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Towards the Decarbonization of Industrial Districts through Renewable Energy Communities: Techno-Economic Feasibility of an Italian Case Study

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Abstract: In Europe, the recast of Directive 2018/2001 defined Renewable Energy Communities as innovative configurations for renewable energy sharing between different end user types. In this regard, this work aims to assess the benefits following the constitution of a Renewable Energy Community in the industrial area of Benevento (South of Italy), involving a mixed-use building and an industrial wastewater treatment plant. The alternative single end users' configuration has been also examined, and both solutions have been compared with the current state where the users' electric energy requests are fully met by the power grid. The users have been equipped with a 466 kW_p photovoltaic plant, modelled in HOMER Pro®, providing in input experimental meteorological data (global solar radiation and air temperature) collected by one of the weather control units in Benevento. Real data about users' electric energy demand have been gathered from their electricity bills, and when unavailable their electric load profiles on an hourly basis have been reconstructed based on the aggregated monthly data. Energy sharing has been proven to increase energy self-consumption and the users' self-sufficiency. Annually, the primary energy demand is reduced by 577 MWh (1.2 MWh/kW_p), carbon dioxide emissions by 84 tCO_2 and operative costs by 101 kEUR.

Keywords: Renewable Energy Community; industrial districts; dynamic simulation; energy self-sufficiency; energy sharing; experimental data

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1. Introduction

The recent European "Green Deal Industrial Plan" [1] reaffirms the commitment of the European Union towards the 55% reduction of carbon dioxide (CO_2) emissions compared to the 1990 levels by 2030 [2] and carbon neutrality by 2050 [3] by supporting the roll out of renewable energy sources (RESs) in the industrial sector. Yet, in 2021, the industrial sector's global CO_2 emissions amounted to 9.4 $GtCO_2$ and represented one-quarter of the total (except for indirect emissions due to electricity production for industrial processes) [4]. As such, the industry is nowadays not on track to achieve either the Net Zero Emissions goal by 2050, or the objectives introduced by the Paris Agreement of the United Nations Framework Convention on Climate Change [5]. Albeit the increasing investments of industrial companies, the improvements in energy efficiency, the uptake of low-carbon technologies and the deployment of RES-based plants are advancing more slowly than needed [6,7]. Hence, they would require additional support and incentivization by single countries' policies [8]. Techno-economic issues especially discourage single small and medium-sized enterprises from investing in energy efficiency and RESs, thus hindering the potentialities of these interventions. For instance, the valorization of large unused surfaces often available in industrial areas through RES-based plants would open up the opportunity to reinforce the provision of renewable energy in urban centers [9]. In turn, this solution would increase the social acceptability of industrial parks [10].

The Clean Energy for All European Package [11] may address these shortcomings. In 2018, the recast of the Renewable Energy Directive (REDII) introduced Renewable Energy Communities (RECs) [12], just before the Internal Electricity Market Directive [13] was launched in 2019 defining Citizen Energy Communities. Both directives promote energy sharing by identifying the novel central and active role of the consumer in the electricity market and support the spreading of RES-based plants by means of collective energy initiatives [14,15]. RECs, in particular, can involve different end user types. Indeed, they are open to voluntary participation, not only of natural persons and local authorities, including municipalities but also micro, small or medium-sized enterprises. The co-participation of different user types is beneficial to the performance of RECs [16], since it provides positive outcomes from the energy, economic and environmental point of view, as already stated before the definition of RECs in studies assessing the profitability of the load sharing approach [17]. Broadly speaking, the combination of different load curves increases the generation plants' operating hours [18] and results in a smoother aggregated load profile, which typically lowers the mismatch between energy demand and supply from RES-based plants. In this regard, a REC involving residential consumers and a winery in the city of Reguengos de Monsaraz (South of Portugal) has been examined [19], showing that the centralization of a photovoltaic (PV) plant improves the cost-effectiveness of the investment, but increases the usage of the electricity distribution grid. The optimal combination of different types of prosumers in Citizen Energy Communities and RECs has been assessed from the economic standpoint in [20] being complementarity of loads relevant to the optimal exploitation of dispatchable and non-dispatchable RESs. In particular, costs may be reduced up to 15–20% when coupling two prosumers, one belonging to the residential sector and equipped with a PV plant, and the other belonging to the industrial, agricultural or tertiary sector and served by an internal combustion engine. The heterogeneity of user types characterizing an Italian case study has been recognized as having the potential to highly enhance the flexibility and self-sufficiency of RECs also in [21], where the Schoonschip neighborhood in Amsterdam (The Netherlands) and the Marsciano Community in Marsciano (Central Italy) have been compared. The former involves only residential users, whereas the latter includes a dairy, an engineering studio, a medical center and a household.

As regards industrial areas, they can take advantage of the complementarity of loads as well, being characterized by energy requests relating to different end-use types, such as the activation of production processes, service facilities, safety and transportation systems, as well as the lighting, heating and cooling of office buildings [22]. Hence, the implementation of RECs in industrial areas may combine the potentialities offered by the growing integration of RES-based plants with the opportunities relating to the aggregation of complementary loads. The deployment of such configurations within the industrial sector constitutes a field of research still quite new, although the adoption of collective energy strategies aimed at supporting the implementation of projects involving multiple firms for reducing the reliance on fossil energy resources has been widely discussed in the literature [23,24]. Most scientific works provide insights about industrial and urban-industrial symbiosis [25,26]. In this framework, the concepts of energy industrial parks, zero-carbon industrial parks and positive energy industrial parks have been introduced [27,28]. In [29], the development of a zero-carbon emission industrial park in China has been assessed. The availability of RESs to fully decarbonize the provision of electric energy represents one of the main barriers to its development, as well as the production of waste and the indispensability of fossil materials for some processes, which require the use of carbon capture technologies. In addition to technical issues, insufficient funds may represent a significative financial obstacle and discourage enterprises from pursuing the realization of zero-carbon projects. In [30], the optimal configuration involving different RES-based plants serving a centralized water facility in a Malaysian industrial park has been defined by using mixed-integer non-linear programming techniques. The optimal solution obtained could reduce greenhouse gas emissions up to 70%. With regards to an Italian industrial district, the enhancing exploitation of RESs has been investigated in [31]. Based on the main findings, an increased economic support would make the adoption of RES-based plants more attractive from the economic point of view. The development of community energy systems in industrial clusters has been examined in [32] by focusing on a case study in Arak (Iran). Again, this solution has been proven to be affected by economic and institutional barriers, despite the technical feasibility of RES-based plants meeting the electric energy demand of the firms joining the collective intervention. Renewable Energy Cooperatives as clusters of both enterprises and local stakeholders have been analyzed in [33], where they have been recognized as strategic configurations to manage the inherent uncertainty of investments for RES-based plants.

Ultimately, most scientific works dealing with collective actions aiming at supporting the deployment of RES-based plants in the industrial sector do not address the opportunities of constituting RECs. The majority of works focusing on the implementation of RECs refers to residential and tertiary sectors and most of them are based on PV plants because of its technology's readiness. For example, Cirone et al. [34] investigated the implementation of a REC in Soveria Mannelli (South of Italy), composed of four public buildings. Ancona et al. [35] analyzed the application potential of the REC concept with district heating networks, maximizing internal energy sharing through PV systems and heat pumps for self-consumption, self-sufficiency and efficient investments. Results show that the proposed design achieves a significant reduction in energy demand, emissions and costs. Ceglia et al. [36] analyzed a PV-based REC in Southern Italy, demonstrating its potential to significantly reduce the energy poverty index from 9.84% to 5.25% regarding a typical residential user. Among all others, these few examples demonstrate the potential of PV technology to provide clean and sustainable energy to communities in a cost-effective manner. However, according to Directive REDII, there is a need to support the uptake of renewable-based plants by citizens as well as small, medium and micro-enterprises by simplifying the notification procedures for the connection of small-size and decentralized renewable-based plants to the grid and clarifying the time-limits for authorization issues and administrative permit granting processes [12]. As regards industrial RECs, these actions are advocated considering their significant potential in terms of carbon emission reduction at the national level, which depends on the specific context, policies and regulations put in place to support their development. The International Energy Agency estimated the potential global carbon emission reduction achievable by 2050 through the implementation of RECs in the industrial sector as equal to 40% [37]. For this purpose, industrial RECs may take advantage of the collaboration between small and medium-sized enterprises, characterized by a high sense of community, social responsibility and openness to technological innovation. As additional benefits, the analysis and demonstration of social, economic and environmental benefits of a PV-based REC in an industrial district may provide to policy makers valuable information about the design and implementation of policies supporting the growth of sustainable communities, enhance the understanding of factors fostering community engagement and cooperation and identify potential barriers to their implementation and constitution. Yet, to the best of authors' knowledge, the literature lacks studies focused on industrial RECs. The exclusion of large companies from participation in such configurations may be a reason for the lack of interest in their constitution at the European level [38]. However, their potential is usually disregarded not only in the pathways towards the full decarbonization of the European industry [39] but also in studies focusing on the reduction of energy requests and carbon emissions of small- and medium-sized enterprises [40].

Therefore, this study aims at bridging this gap and investigates the constitution of a REC in the industrial area of Benevento (Italy). The REC under examination involves two different kinds of user, namely a mixed-use building and the consortium wastewater treatment plant (WWTP). 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. The ultimate goal is to demonstrate the feasibility of RECs in industrial areas without restraining the scope of interest to the boundaries of the industrial site being analyzed, but rather to stimulate the replication of the analysis performed in this study within the literature in order to foster real applications. The users under examination have been equipped with a PV plant. Within the REC boundaries, energy sharing has been implemented according to the Italian regulation, that is, under the virtual self-consumption scheme. In addition to this proposed scenario, the alternative single end users' configuration where energy sharing has been neglected has been investigated too. In this case, the PV plant has been divided into two portions, each owned by one user. Accordingly, each portion of the PV plant has been assumed to supply electric energy only to its owner, and the potential surplus to be fed to the grid. Both examined scenarios have been compared with the current status, where the users' electric energy demand is covered by the power grid (PG), as detailed in Section 2, along with the users' load profiles, design and model adopted to simulate the PV plant. The results obtained from the comparison of both scenarios with the baseline case are introduced and discussed in Section 3, whereas in Section 4, the conclusions have been drawn.

2. Materials and Methods

In this section, the steps followed for developing the analysis carried-out in this work are detailed, starting from the characterization of investigated users' electric energy requests (Section 2.1) and then focusing on the design of the PV plant serving them (Section 2.2). Lastly, the models adopted for performing the dynamic simulation and the energy, environmental and economic analysis under two different scenarios are described (Section 2.3).

2.1. Users' Electric Energy Requests Characterization

The industrial area of Benevento covers a surface of 3,179,357 m^2. It is divided into seven zones and includes several micro, small, medium, as well as internationally renowned enterprises. The collective services center (CSC) building and the consortium WWTP have been considered as users in this study (*Us*#1 and *Us*#2, respectively). Their location is shown in the satellite view obtained from Google Earth [41] in Figure 1. The CSC building is the setting of the Consortium Centre for Management, which is responsible for the management of the industrial area and common services, and four companies operating in the services sector. The WTTP is deputed to the treatment of the wastewater produced from the office building, the enterprises located in the area and urban wastewater produced in one of the districts of a municipality nearby.

Figure 1. Aerial view of users' location.

The data about users' electric energy demand in 2021 have been gathered from their electricity bills. They are referred to nine points of delivery (PODs), seven serving *Us*#1 and two serving *Us*#2. In the case of two PODs (one serving *Us*#1 and one serving *Us*#2), the 2021 electric load curves with a quarter-hour time step have been made available by the Italian electricity distributor [42]. For the remaining seven PODs, the load curves on a quarter-hourly basis have been constructed, manipulating the aggregated monthly data known from the bills. Namely, the monthly electric energy demand has been split into hours, depending on the day of the week and distinguishing between peak hours (belonging to the F1 band), intermediate hours (belonging to the F2 band) and evening and weekend hours (belonging to the F3 band) [43], as detailed in Table 1.

Table 1. Time bands for electric energy purchase.

Time Band	Days	Time
F1: Peak hours	From Monday to Friday, excluding public holidays	From 8:00 a.m. to 7:00 p.m.
F2: Intermediate hours	From Monday to Friday, excluding public holidays	From 7:00 a.m. to 8:00 a.m. and from 7:00 p.m. to 11:00 p.m.
	Saturday, excluding public holidays	From 7:00 a.m. to 11:00 p.m.
F3: Evening and weekend hours	From Monday to Saturday	From 11:00 p.m. to 7:00 a.m.
	Sunday and public holidays	All-day

The users' total load profiles on a quarter-hourly basis are shown in Figure 2 with reference to 2021. The graphs have been constructed by varying the color of indicators depending on the time in order to emphasize the distribution of the electric load during the day. In the case of *Us*#1, the electric load is clearly higher during morning hours, and minimum load values are detected in the evening. By contrast, in the case of *Us*#2, the distinction between morning and evening loads is not straightforward. As it can be seen, the loads of the two users are characterized by different orders of magnitude. Indeed, the load of *Us*#1 is at most equal to 46.5 kW in January. By contrast, *Us*#2 has significantly higher requests, and its maximum load amounts to 186.0 kW in July. Moreover, the two load profiles are differently distributed throughout the year. In 2021, starting from January, the maximum electric energy requests of *Us*#1 decrease during spring until June. In June, a rising trend can be found, which stops in July, and restarts from August onwards. Conversely, the electric energy requests of *Us*#2 are characterized by a rising trend in the spring months until the end of June, when the maximum load is found. From July onwards, maximum load values start decreasing.

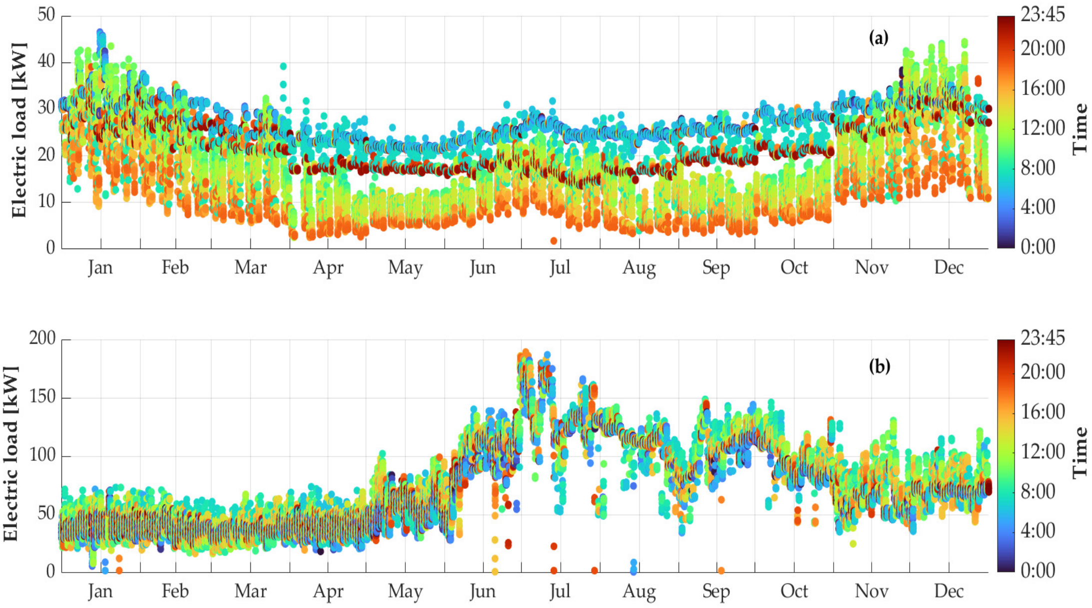

Figure 2. Electric load profile on a quarter-hourly basis of *Us*#1 (**a**) and *Us*#2 (**b**) in 2021.

The two users' electric energy demand (E_{el}^{Us}) is quantified on a monthly basis in Table 2, along with the relating average unitary purchase cost (c_{el}^{Us}) incurred by the users for electricity purchase (VAT included). First, the distinction between *Us*#1 and *Us*#2 has been made; then, their loads have been considered as a whole. In the latter case, the average unitary purchase cost of electricity (c_{el}^{REC}) has been evaluated as the ratio between the monthly grand total of users' expenses for electric energy purchase (that is, the sum of the costs monthly incurred by *Us*#1 and *Us*#2) and the total monthly electric load (that is, the sum of $E_{el}^{Us\#1}$ and $E_{el}^{Us\#2}$). As it can be seen, in all months of 2021 $E_{el}^{Us\#2}$ is higher than $E_{el}^{Us\#1}$, especially in summer and autumn months. Overall, in 2021, the electric energy demand of *Us*#1 is equal to 190 MWh/y, whereas it amounts to 655 MWh/y regarding *Us*#2. Hence, on a yearly basis, the two users require in total 846 MWh/y. c_{el}^{Us} ranges between 0.20 and 0.49 EUR/kWh. This maximum value is detected in December as regards #Us1, whereas the maximum $c_{el}^{Us\#2}$, found again in December, is equal to 0.45 EUR/kWh. The maximum c_{el}^{REC} is intermediate compared to the maximum $c_{el}^{Us\#1}$ and $c_{el}^{Us\#2}$, being equal to 0.46 EUR/kWh in December.

Table 2. Users' monthly electric energy demand and relating average unitary purchase price of electricity in 2021.

Month	Electric Energy Demand [MWh]			Electricity Average Unitary Purchase Price [EUR/kWh]		
	***Us*#1**	***Us*#2**	***Total***	$c_{el}^{Us\#1}$	$c_{el}^{Us\#2}$	c_{el}^{REC}
January	21.6	29.9	51.5	0.22	0.20	0.21
February	17.0	25.9	42.9	0.23	0.20	0.21
March	15.7	26.9	42.6	0.24	0.21	0.22
April	12.4	28.1	40.6	0.23	0.22	0.22
May	12.2	42.0	54.2	0.23	0.22	0.22
June	13.3	71.0	84.4	0.23	0.23	0.23
July	14.5	100.2	114.7	0.23	0.22	0.22
August	13.3	83.6	96.9	0.28	0.23	0.24
September	13.4	74.7	88.2	0.33	0.29	0.30
October	15.8	71.6	87.4	0.38	0.37	0.37
November	19.0	47.9	66.9	0.41	0.39	0.39
December	22.1	53.5	75.5	0.49	0.45	0.46
Total	190	655	846	0.30	0.28	0.28

2.2. Photovoltaic Plant Design

The surfaces selected for installing the PV panels have been highlighted in Figure 3. Specifically, the PV panels belonging to *Us*#1 have been assumed to be placed on the rooftop of the CSC building, on unused land nearby, and on PV canopies in the parking area, whereas those belonging to *Us*#2 on the horizontal rooftop of seven establishments. Monocrystalline cell PV panels with 327 W of peak power have been chosen for installation [44]. Their main features are listed in Table 3.

The area of each surface has been measured by excluding the portions subjected to shading phenomena and considering a 15% reduction in order to ensure enough service spaces. Concerning PV canopies, the area of each parking spot has been estimated as equal to 12.5 m^2, being the minimum length and the minimum width of each equal to 5 m and 2.5 m, respectively [45]. Optimal installation conditions for the PV panels have been chosen in order to maximize the PV plant producibility by maximizing the solar radiation captured by each module and by avoiding shading phenomena between consecutive rows of panels [46]. In this regard, the minimum spacing distance D between adjacent panel rows needed to avoid shading phenomena has been determined using Equation (1),

$$D = L\cos\beta\left(1 + \frac{\tan\beta}{\tan\alpha}\right), \quad (1)$$

where the term *L* represents the height of each panel, α the sun elevation angle and β the tilt angle. Concerning the type of panel chosen, *L* is equal to 1.6 m. Both α and β depend on the latitude of the installation site, which is equal to 41° in the case of Benevento. For determining *D*, α has been evaluated on December 21st at noon. Hence, the resulting α is equal to 25.5° at the latitude of the installation site being analyzed. As regards β, in Italy its optimal value is equal to the difference between the latitude angle itself and 10° [46]. As a result, being β equal to 31° and α equal to 25.5°, *D* is equal to 3.0 m. The gross area of each panel, equal to 1.6 m^2, has been increased by 1.5 m^2, resulting in 3.1 m^2. For estimating the number of panels installed on the tilted sector of the rooftop of the CSC building, the panels' gross area has not been increased since they are supposed to be directly integrated into the roof. Instead, as regards the parking area, four panels are supposed to be installed in each spot for a total of 63 spots. Overall, the total number of PV panels installable is equal to 1424, and the PV plant peak power is equal to 466 kW, of which 431 and 35 kW are installed in sites pertaining to *Us*#1 and to *Us*#2, respectively. The results obtained are detailed in Table 4. For each installation site, the type of surface (horizontal or tilted), the exposure, the area, the number of panels and the peak power are reported. The only tilted surface available is the semicircular sector representing the central portion of the rooftop of the CSC building. In particular, it is tilted about 5° and measures 170 m^2. Since the gross area of each panel is equal to 1.6 m^2, 104 panels have been assumed to be installed on this surface. The remaining surfaces are all horizontal and have an overall extension of 4163 m^2. In particular, the horizontal portion of the rooftop of the CSC building measures 486 m^2, the unused land 2550 m^2 and the rooftops of WWTP 340 m^2 in total. Considering the panels' gross area increased by the space needed to avoid the shading phenomena, 154, 807 and 107 panels have been assumed to be installed on each surface, respectively. In accordance with the assumptions of the dynamic simulation software and when not prevented by the installation site, the azimuth angle of panels installed on horizontal surfaces has been set as equal to 0° in order to have south-facing panels in compliance with optimal installation conditions in Italy.

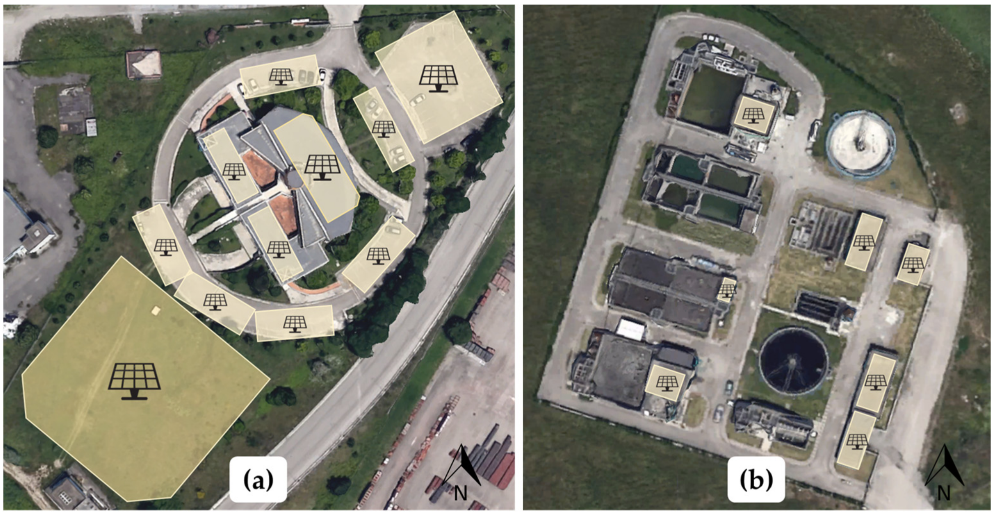

Figure 3. Aerial view of the surfaces selected for installing the PV plant, belonging to *Us*#1 (**a**) and *Us*#2 (**b**).

Table 3. PV panels' technical parameters [44].

Parameter	Value
Peak power [W]	327
Efficiency [%]	20.1
Maximum power voltage [V]	54.7
Maximum power current [A]	6.0
Open circuit voltage [V]	64.9
Short circuit current [A]	6.5
Temperature coefficient of power [%/°C]	−0.4
Temperature coefficient of voltage [mV/°C]	−176.6
Temperature coefficient of current [mA/°C]	2.6
Gross area [m^2]	1.6

Table 4. Characterization of surfaces available for the installation of the PV panels.

User	Installation Site	Type of Surface	Exposure	Area [m^2]	Number of Panels	Peak Power [kW]
Us#1	CSC building's rooftop	Horizontal	South	486	154	50
	CSC building's rooftop	Tilted	South-West	170	104	34
	Parking area	Horizontal	South	200	64	21
			South-West	475	152	50
			South-East	112	36	12
	Unused land	Horizontal	South	2550	807	264
Us#2	Buildings' rooftop	Horizontal	South	340	107	35
Total	-	-	-	4333	1424	466

2.3. Model Description

A schematic overview of the methodology adopted in this work is shown in Figure 4. The electric energy production profile of each portion of the PV plant, distinguished based on the installation site and the exposure, has been evaluated on a quarter-hourly basis by using the software HOMER Pro® [47]. The dynamic simulation has been carried out over one year. Hourly meteorological data about global solar radiation and air temperature, evaluated as hourly average values of the data collected by one of the weather control units in Benevento during 2021 with a ten-minute time step, have been provided as input to the software.

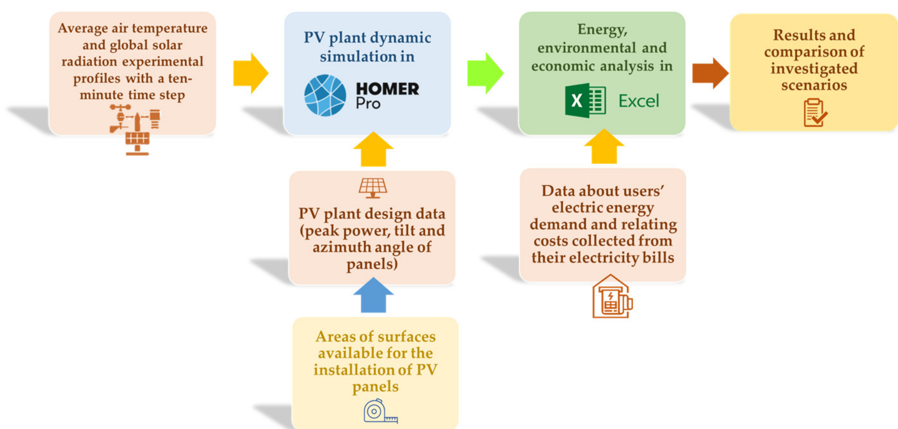

Figure 4. Methodology.

The PV generation curves resulting from the simulation carried out in HOMER Pro® have been post-processed in Microsoft Excel [48] for evaluating with a one-hour time step (θ), the electric energy consumed on-site by the users ($E_{el}^{OSC}(\theta)$), the surplus fed into the grid ($E_{el}^{TG}(\theta)$) and the residual electric load drawn from the grid ($E_{el}^{PG}(\theta)$). Namely, $E_{el}^{OSC}(\theta)$ has been evaluated using Equation (2),

$$E_{el}^{OSC}(\theta) = \min\left(E_{el}^{PV}(\theta), E_{el}^{Us}(\theta)\right). \quad (2)$$

where the term $E_{el}^{PV}(\theta)$ represents the electric energy hourly supplied by the PV plant, evaluated starting from the quarter-hour data resulting from the dynamic simulation, and $E_{el}^{Us}(\theta)$ the users' hourly electric energy demand. $E_{el}^{PG}(\theta)$ and $E_{el}^{TG}(\theta)$ have been easily determined once estimated $E_{el}^{OSC}(\theta)$.

The profitability of the PV plant has been investigated under two different scenarios, shown in Figure 5, along with the reference baseline case (BC), where the users' electric energy demand is fully met by the PG. The two alternative solutions have been outlined as follows:

- in the single end users' scenario (hereinafter recalled as noREC scenario), the PV plant has been divided into two portions, each owned by one user, and the sharing of electric energy has been neglected. Thus, the PV panels installed in the sites pertaining to *Us*#1 (the rooftop of the CSC building, the parking area and the unused land) have been assumed to supply renewable electricity only to *Us*#1 itself. Likewise, those installed on the rooftop of the WWTP buildings only to *Us*#2. Hence, each user has the opportunity to self-consume the renewable electricity supplied by his own plant and inject into the PG the potential surplus;
- in the REC scenario, the PV plant has been treated as a whole and supplies electricity both to *Us*#1 and *Us*#2, which are involved in the REC. Electricity sharing has been implemented in compliance with the Italian regulation about RECs, that is, according to the virtual self-consumption scheme for users under the same primary electric substation. On the one hand, all the electric energy supplied by the PV plant is injected into the primary substation; on the other, the users draw electric energy from the primary substation to meet their requests since no physical self-consumption takes place. Electric energy virtual self-consumption is realized when the absorption from and injection to the primary substation occur simultaneously. The energy balance on the primary substation is evaluated on an hourly basis [49].

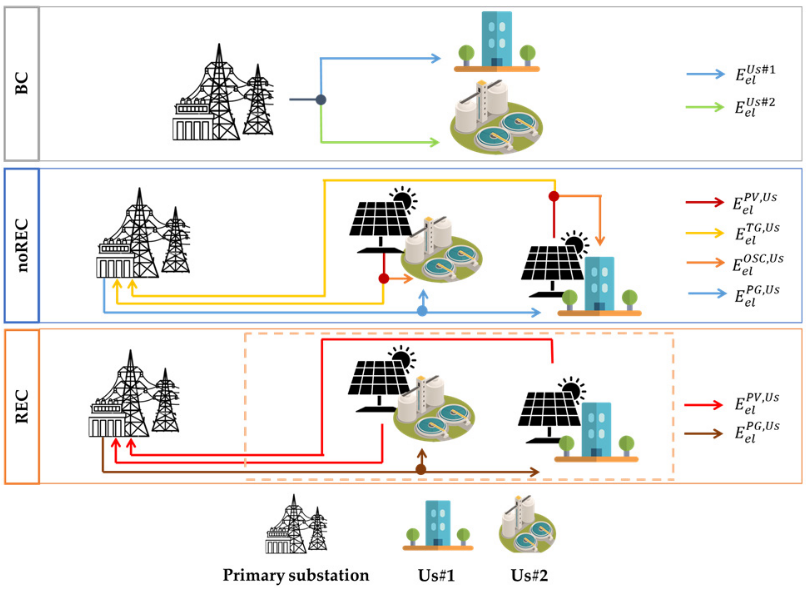

Figure 5. Layout of investigated scenarios.

No-REC and REC scenarios have been compared with the BC case from the energy, environmental and economic points of view. As for the energy analysis, the self-consumption d_i and self-sufficiency s_i indexes have been evaluated on a monthly basis. Namely, the subscript i accounts for the months in 2021 and thus ranges between January and December. In the no-REC scenario Equations (3) and (4) have been used, respectively. $E_{el,i}^{PV}$ and $E_{el,i}^{OSC}$ have been evaluated as stated in Equations (5) and (6), respectively, where the subscript k accounts for the hour of the i-th month in 2021, thus ranging between 1 and the total number of hours in the same month (NH_i). Two values of d_i^{Us} and s_i^{Us} have been determined, relating to Us#1 ($d_i^{Us\#1}$ and $s_i^{Us\#1}$, respectively) and Us#2 ($d_i^{Us\#2}$ and $s_i^{Us\#2}$, respectively). In particular, $d_i^{Us\#1}$ and $s_i^{Us\#1}$ have been evaluated by using the electric energy supplied on a monthly basis by the portion of the PV plant serving Us#1 ($E_{el,i}^{PV,Us\#1}$), its monthly on-site electric energy consumption ($E_{el,i}^{OSC,Us\#1}$) and its monthly electric load ($E_{el,i}^{Us\#1}$), known from the bills. Likewise, $d_i^{Us\#2}$ and $s_i^{Us\#2}$ have been estimated by using the same variables but referred to as Us#2 ($E_{el,i}^{PV,Us\#2}$, $E_{el,i}^{OSC,Us\#2}$ and $E_{el,i}^{Us\#2}$).

$$d_i^{Us} = \frac{E_{el,i}^{OSC,Us}}{E_{el,i}^{PV,Us}} \tag{3}$$

$$s_i^{Us} = \frac{E_{el,i}^{OSC,Us}}{E_{el,i}^{Us}} \tag{4}$$

$$E_{el,i}^{PV,Us} = \sum_{k=1}^{NH_i} E_{el}^{PV}(\theta_{k,i}) \tag{5}$$

$$E_{el,i}^{OSC,Us} = \sum_{k=1}^{NH_i} E_{el}^{OSC,Us}(\theta_{k,i}) \tag{6}$$

Conversely, in the REC scenario, d_i^{REC} and s_i^{REC} have been evaluated, as stated in Equations (7) and (8), respectively. In each month, $E_{el,i}^{PV,REC}$ has been evaluated as the sum of $E_{el,i}^{PV,Us\#1}$ and $E_{el,i}^{PV,Us\#2}$. Accordingly, $E_{el,i}^{REC}$ has been evaluated as the sum of $E_{el,i}^{Us\#1}$ and $E_{el,i}^{Us\#2}$. Instead, $E_{el,i}^{OSC,REC}$ has been determined according to Equation (9), where the sum of $E_{el}^{PV,Us\#1}(\theta_{k,i})$ and $E_{el}^{PV,Us\#2}(\theta_{k,i})$ amounts to $E_{el}^{PV,REC}(\theta_{k,i})$ and the sum of $E_{el}^{Us\#1}(\theta_{k,i})$ and $E_{el}^{Us\#2}(\theta_{k,i})$ amounts to $E_{el}^{REC}(\theta_{k,i})$ $E_{el}^{TG,REC}(\theta_{k,i})$ and $E_{el}^{PG,REC}(\theta_{k,i})$ have been determined as in the single end users' configuration once evaluated $E_{el}^{PV,REC}(\theta_{k,i})$ and $E_{el}^{REC}(\theta_{k,i})$.

$$d_i^{REC} = \frac{E_{el}^{OSC,REC}}{E_{el}^{PV,REC}} \tag{7}$$

$$s_i^{REC} = \frac{E_{el}^{OSC,REC}}{E_{el}^{REC}} \tag{8}$$

$$E_{el,i}^{OSC,REC} = \sum_{k=1}^{NH_i} \min\left(E_{el}^{PV,Us\#1}(\theta_{k,i}) + E_{el}^{PV,Us\#2}(\theta_{k,i}), E_{el}^{Us\#1}(\theta_{k,i}) + E_{el}^{Us\#2}(\theta_{k,i})\right) \tag{9}$$

Still referring to the energy analysis, the primary energy saving ($\Delta E_{p,i}$) compared to the BC has been evaluated on a monthly basis according to Equation (10) in the no-REC scenario and according to Equation (11) in the REC scenario. In both Equations, the term η_{el}^{PG} represents the average Italian power grid efficiency, equal to 0.509 in 2020 (the year for which the most recent data are available) [50]. $E_{el,i}^{PG,Us}$ and $E_{el,i}^{TG,Us}$ have been estimated on a monthly basis as the sum across the number of hours of the i-th month of $E_{el}^{PG,Us}(\theta_{k,i})$ and $E_{el}^{TG,Us}(\theta_{k,i})$, respectively. $E_{el,i}^{PG,REC}$ and $E_{el,i}^{TG,REC}$ have been estimated on a monthly basis as the sum across the number of hours of the i-th month of $E_{el}^{PG,REC}(\theta_{k,i})$ and $E_{el}^{TG,REC}(\theta_{k,i})$, accordingly.

$$\Delta E_{p,i}^{noREC} = \frac{E_{el,i}^{Us\#1} + E_{el,i}^{Us\#2} - E_{el,i}^{PG,Us\#1} - E_{el,i}^{PG,Us\#2}}{\eta_{el}^{PG}} \quad (10)$$

$$\Delta E_{p,i}^{REC} = \frac{E_{el,i}^{REC} - E_{el,i}^{PG,REC}}{\eta_{el}^{PG}} \quad (11)$$

With regards to the environmental analysis, the CO_2 emissions reduction $\Delta CO_{2,i}$ owing to the installation of the PV plant, has been evaluated on a monthly basis. To this purpose, Equation (12) has been adopted in the noREC and Equation (13) in the REC scenario. In both Equations, the term α_{CO_2} represents the 2020 Italian power grid CO_2 emission factor, equal to 286.55 gCO_2/kWh_{el} [50].

$$\Delta CO_{2,i}^{noREC} = \left(E_{el,i}^{Us\#1} + E_{el,i}^{Us\#2} - E_{el,i}^{PG,Us\#1} - E_{el,i}^{PG,Us\#2}\right) \cdot \alpha_{CO_2} \quad (12)$$

$$\Delta CO_2^{REC} = \left(E_{el,i}^{REC} - E_{el,i}^{PG,REC}\right) \cdot \alpha_{CO_2} \quad (13)$$

Finally, as for the economic analysis, the variation in operating costs ΔOC in the noREC and REC scenario compared to the BC has been evaluated on a monthly basis. The monthly operative costs in the BC ($OC_i^{BC,Us\#1}$ and $OC_i^{BC,Us\#2}$) are known from the users' electricity bills. Instead, in the proposed scenarios, they have been evaluated as follows:

- in the noREC scenario, the electricity purchase price has been considered equal to the monthly average value paid in 2021 by each user in the BC, as stated in Table 2 (that is, equal to $c_{el}^{Us\#1}$ and $c_{el}^{Us\#2}$ regarding $Us\#1$ and $Us\#2$, respectively). The surplus electric energy injected into the grid has been supposed to be sold to the Italian "*Gestore dei Servizi Energetici*" (GSE) according to the Dedicated Withdrawn scheme [51]. In this framework, the hourly electricity selling price ($p_{el}(\theta_{k,i})$) has been assumed to be equal to the 2021 hourly zonal price of electricity in the Central-South bidding zone of the Italian day-ahead electricity market distinguished per month and time-band. As a result, Equation (14) has been used for estimating both $OC_i^{noREC,Us\#1}$ and $OC_i^{noREC,Us\#2}$,

$$OC_i^{noREC,Us} = \left(E_{el,i}^{PG,Us} \cdot c_{el,i}^{Us} + MC_i\right) - \sum_{k=1}^{NH_i} \left(E_{el}^{TG,Us}(\theta_{k,i}) \cdot p_{el}(\theta_{k,i})\right) \quad (14)$$

  In Equation (14), the subscript i keeps the same meaning as above, as well as NH_i. The term MC_i represents the costs due to the maintenance of the PV plant, which have been assumed to be constant and evaluated starting from an annual specific value equal to 10 EUR/kW_p [52]. Finally, ΔOC^{noREC} has been evaluated on a yearly basis as stated in Equation (15). Hereinafter, the sum of $OC_i^{noREC,Us\#1}$ and $OC_i^{noREC,Us\#2}$ will be recalled as OC_i^{noREC}.

$$\Delta OC^{noREC} = \sum_{i=Jan}^{Dec} \left(OC^{BC,Us\#1} + OC^{BC,Us\#2} - OC_i^{noREC,Us\#1} - OC_i^{noREC,Us\#1}\right) \quad (15)$$

- in the REC scenario, the monthly average electricity purchase price $c_{el,i}^{REC}$ has been evaluated as stated in Equation (16). The values obtained are reported in the last column of Table 2. Regarding the users' revenues, a distinction has been made between the electric energy shared within the REC boundaries ($E_{el}^{OSC,REC}(\theta)$) and sold to the grid ($E_{el}^{TG,REC}(\theta)$) on an hourly basis. Indeed, in Italy, article 42-bis of the Decree Law n.162/2019 [53] states that the sharing of electric energy hourly virtually self-consumed by the REC members is eligible for a network charge restoration due to avoided transit on the PG, which accounts in total for 8.6 EUR/MWh in 2021 [54,55]. This contribute combines with the 110.0 EUR/MWh incentive recognized to the REC members by the Italian GSE [56], resulting in a total incentive (I_{el}^{REC}) equal to 118.6 EUR/MWh. Conversely, the share of surplus electric energy has been assumed to be sold to the Italian GSE in the same way as in the no-REC scenario. This additional revenue has been neglected with respect to $E_{el}^{OSC,REC}(\theta)$, in part because of the lack of clarity of the Italian legislation, which is still being defined, and in part to compensate the management costs of the REC, which have not been explicitly taken into account. The monthly values of OC_i^{REC} have been evaluated according to Equation (17). Instead, ΔOC^{REC} has been evaluated on a yearly basis as stated in Equation (18).

$$c_{el,i}^{REC} = \frac{E_{el,i}^{Us\#1} + E_{el,i}^{Us\#2}}{OC_i^{BC,Us\#1} + OC_i^{BC,Us\#1}} \tag{16}$$

$$OC_i^{REC} = \left(E_{el,i}^{PG,REC} \cdot c_{el,i}^{REC} + MC_i\right) - \sum_{k=1}^{NH_i} \left(E_{el}^{TG,Us}(\theta_{k,i}) \cdot p_{el}(\theta_{k,i}) + E_{el,i}^{OSC,REC}(\theta_{k,i}) \cdot I_{el}^{REC}\right) \tag{17}$$

$$\Delta OC^{REC} = \sum_{i=Jan}^{Dec} \left(OC_i^{BC,Us\#1} + OC_i^{BC,Us\#2} - OC_i^{REC}\right) \tag{18}$$

In the end, two economic performance indicators have been determined to estimate the profitability of the investment in the PV plant in the two scenarios: the discounted pay-back time (PBT) and the net present value (NPV). To this purpose, Equations (19) and (20) have been used, respectively. The former amounts to the number of years required to balance the investment cost (IC) by considering the yearly cashflows (F_j) throughout the investment horizon (N), equal to 20 y. During the investment horizon, which has been supposed to start in 2021, the values of F_j have been evaluated by assuming the electricity purchase and selling prices constant and equal to the values available in 2021. After the first year, the producibility of the PV plant has been assumed to be affected by reduced performance, according to the information reported in the panels' technical datasheet [44]. The discount rate (a) has been assumed to be equal to 1%. The IC has been estimated by using a specific price of 1000 EUR/kW$_\text{p}$ [52].

$$PBT = \frac{IC}{\sum_{j=1}^{N} \frac{F_j}{(1+a)^j}} \tag{19}$$

$$NPV = \sum_{j=1}^{N} \frac{F_j}{(1+a)^j} - IC \tag{20}$$

3. Results

In this section, the results obtained from the energy (Section 3.1), environmental (Section 3.2) and economic (Section 3.3) analysis will be introduced.

3.1. Energy Analysis

In the next Figures, the results obtained in the noREC scenario are reported by distinguishing between Us#1 and Us#2. The stacked bars in Figure 6 amount to $E_{el,i}^{PV,Us\#1}$. The green bars are equal to $E_{el,i}^{OSC,Us\#1}$, whereas the orange bars are equal to the share of $E_{el,i}^{PV,Us\#1}$ fed to the grid, that is $E_{el,i}^{TG,Us\#1}$. As shown by the azure line, which plots the trend of $d_i^{Us\#1}$ in 2021 with respect to the secondary axis, Us#1 self-consumes at most 34.8% of $E_{el,i}^{PV,Us\#1}$ in December, being $E_{el,Dec}^{PV,Us\#1}$ equal to 11.8 MWh and $E_{el,Dec}^{OSC,Us\#1}$ equal to 4.1 MWh. In the months of highest producibility, such as May and July, when $E_{el,i}^{PV,Us\#1}$ is equal to 70.3 and to 68.8 MWh, respectively, $d_{May}^{Us\#1}$ and $d_{Jul}^{Us\#1}$ reduces to 7.9 and 10.4%, respectively. In particular, $d_{May}^{Us\#1}$ is the minimum value detected in 2021. Indeed, $E_{el,May}^{OSC,Us\#1}$ is equal to 5.6 MWh and

$E_{el,May}^{OSC,Us\#1}$ is equal to 7.1 MWh. In Figure 7, the stacked bars amount in total to $E_{el,i}^{Us\#1}$. The green bars keep being equal to $E_{el,i}^{OSC,Us\#1}$, whereas the blue bars equal $E_{el,i}^{PG,Us\#1}$. As shown by the orange indicators plotting the time trend of $s_i^{Us\#1}$ during 2021 with respect to the secondary axis, the maximum self-sufficiency is measured in June, being $s_{Jun}^{Us\#1}$ equal to 49.8%. As a matter of fact, $E_{el,Jun}^{Us\#1}$ and $E_{el,Jun}^{PG,Us\#1}$ are equal to 13.3 and 6.7 MWh, respectively. Conversely, $s_i^{Us\#1}$ reaches its minimum value in December, when it is equal to 18.6%, being $E_{el,Dec}^{Us\#1}$ and $E_{el,Dec}^{PG,Us\#1}$ equal to 22.1 and 4.1 MWh, respectively. In fact, December is the month characterized by the highest $E_{el,i}^{Us\#1}$ but the minimum $E_{el,i}^{PV,Us\#1}$.

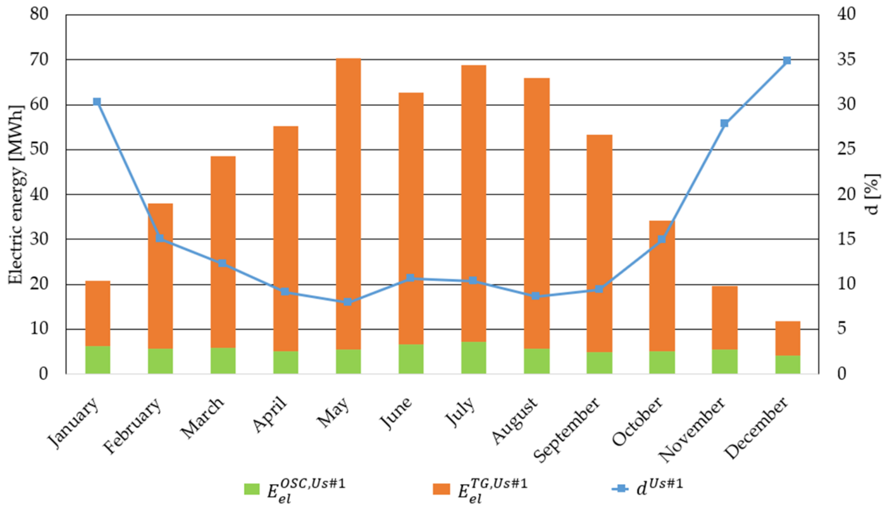

Figure 6. Producibility of the PV plant serving *Us*#1 in the noREC scenario. Electric energy consumed on-site and fed to the grid and self-consumption index in 2021.

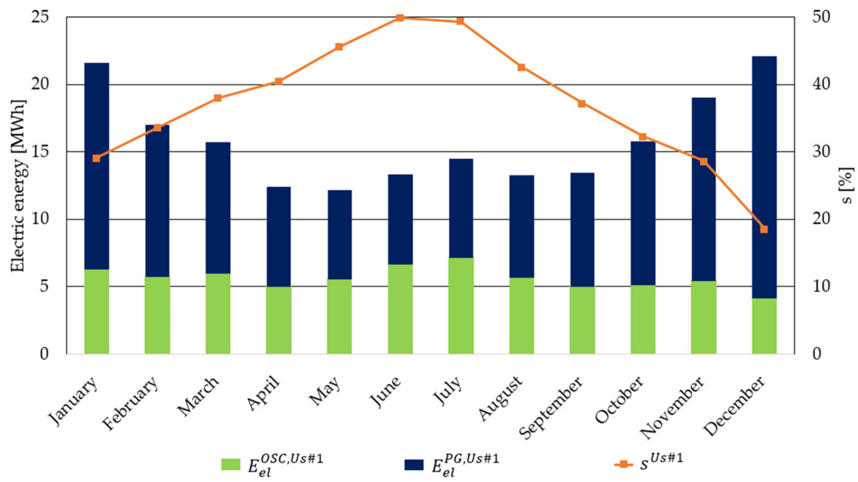

Figure 7. Load of *Us*#1 in the noREC scenario. Load covered by the PV plant, the grid and self-sufficiency index in 2021.

Still referring to the noREC scenario, the next Figures characterize the results obtained in regard to *Us*#2. The stacked bars in Figure 8 amount to $E_{el,i}^{PV,Us\#2}$, being the sum of $E_{el,i}^{OSC,Us\#2}$ and $E_{el,i}^{TG,Us\#2}$. As it can be seen, 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 $d_i^{Us\#2}$ is detected in January and is equal to 99.5%. Nevertheless, the results shown in Figure 9 highlight that the high on-site consumption rates do not imply high energy self-sufficiency. The maximum $s_i^{Us\#2}$ is measured in April, and it is equal to 16.1%

since $E^{Us\#2}_{el,Apr}$ is equal to 28.1 MWh and $E^{OSC,Us\#2}_{el,Apr}$ is equal to 4.5 MWh. By contrast, the minimum $s^{Us\#2}_{i}$ is measured in December when it is equal to 1.9% and $E^{Us\#2}_{el,Dec}$ and $E^{OSC,Us\#2}_{el,Dec}$ are equal to 53.5 and 1.0 MWh, respectively. The reason for the outcomes shown so far relies on the under-sizing which characterizes the portion of the PV plant serving *Us*#2 compared to its electric load. As a matter of fact, the PV plant supplies at most 5.7 MWh in May, whereas the maximum load is equal to 100 MWh in July. On the other hand, the results regarding *Us*#1 emphasize a significative mismatch between demand and supply. The summer months are characterized by high self-sufficiency but low self-consumption rates, as it happens in May, which is characterized by the highest supply of electric energy from the PV plant (70.3 MWh), but the load is much lower, being equal to 12.2 MWh. By contrast, the load is maximum in December (22.1 MWh), when the producibility of the PV plant reaches its minimum value (11.8 MWh). These issues are less pronounced in the REC scenario.

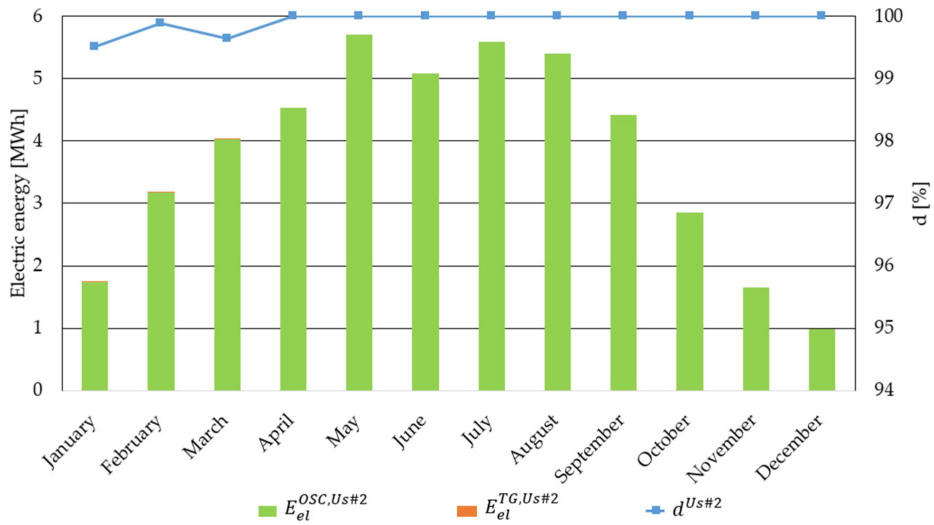

Figure 8. Producibility of the PV plant serving *Us*#2 in the noREC scenario. Electric energy consumed on-site and fed to the grid and self-consumption index in 2021.

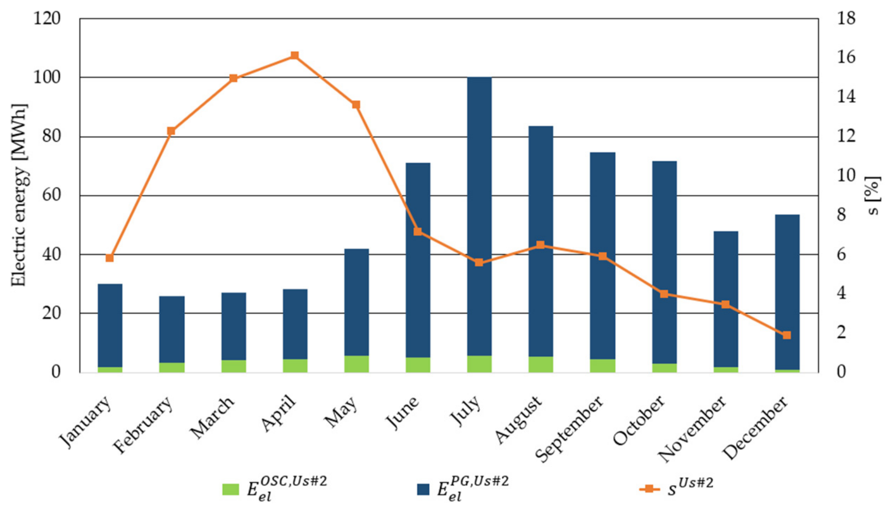

Figure 9. Load of *Us*#2 in the noREC scenario. Load covered by the PV plant, the grid and self-sufficiency index in 2021.

By analogy with the previous cases, the stacked bars in Figure 10 amount in total to $E^{PV,REC}_{el,i}$ and represent the sum of $E^{OSC,REC}_{el,i}$ and $E^{TG,REC}_{el,i}$, whereas those in Figure 11 are equal to $E^{REC}_{el,i}$, being the sum of $E^{OSC,REC}_{el,i}$ and $E^{PG,REC}_{el,i}$. The sharing of energy between

Us#1 and *Us*#2 increases both the energy self-consumption and the self-sufficiency of users. Considering the month of May, which is the month of maximum producibility of the PV plant, $E_{el,May}^{OSC,REC}$ is equal to 26.9 MWh and is higher than the sum of $E_{el,May}^{OSC,Us\#1}$ (5.6 MWh) and $E_{el,May}^{OSC,Us\#2}$ (5.7 MWh) determined in the noREC scenario. As a result, in May s_i^{REC} is the maximum, being equal to 49.7%. The amount of electric energy in total fed to the grid reduces accordingly: $E_{el,May}^{TG,REC}$ and $E_{el,May}^{TG,Us\#1}$ are equal to 26.3 and 61.7 MWh, respectively. Similar considerations apply to July, which is the month characterized by the highest total load, being $E_{el,Jul}^{Us\#1}$ and $E_{el,Jul}^{Us\#2}$ equal to 14.5 and 100.2 MWh, respectively. In particular, $E_{el,Jul}^{OSC,REC}$ is equal to 49.1 MWh, $E_{el,Jul}^{OSC,Us\#1}$ is equal to 7.1 MWh and $E_{el,Jul}^{OSC,Us\#2}$ is equal to 5.6 MWh. As a consequence of increased self-consumption, the amount of electric energy drawn from the grid reduces compared to the noREC scenario. As a matter of fact, $E_{el,Jul}^{PG,REC}$ is equal to 66.6 MWh, whereas $E_{el,Jul}^{PG,Us\#1}$ and $E_{el,Jul}^{PG,Us\#2}$ are equal to 7.3 and 94.6 MWh, respectively. As regards the minimum value of d_i^{REC}, it is found in April and is equal to 29.9%. Hence, it is more than tripled compared to $d_{Apr}^{Us\#1}$, equal to 9.1%.

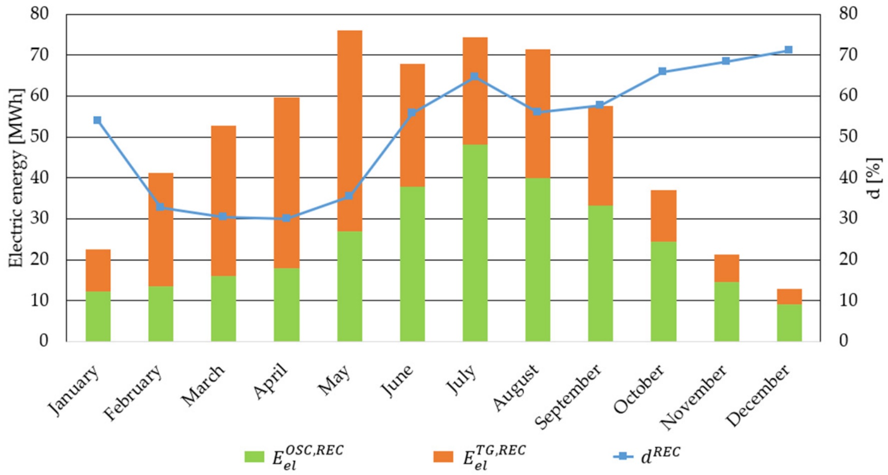

Figure 10. Producibility of the PV plant serving *Us*#1 and *Us*#2 in the REC scenario. Electric energy virtually shared and fed to the grid and self-consumption index in 2021.

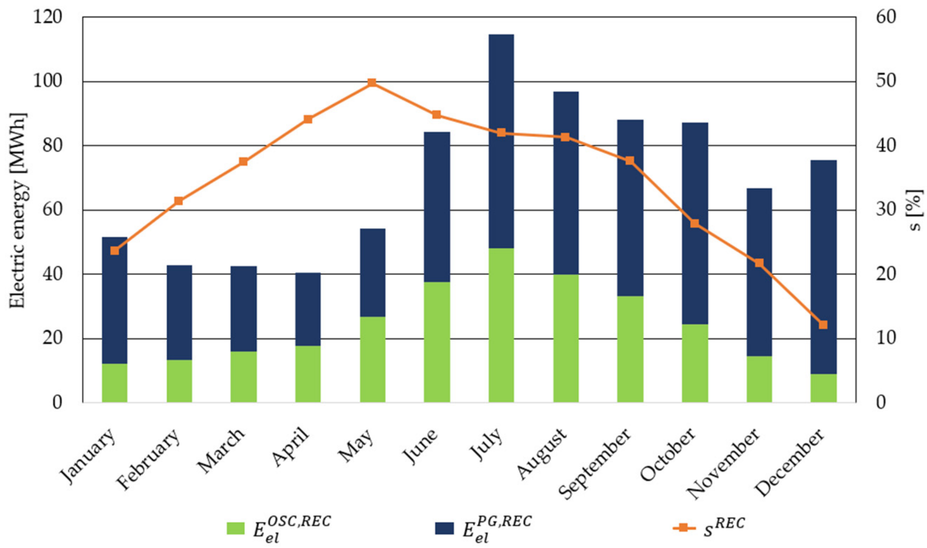

Figure 11. Load of *Us*#1 and *Us*#2 in the REC scenario. Load covered by the PV plant, the grid and self-sufficiency index in 2021.

The increased energy self-consumption and self-sufficiency, owing to the energy sharing and characterizing the REC scenario, results in a reduction of the primary energy demand higher than in the noREC scenario, as shown in Figure 12. Indeed, $\Delta E_{p,i}^{noREC}$ is, at most, equal to 25.0 MWh in July, whereas $\Delta E_{p,Jul}^{REC}$ is equal to 94.5 MWh. Overall, the primary energy demand in 2021 is equal to 1.1 GWh in the REC scenario and to 1.4 GWh in the no-REC. In the BC, the annual primary energy demand is equal to 1.7 GWh/y. 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 noREC scenario.

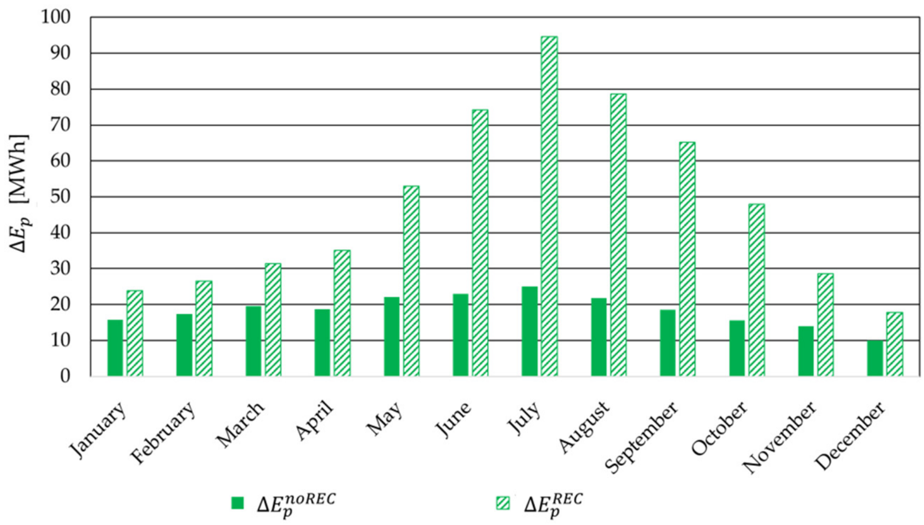

Figure 12. Primary energy saving in the noREC and REC scenario in 2021.

3.2. Environmental Analysis

Energy sharing further supports the mitigation of CO_2 emissions compared to the noREC scenario; in 2021, the emissions are equal to 242.3 tCO_2 in the BC, to 210.0 tCO_2 in the noREC scenario and to 158.2 tCO_2 in the REC scenario. Hence, the 13.3% reduction in CO_2 emissions characterizing the noREC scenario increases to 34.7% in the REC scenario. As shown in Figure 13, the best reduction on a monthly basis is found in July, and it is equal to 3.6 tCO_2 in the noREC and to 13.8 tCO_2 in the REC scenario.

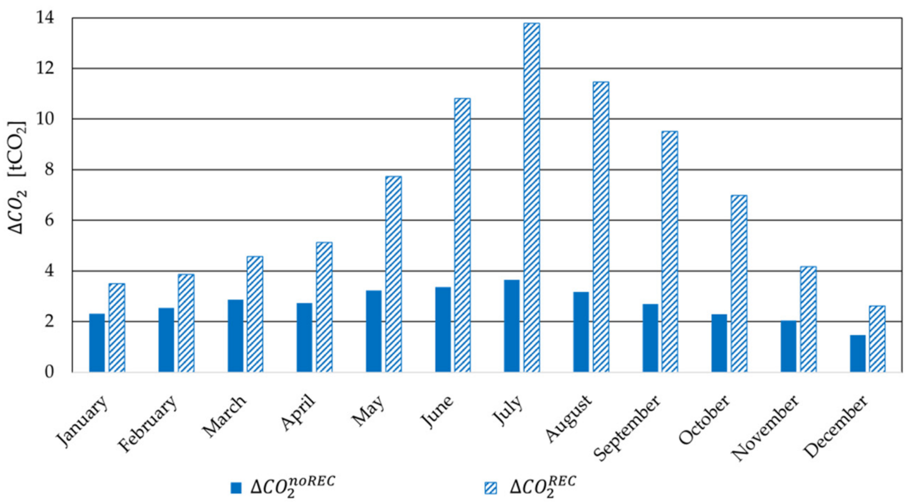

Figure 13. CO_2 emissions avoided in the noREC and REC scenarios in 2021.

3.3. Economic Analysis

In Figure 14, the operating costs relating to the first year of the investment horizon (2021) are shown. In particular, the values of OC_i^{BC} are compared with OC_i^{noREC} and OC_i^{REC}, showing that the constitution of the REC is profitable from the economic point of view since it ensures increased economic savings. As a matter of fact, OC_i^{REC} are always lower than OC_i^{noREC}. On a yearly basis, OC^{REC} are reduced by 24.6 kEUR compared to OC^{noREC} and by 100.8 kEUR compared to OC^{BC}. Instead, the annual reduction of OC^{noREC} compared to OC^{BC} is equal to 76.2 kEUR. Indeed, OC^{BC}, OC^{noREC} and OC^{REC} are equal to 238.5, 162.3 and 137.7 kEUR, respectively. Hence, the annual 31.9% economic saving characterizing the noREC scenario increases to 42.3% in the REC scenario.

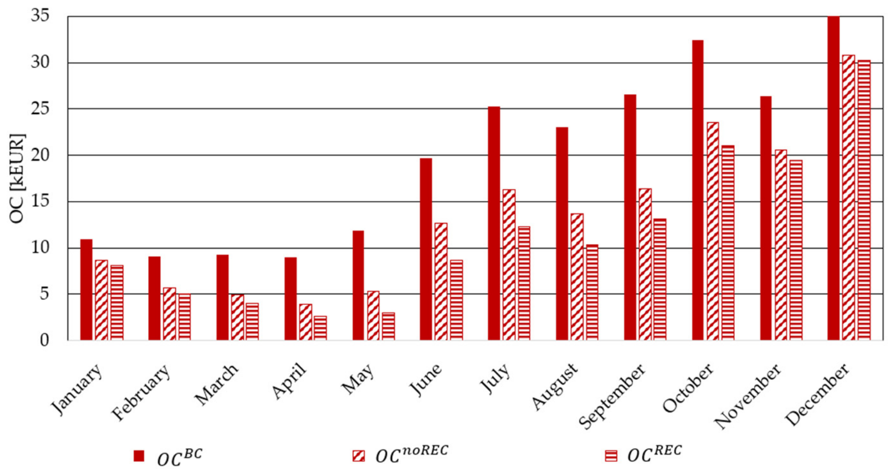

Figure 14. Operative costs in the BC, noREC and REC scenario in 2021.

Economic indexes evaluated regarding both scenarios are reported in Table 5, and further demonstrate the economic convenience of energy sharing. The value of ΔOC is referred to the first year of the investment horizon (2021) and is reported on annual basis. Although the constitution of the REC extends the PBT for *Us*#2, the larger increase detected in the NPV highlights the profitability for both users, as further shown in Figure 15, where the yearly cashflows are shown with reference to *Us*#1 and *Us*#2 in the noREC scenario and to the REC in the REC scenario. These results encourage the implementation of RECs in industrial parks according to the current Italian regulatory framework, which provides specific economic support mechanisms. Nevertheless, the transposition of European Directives in Italy has not yet been completed. Once the transposition has ended, the economic incentives defined by the final Italian regulation might confirm or overturn the results obtained in this work.

Table 5. Results of economic analysis.

Item		noREC		REC
		***Us*#1**	***Us*#2**	
IC	[kEUR] [EUR/kW$_p$]	431	35.0 1000	466
ΔOC	[kEUR/y] [EUR/kW$_p$]	65.3 152	10.8 309	101 216
PBT [y]		7.1	4.8	4.9
NPV [kEUR]		695	84.1	1273

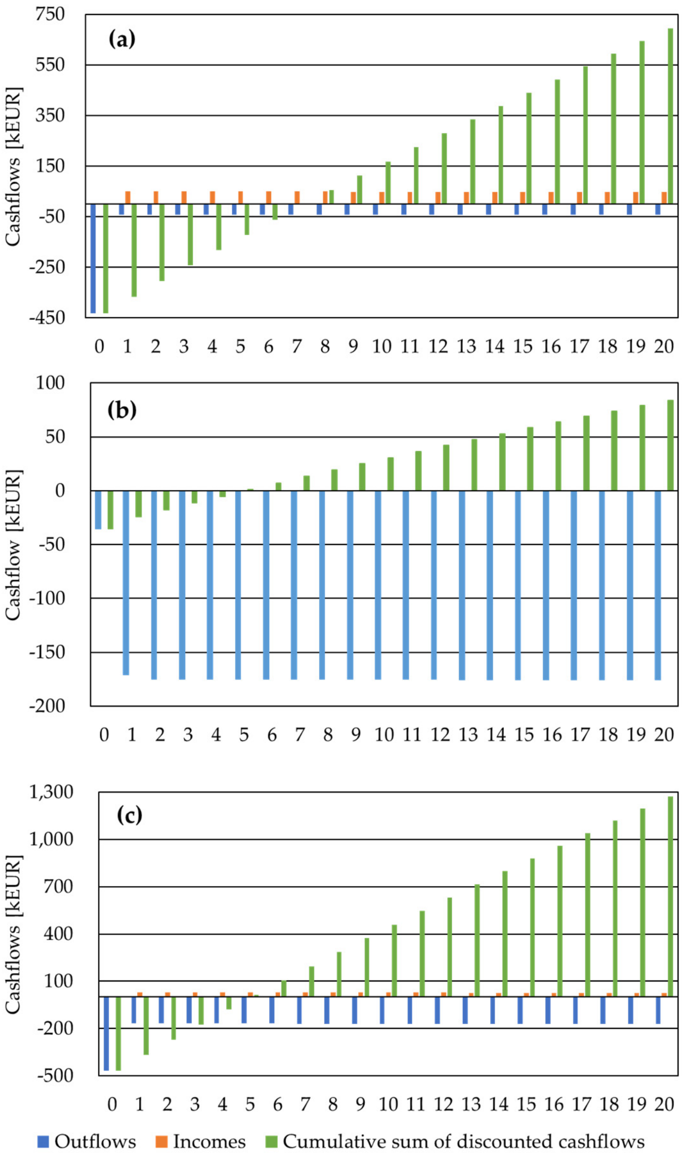

Figure 15. Yearly cashflows over the investment horizon for *Us*#1 (**a**) and *Us*#2 (**b**) in the noREC scenario and the REC (**c**) in the REC scenario.

4. Conclusions

The recast of the European Directive 2018/2001 defined in the European regulatory framework innovative configurations for energy sharing, collective production and self-consumption, known as Renewable Energy Communities. Micro, small or medium-sized enterprises have been listed as their potential members or shareholders, in addition to natural persons and local authorities. Hence, this work aims at assessing the energy, environmental and economic performance of a Renewable Energy Community, including two members located in the industrial area of Benevento (Southern Italy), namely a mixed-use building and an industrial wastewater treatment plant. This configuration has been compared with the baseline case, where the two users' electric energy demand is fully met by the power grid. Moreover, the traditional single end users' configuration has been investigated as an additional scenario in order to further emphasize the benefits owing to energy sharing. In both proposed scenarios, the users have been equipped with a 466 kW_p photovoltaic plant, which has been sized based on the surfaces available for installation. In the traditional single end users' configuration, the plant has been divided into two portions, each belonging to one user depending on its installation site. As such, each portion of the plant has been assumed to supply electric energy only to its owner, since the electric energy sharing has been neglected, and to feed to the grid the potential surplus. By contrast, the photovoltaic plant has been treated as a whole in the Renewable Energy Community, where the virtual self-consumption scheme has been applied according to the Italian regulation for sharing energy between the community's members. In both scenarios, the plant has been modelled in HOMER Pro® in order to simulate its generation curve on a quarter-hour basis. As regards the users' requests, real data about their electric energy demand have been collected from their electricity bills. In addition, their electric load curves have been constructed on a quarter-hour basis when not made available by the Italian electric energy distributor. In this way, the shares of electric energy hourly supplied by the photovoltaic plant, consumed on site and fed into the grid have been evaluated, as well as the electricity withdrawn from the power grid to cover the residual load. The results obtained from the energy, environmental and economic analysis are listed as follows:

- from the energy point of view, energy sharing increases users' self-sufficiency and renewable energy on-site consumption compared to the single self-consumers' configuration. As a result, the primary energy saving owing to the constitution of the Renewable Energy Community is equal to 34.7%, and is higher than in the single end users' configuration, where it is equal to 13.3%;
- because of the reduced primary energy demand, carbon dioxide emissions are further reduced by energy sharing. In particular, carbon dioxide emissions decrease by 13.3% and 34.7% without and with the energy sharing, respectively;
- the energy sharing increases the annual operative costs' savings from 76.2 to 101 kEUR/y, reduces the pay-back time to 4.9 y and increases the net-present value to 1273 kEUR. Thus, the Renewable Energy Community scenario is characterized by higher profitability of the investment.

To sum up, the constitution of the Renewable Energy Community provides better performances than the traditional end users' configuration. In future works, it would be interesting to investigate the installation of an electric energy storage in order to further increase the users' energy self-sufficiency and renewable energy self-consumption, according to the Italian regulation on Renewable Energy Communities, which also promotes the installation of storage systems to increase the programmability of sources. Moreover, other renewable energy technologies (such as biomethane-based cogeneration plants or wind turbines) able to meet the community's loads can be investigated as solutions to reduce carbon dioxide emissions. Yet, their economic feasibility must be verified as they are less mature technologies compared to photovoltaic plants. In addition, the possibility of including other industrial members in energy sharing will be addressed, also to promote the constitution of such configurations within the industrial sector considering their many positive effects.

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Nomenclature

Acronyms and abbreviations

BC	Baseline case
CO_2	Carbon dioxide
CSC	Collective services center
GSE	*Gestore dei Servizi Energetici* (Italian energy services operator)
PG	Power grid
POD	Point of delivery
PV	Photovoltaic
REC	Renewable Energy Community
RES	Renewable energy source
Us#1	First user (collective services center building)
Us#2	Second user (consortium wastewater treatment plant)
WWTP	Wastewater treatment plant

Symbols

a	Discount rate [%]
D	Minimum spacing distance between adjacent panels' rows [m]
c_{el}	Monthly average purchase cost of electricity [EUR/kWh]
d	Self-consumption index [%]
E_{el}^{OSC}	Electric energy consumed onsite [MWh/y, MWh/m]
E_{el}^{PG}	Electric energy drawn from the grid [MWh/y, MWh/m]
E_{el}^{PV}	Electric energy supplied by the photovoltaic plant [MWh/y, MWh/m]
E_{el}^{TG}	Electric energy delivered to the grid [MWh/y, MWh/m]
E_{el}^{Us}	User's electric load [MWh/y, MWh/m]
F_j	Cashflow in the j-th year of investment horizon [kEUR/y]
I_{el}^{REC}	Incentive for electric energy sharing [EUR/MWh]
IC	Investment cost [kEUR]
L	Photovoltaic panel's height [m]
MC	Maintenance costs [EUR/kW_py, EUR/kW_pm]
N	Investment horizon [y]
NH	Number of hours [-]
NPV	Net present value [kEUR]
OC	Operative costs [kEUR/y, kEUR/m]
p_{el}	Hourly electricity selling price [EUR/MWh]
PBT	Pay-back time [y]
s	Self-sufficiency index [%]
ΔE_p	Primary energy demand saving [MWh/y, MWh/m]
ΔCO_2	Carbon dioxide emission reduction [tCO_2/y, tCO_2/m]

Superscripts, subscripts and Greek symbols

el	Electric energy
i	Month index in a year
j	Year index in the investment horizon
k	Hour index in the total number of hours in the i-th month
P	Primary energy
noREC	Scenario without the REC
OSC	Electric energy consumed on-site
PG	Electric energy drawn from the power grid
REC	Scenario with the REC
TG	Electric energy fed to the grid
Us#1	First user
Us#2	Second user
α	Sun elevation angle [°]
α_{CO_2}	Carbon dioxide emission factor [$kgCO_2/kWh_{el}$]
β	Tilt angle [°]
η_{el}^{PG}	Power grid efficiency [-]
θ	One-hour time step

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