bidirectionally with PG.

In relation to the no SH case, the electricity taken from the grid by Office 1 and Office 2 amounts respectively to 4.93 MWh/y and 5.19 MWh/y. However, Office 2 exports significantly more electricity to PG (9.47 MWh/y) than Office 1 (6.53 MWh/y). This is because the Office 2 PV plant has a large size, resulting in more electricity available, despite the increased electric load from the EV.

Nevertheless, the Office 2 PV plant fulfils 32.7% of the overall EV demand. The PV plant provides more electricity for EVs in months with moderate temperatures compared to summer months due to the absence of space heating and cooling needs. Additionally, in winter months, when there is limited solar electricity production, the PV plant's contribution to EV electricity demand is also limited.

In Office 1, 57.2% of the electric load is covered by electricity from the PV plant, while in Office 2 it increases to 65.8%. The d index for Office 1 and Office 2 in cases where no sharing occurs is 50.2% and 51.2%, indicating potential for enhancing the outcomes.

Certainly, an electricity SH system among community members leads to an increase in s and d indices. The s index increases to 81.3% and 77.8%, while the d index goes up to 74.4% and 60.7%, for Office 1 and Office 2, respectively. Additionally, by sharing electricity within the community, the amount of electricity being exported and imported to/from the PG is decreased, resulting in fewer grid perturbations. In this study, the REC's primary energy demand and CO2 emissions has been evaluated by considering both fixed and time-varying efficiency and environmental indicators for electricity production.

The REC's primary energy demand is assessed at 8.76 MWh/y based on average values and 7.15 MWh/y for indicators that vary hourly, showing a decrease of 18%. In terms of environmental assessment for REC, there is a 12% reduction in CO_2 emissions when comparing annual basis values to using a time-dependent emission factor for electricity. The results show that relying on average indicators can result in an overestimation of the primary energy demand and CO_2 emissions. Therefore, variable indicators may be utilized to assess the effectiveness of systems relying on intermittent and variable sources. In conclusion, it is clear that increased electricity sharing within the community leads to better PV electricity exploitation, thereby decreasing the amount of electricity fed into the PG. This fact has benefits both for the community and the PG. It might be interesting to examine situations where EVs act as a link between vehicles and buildings, allowing the EV battery to serve as storage in REC configurations.

3 Conclusions

The European Directive 2018/2001 defined in the European regulatory framework innovative configurations for energy sharing, collective production and self-consumption, known as RECs. Different typologies of included members, the goal of the project and provided services are only some of the features on which characterization could be done. In any case, advantages offered by a REC are several, though they can be different on an application basis. This study investigated three case studies in order to highlight the benefits of RECs in different application fields: residential, industrial and officies with vehicles inclusion. As mentioned, a REC is not univocally determined, leading to potential variations across various cases.

Examined case studies show findings from evaluating the energy, environmental, and economic impact of the proposed REC compared to the conventional energy conversion system. Analysis was conducted by evaluating the parameters outlined in Section 2.1, with some studies including extra evaluation indexes related to specific assessments. Typically, energy analysis involves assessing the primary energy savings achieved by using a REC configuration compared to a TS. The environmental analysis focuses on determining the amount of CO_2 equivalent emissions saved, while the economic analysis assesses the SPB, which indicates the time needed to balance the higher investment cost.

How residential members of a REC can reduce their energy poverty condition has been analyzed through the first case study. Three residential flats located in two buildings, with an 18 kW PV plant installed on the roof of one building, constitute the REC, compared with a configuration where end-users are individually connected to the PG.

The results from the simulation show that the REC could guarantee a 61% reduction in primary energy consumption and a 64% decrease in CO_2 emissions annually, compared to the layout of simple end-users. Furthermore, the socio-economic indicators demonstrate enhancements in energy poverty levels for all users, lifting some of them out of poverty conditions. In terms of economic assessment, a 10-year SPB was determined for the REC. This shows through data the social benefits of REC in alleviating energy poverty for individuals who allocate a substantial portion of their income towards paying for energy services.

The second case study presents a REC with industrial application field. Indeed, a mixed-use building and an industrial WWTP located in the industrial area of Benevento (Southern Italy) are the two members. This layout was compared to the standard scenario and to an additional one with end-users equipped with their own PV plants. Energy sharing allowed in the REC scenario with a unitary PV plant highlights the increase in users' self-sufficiency and renewable energy on-site consumption, primary energy saving equal to 34.7% and CO_2 emissions decrease by 13.3% with respect to the baseline case.

The integration of EV in a REC configuration is presented in the last case study. The REC consists of two office buildings, both with a PV rooftop installation. The office with the larger size PV plant provides a charging station for EVs charged throughout the day. The simulation outcomes show different electric flows when electricity sharing is permitted and when it is prohibited. The REC's primary energy demand and CO_2 emissions were assessed by taking into account both constant and fluctuating efficiency and environmental indicators related to electricity generation. The results obtained in two situations vary significantly, with the use of average indicators specifically causing an overestimation of the primary energy demand and CO_2 emissions attributed to the REC.

The EV-integrated REC case study showcases charging services for EVs as extra services for REC members, playing a role in spreading across the territory and giving end users the opportunity to cut costs on buying other energy carriers. This also allows making more attractive internal areas, otherwise at risk of depopulation.

To sum up, the constitution of the REC provides better performance than the traditional end users' configuration, whichever is the application field or the typology of involved members.

Author Contributions

Conceptualization, E.M., C.M., G.P., C.R. and M.S..; methodology, E.M., C.M., G.P., C.R. and M.S.; validation, E.M., C.M., G.P., C.R. and M.S.; formal analysis, E.M., C.M., G.P., C.R. and M.S.; investigation, E.M., C.M., G.P., C.R. and M.S.; resources, E.M., C.M., G.P., C.R. and M.S.; data curation, E.M., C.M., G.P., C.R. and M.S.; writing—original draft preparation, E.M., C.M., G.P., C.R. and M.S.; writing—review and editing, E.M., C.M., G.P., C.R. and M.S.; visualization, E.M., C.M., G.P., C.R. and M.S.; supervision, E.M., C.M., G.P., C.R. and M.S. All authors have read and agreed to the published version of the manuscript.

Data Availability

The data presented in this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare no conflict of interest.

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Nomenclature

C	Operation cost, €/y
CO_2	Equivalent carbon dioxide emission, kgCO_2/y
d	Self-consumption index, -
E	Energy, kWh, kWh/y
F	Cash flow, €/y
I	Incentive, €/y
IC	Investment cost, €
IN	Income, €/y
$ISEE$	Equivalent economic situation indicator, €/y
OC	Energy cost, €/y
R	Revenue, €/y
s	Load covered index, -
SPB	Simple Payback Period, y
10%	10% index, -

Acronyms

BC	Reference baseline case
CSC	Collective Services Center
DHW	Domestic Hot Water
DSM	Demand Side Management
EHP	Electric Heat Pump
EU	European Union
EV	Electric Vehicle
GHG	Greenhouse Gas
$ISEE$	Equivalent economic situation indicator
HV	High Voltage
$IEMD$	International Market Energy Directive
LV	Low Voltage
MV	Medium Voltage
$PDCA$	Plan-Do-Check-Act
PG	Power Grid
PV	Photovoltaic
REC	Renewable Energy Community
$REDII$	Renewable Energy Directive
RES	Renewable Energy Source
SH	Sharing
SME	Small and Medium Enterprise
$WWTP$	Wastewater Treatment Plant

Greek symbols

α	Electricity emission factor, $kgCO_2$/kWh
η	Electricity production efficiency, -

Subscripts and superscripts

El	Electric
$ISEE$	Equivalent economic situation indicator
p	Primary
POD	Point of Delivery
REC	Renewable Energy Community
RES	Renewable Energy Sources
Sh	Shared
TS	Traditional system
US	User