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Small Renewable Energy Community: The Role of Energy and Environmental Indicators for Power Grid

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Abstract: The Clean Energy for all Europeans Package pushes for the diffusion of renewable energy communities, introducing their definition in the European legislative framework. Following this interest, this paper analyses the energy and environmental performance of a renewable energy community composed of two office buildings located in Naples (Italy). Each building has a rooftop photovoltaic plant and one office presents an electric vehicle. The heating and cooling demands of both offices are satisfied by two reversible air to water heat pumps. The offices are connected through an electric microgrid and they are in parallel with a power grid. Buildings and plants are modelled and simulated by means of TRNSYS 17 simulation software. The first analysis has concerned the comparison of the results achieved in renewable energy community configuration and from individual buildings in terms of quantity of electricity imported, exported from/to power grid and consumed on-site. The share of self-consumed photovoltaic electricity rises up to 79% when energy sharing is allowed. The second analysis has been carried out to evaluate the energy and environmental performance of a renewable energy community by means of fixed and hourly varying values for power grid efficiency and emission factors for electricity. The use of time-dependent indicators has led to a lower community primary energy demand and carbon dioxide emissions of 18% and 12%, respectively, in comparison with the scenario in which the fixed parameters have been adopted.

Keywords: energy community; renewables; electric vehicle; hourly efficiency power gird; hourly emission factor; photovoltaic; dynamic simulation

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1. Introduction

Starting from 2011, the European Union (EU) has committed itself to reach the full decarbonization of the European energy system by 2050 [1]. For this scope, a series of intermediate energy and climate milestones have been set for 2020 and 2030. The most updated goals establish the achievement of a 32% share of Renewable Energy Sources (RESs) in final energy consumption, a reduction in greenhouse gas emissions by up to 40% and an increase of 32.5% in energy efficiency by 2030 compared to the 1990 baseline [2]. The accomplishment of these targets determines ambitious challenges and opportunities for the development of innovative energy supplying systems, giving a priority role to European *consumers* as main actors of energy transition. Moreover, the set of European policies, approved to achieve the above reported objectives and move towards a sustainable energy system accessible to everybody, provides precisely this "central" role for European citizens who are also becoming increasingly *active* and responsible with respect to their own energy consumption. In this context, in 2016 the European Commission launched the Clean Energy for all Europeans Package, a set of directives aimed to "redesign" the EU energy sector by means of measures for energy efficiency, renewable energy sources, electricity market structure, the security of electricity supply and governance regulations [3]. In particular, two laws of this package recognize the rights of citizens and communities to be directly involved in the energy sector, providing, for the first time, a formal definition of an energy community. The aforementioned legislations are the recast of the Renewable Energy Directive (RED II), which came into force in December 2018 [4], followed by the Internal Electricity Market Directive (IEMD) launched in June 2019 [5]. More precisely, RED II refers to the promotion of renewable-based distributed systems that share electricity produced exclusively from RESs among neighbours connected by electric micro-grids, constituting so-called Renewable Energy Communities (RECs), whereas IEMD introduces the concept of Citizen Energy Community (CEC), in which the shared energy can be produced from RESs or fossil fuels and the active participants of the community can be geographically distant. These are the main differences between RECs and CECs, but they have in common two main aspects: to give a legal entity to the emergent phenomenon of energy sharing among European citizens, and to delineate the central role in energy markets of the consumers defined as *Active Consumer* in IEMD and *Renewable Self-consumer* in RED II. Under these regulations, all Member States are called to transpose RED II and IEMD in national laws by the end of 2021. After this date, the European citizens united as RECs or CECs will be able to produce, share, store and sell the "produced" electricity within the community and with the power grid.

The intense regulatory activity concerning the definition of RECs in the last few years has made this theme a hot topic. Nevertheless, the interest in benefits deriving from renewable energy sharing among different users has been already evidenced in the scientific literature before the official recognition of RECs. Furthermore, in rural villages, remote places and islands, the decentralised production and sharing of RES-based electricity has represented for a long time the mainstream way to a low-cost access to electricity [6,7].

In particular, among all RESs, solar photovoltaic (PV) has experienced a great rise in the last decade, not only in the power industry but also through decentralised system applications. This is due to the reduction in PV technologies' cost and the approach to grid-parity in many EU countries [8]. This trend can be observed in RECs' context too. Different researchers have investigated the profitability and models of PV electricity sharing in RECs at different dimension levels: urban [9,10], city/district [11–13], and condominium [14,15]. More precisely, Fina et al. [9] have developed a model to investigate the convenience of PV system installation for an urban energy community constituted by historical or multi-apartment buildings in comparison to individual constructions. The comparison of outcomes for separate buildings and their mixing in RECs evidences the added value of a REC depending upon the building types and users' load profiles. Again in reference to an urban level scale, Syed et al. [10] have evaluated the reduction in the amount of electricity taken from the grid thanks to the installation of an electric microgrid and electric storage serving three buildings equipped with PV systems located in Perth, Australia. The analysis has been conducted by means of real data acquired from smart meters installed in each building, and it has demonstrated that the REC has reached a self-sufficiency of more than 60% thanks to PV electricity sharing.

Referring to the district level, Fichera et al. [11] have examined the energy, environmental and economic performance of an REC located in southern Italy counting 370 buildings with rooftop PV panels connected by an electrical microgrid. The system has been analysed by means of a multi-agent model by considering the total PV power installed varying from 2000 to 18,000 kW, and it has been compared with the case in which buildings are not connected in an REC. The results have shown that the REC configuration ensures a fossil primary energy saving ranging from 12% to 80% and an avoided operating cost that reaches the highest value (383,000 EUR/year) at 12,000 kW photovoltaic installed power. Furthermore, Rezk et al. [12] have developed a model to optimize size and manage a PV system coupled with fuel cells and a battery supplying a small community with a mean electrical load of 500 kW/day in Saudi Arabia. They have modelled the system in a Homer environment with the aim of finding the optimal components' size that allows them to minimize the net present value. Huang et al. [13] have compared the performance of PV-battery plants serving a cluster of buildings that share photovoltaic electricity with that achieved by each system when energy sharing is not enabled. The results have demonstrated that the sharing of PV electricity by means of a microgrid significantly reduces the electricity bills of each user, maximizing the PV electricity self-consumption of the overall cluster. On the other hand, solar-driven RECs ensure sustainable electricity, supplying an alternative for off-grid rural communities. This is the case investigated by Mandelli et al. [14], who have studied a sizing method for a standalone rural PV-driven REC in Uganda by taking into account as constraints the levelized cost of "produced" electricity. The considered factors for the sizing methodologies include the investment costs (PV panels, batteries, inverter, micro-grid) and operation and maintenance costs. Another example of a PV-driven REC in a remote area is provided by Okoye et al. [15], who have implemented a cost benefit model to evidence the economic profitability of sharing PV electricity among 300 households of rural communities in Nigeria. They have demonstrated that the designed PV-driven REC allows the achievement of positive discounted cash flows with a net present value of about EUR 108,747, guaranteeing the electrification of a rural area. In addition, Fikari et al. [16] have modelled in a Homer environment a hybrid power system (composed by a wind turbine, photovoltaic plants, batteries and diesel gensets) that interacts with an electric microgrid serving a remote village of 100 households in Kenya. The simulation results have demonstrated that only a small percentage (about 30%) of the "produced" electricity is not used, and this fraction can be reduced even more by implementing an energy management strategy. The electric microgrids serving a total load less of 20 kW_{El} (well-known as nanogrids) can represent a key element for the electrification of small remote villages in Colombia (South America). Indeed, only 87% of the population is power grid-connected and there is a great potential for renewable energy sources exploitation in this area. Thus, Vives et al. [17] have investigated the feasibility of 23 nanogrid projects in Colombia by considering different locations, installed power and a combination of renewable and conventional technologies. These projects have allowed the determination of the benefits and challenges deriving from small RECs' development in remote villages of South America, such as the increase in energy demand, the change in households' habits thanks to electrification or the appropriate/inadequate use of energy.

As a matter of fact, a key point in RECs' development is the combination of the energy and mobility sectors. Indeed, electric vehicles (EVs) can be charged by means of photovoltaic electricity, acting as both an added electric load and a storage system for surplus-electricity [18]. The central concept that links PV-driven RECs and EVs is the photovoltaic electricity produced by PV systems and consumed within RECs: the so-called self-consumed electricity. A maximization of self-consumed electricity results in a lower perturbation on the power grid, and the introduction of EVs in RECs allows people to reach this scope [19].

Thus, some researchers have investigated the benefits deriving from coupling EVs and PV-driven RECs. For instance, Munkhammar et al. [20] have found that the aggregation of multiple users' EV electricity requests and PV electricity production results in an increase in self-consumed electricity with respect to the case in which each user is served only by his own PV+EV system. Bartolini et al. [21] have analysed the impact of the integration of a great number of EVs in a real PV-based urban district located in an Italian city in order to define the amount of self-consumed electricity and CO_2 emission reduction with respect to the district without EVs. The results have demonstrated that a 10% EV penetration can put to zero the amount of exported electricity at the current installed PV capacity, lowering RECs' CO_2 emissions by 3.5%. Sehar et al. [22] and Liu et al. [23] have presented a heuristic model for the operation strategy management of a commercial building microgrid coupled with EVs and a PV plant system with the aim of maximising the self-consumed electricity. Moreover, Longo et al. [24] have proposed an optimization methodology based on a genetic algorithm to simulate the integration of EVs in a residential district, considering different charging scenarios and installed PV powers. They have found that the cases including EVs ensure an economic saving with respect to the case without EVs. This money-saving ranges from a minimum of 158.9 EUR /year/person to a maximum of 184.46 EUR /year/person according to different scenarios. In another work, Gudmunds et al. [25] have investigated how EVs influence the electricity self-consumption of a household community equipped with PV panels. The results have demonstrated that the residential community can reach the same level of self-consumed electricity with EVs as well as with a stationary battery.

On the other hand, it has to be noticed that the European Directives only pay attention to the sharing of electricity in an REC, and they refer to the possibility of renewable-based thermal energy share only in a few configurations. However, the introduction of a thermal microgrid in a REC, interacting with both fossil-based and renewable-based energy systems, can lead to great advantages. Indeed, the diversity of technologies, applications, and interactions between energy vectors and users requires the flexibility of energy systems, as reported by Sayegh et al. [26]. Many researchers have already evidenced the benefits deriving from such systems. For instance, Rosato et al. [27,28] have modelled and simulated a small district constituted by schools and residential buildings served by different configurations of photovoltaic/thermal panels, flat plate solar thermal collectors coupled with seasonal and short-term thermal energy storages and a series of back-up systems. The small district is located in Naples (South Italy) and is able to ensure a primary energy saving in all considered configurations—up to 11.3% in the case of the installation of photovoltaic/thermal panels with respect to the case in which the sharing of thermal energy is not allowed. Rad et al. [29] have carried out a review on solar thermal and photovoltaic communities connected with borehole thermal energy storage, concluding that the sharing of solar energy for space heating, cooling and electricity needs guarantees environmental and energy benefits in all analysed applications in comparison to the decentralised configurations. Moreover, by also considering a hybrid application based on solar thermal collectors coupled with natural-gas fed back-up systems (such as condensing boilers or cogenerators) serving a residential energy community, it is possible to achieve significant primary energy savings and a reduction in carbon dioxide emissions (up to 11.3%) with respect to decentralised plants [30].

Nevertheless, by focusing the attention on the strict REC definition proposed by European Directives, it can be stressed that the majority of the previously cited works refer to PV-driven large size RECs composed by both commercial and residential users. However, great attention should be reserved for small RECs of only commercial or office buildings equipped with PV systems and EVs since tertiary buildings show a repetitive daily pattern of electricity consumption, which usually occurs within the maximum solar radiation hours [31]. Since only few works investigate this issue, under the pushes of the recent regulatory framework, the authors recognize that the advantages deriving from the sharing of PV electricity in a small REC composed only of office users equipped by EVs are a fundamental feature that needs to be further explored in depth. Thus, the main aim of this paper is to overcome this literature gap by assessing the energy and environmental performance of a small REC composed of two offices located in Naples (South of Italy) and linked by an electric microgrid modelled and simulated through TRNSYS 17 software [32].

Both offices are served by an individual Electric Heat Pump (EHP) coupled with a rooftop PV plant with a different peak power (9 kW_{El} and 14.25kW_{El}), and one of them is equipped with a charging station for an EV that runs for 120 km a day. The two offices constituting the REC are co-owners of the PV plants and they are able to share only the renewable electricity as proposed by the REC definition of European Directive RED II [4].

The performances of the REC are compared with those achieved by two offices when they are not allowed to share photovoltaic electricity by means of a microgrid. In addition, it has to be stressed that the contribution of this study is twofold. Indeed, besides the aforementioned issues, it goes beyond another literature gap. Traditionally, the energy and environmental performances of RECs in comparison or not with conventional systems have been assessed using average power grid efficiency and electricity emission factors, assuming implicitly that these parameters are constant all year long. Actually, environmental and energy indicators describing power grid behaviour fluctuate during the year, season, day and hour by hour as a result of the penetration of intermittent RESs in the electricity production mix and the economic dispatch of the conventional power plant. Thus, it seems improper to evaluate the performance of an REC that is by its nature driven by RESs, using fixed indicators, especially if you think that the estimation of economic support incentives for unconventional technologies often depends upon these parameters. For these reasons, in this work the energy and environmental comparison analysis of REC and no-REC configurations has been assessed with reference to two scenarios: scenario#1 accounted for fixed indicators and scenario#2 referred to time-varying parameters evaluated by the authors in a previous work [33].

2. Materials and Methods

This section provides the procedure followed to perform the proposed analysis. It is divided into four subsections. First of all, a description of the buildings and users composing the analysed REC is presented (Section 2.1), then, the systems' configuration including components' size and their rated characteristics is introduced (Section 2.2). Finally, the models developed in TRNSYS software and the methodology used to evaluate the dynamic simulation results are defined in Sections 2.3 and 2.4, respectively.

2.1. The Renewable Energy Community: Buildings and Users' Characterization

A small REC according to [4] and consisting of two office buildings located in Naples (South of Italy, 1034 heating degree days, Italian climatic zone C) is considered. Hereinafter, the two offices are named Office#1 and Office#2 in order to distinguish them.

Both Office#1 and Office#2 are one-store flat roof buildings with a total area of 200 m^2 and a heated volume of 600 m^3. Office#1 is occupied by 13 workers during weekdays while it is empty on weekends. Office#2 is divided into two apartments of 100 m^2 intended for office use, and each of them is occupied by a maximum of 6 employees and 6 users during working hours while it is vacant on weekends. The occupancy schedule for both buildings during weekdays is reported in Figure 1, where the occupancy profile of Office#2 is the cumulative one referring to both apartments.

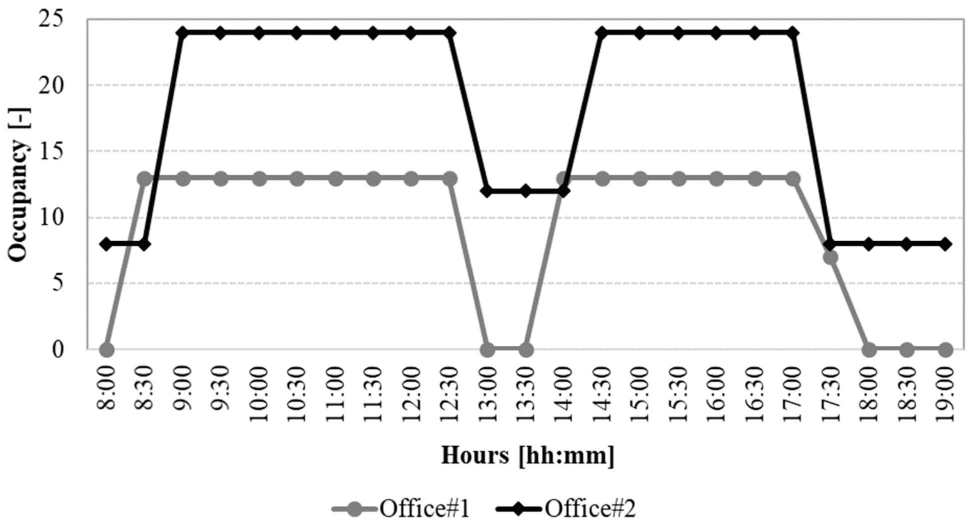

Figure 1. Occupancy schedule for Office#1 and Office#2 on weekdays during working hours.

The main building envelope features are listed in Table 1 for Office#1 and Office#2. In both buildings, the transmittance of windows is referred to as whole transparent component (glass and frame). The window area is 48 m^2 and 45 m^2 for Office#1 and Office#2, respectively, constituting about 20% of the total vertical external wall area. The transmittance of each component and g-values are in line with the typical values of existing buildings in the considered geographical area [34]. The electric load has been determined for each office by considering the occupancy schedule, the lighting and the power of typical electric equipment installed in an office (printers, fax, laptop, copiers, etc.) as defined in [35]. Thus, since the lighting loads can be different from one season to another, a daily electric load for a typical weekday of heating, cooling and intermediate period has been outlined for Office#1 (Figure 2a) and Office#2 (Figure 2b). However, only one type of electric load has been defined for weekends. The depicted electric loads in Figure 1 do not include the Heating, Ventilation and Air Conditioning (HVAC) requirements. It can be noticed that the electric load is never null; a base load (equal to 0.255 kW and 0.80 kW for Office#1 and Office#2, respectively) is recorded when the offices are empty (during weekends and night hours) and it refers to loads that are powered when no one occupies the building (such as emergency lights, parking lights, Uninterruptible Power Supply, etc.). In particular, the annual electricity demand for Office#1 is assumed equal to 35.3 kWh/m^2, while it amounts to 29.9 kWh/m^2 for Office#2.

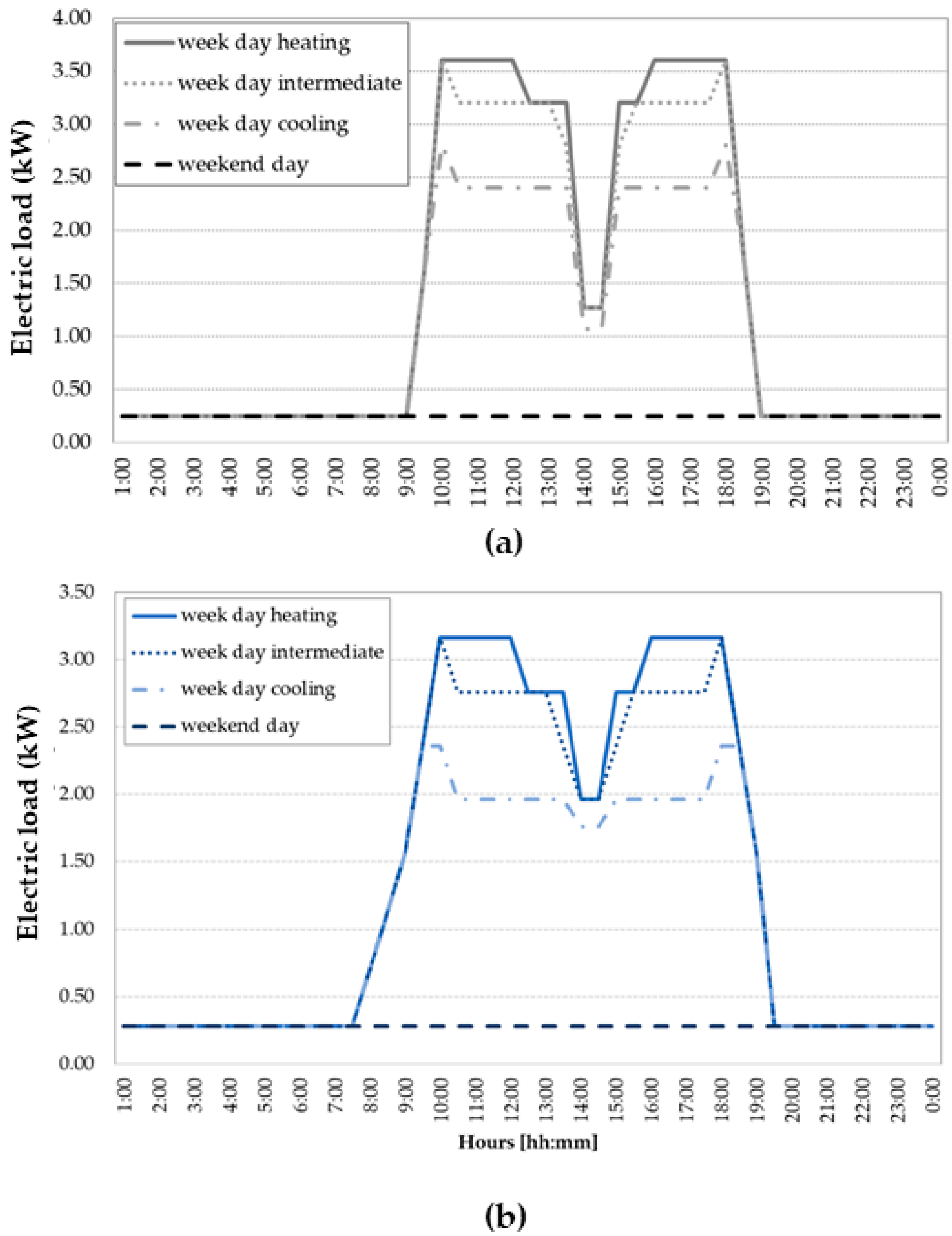

Figure 2. Electric load for Office#1 (**a**) and Office#2 (**b**).

Table 1. Main building envelope features for both offices.

Building Element	Transmittance [W/m^{2}K]		Thermal Mass [kg/m^2]		g-Value [-]	
	Office#1	Office#2	Office#1	Office#2	Office#1	Office#2
External walls	0.39	0.40	373	374	-	-
Roof	0.37	0.38	334	322	-	-
Ground floor	0.42	0.42	689	389	-	-
Window	2.71	2.58	-		0.76	0.75

By taking into account the Italian legislation [36], the allowed heating period for Italian climatic zone C goes from 15 November to 31 March, while the cooling period is assumed from 1 June to 30 September. In both heating and cooling periods, the maximum daily operation hours for energy conversion systems imposed by Italian laws are 10 h/day [37]. Thereby, there is an intermediate period (from 1 April to 31 May, and from 1 October to 14 November) where no space heating and cooling needs to occur, but only electricity requests have to be met. No domestic hot water demand has been accounted since it is significantly lower than the heating and cooling requests for a tertiary building. On the basis of these considerations, the annual heating demand of Office#1 is 3.15 MWh/y, while the space cooling needed for the same building amounts to 5.21 MWh/y. The space heating and cooling requirements of Office#2 are 3.62 MWh/y and 5.32 MWh/y, respectively.

2.2. Energy Conversion Systems and Components Configuration

The schematic layout of the REC composed of two office buildings able to share renewable electricity is reported in Figure 3. More precisely, the energy conversion systems serving the buildings in order to satisfy their electric, thermal and cooling demands are depicted. In detail, both Office#1 and Office#2 are equipped with an EHP coupled with a PV rooftop plant and they are bidirectionally connected with a Power Grid (PG).

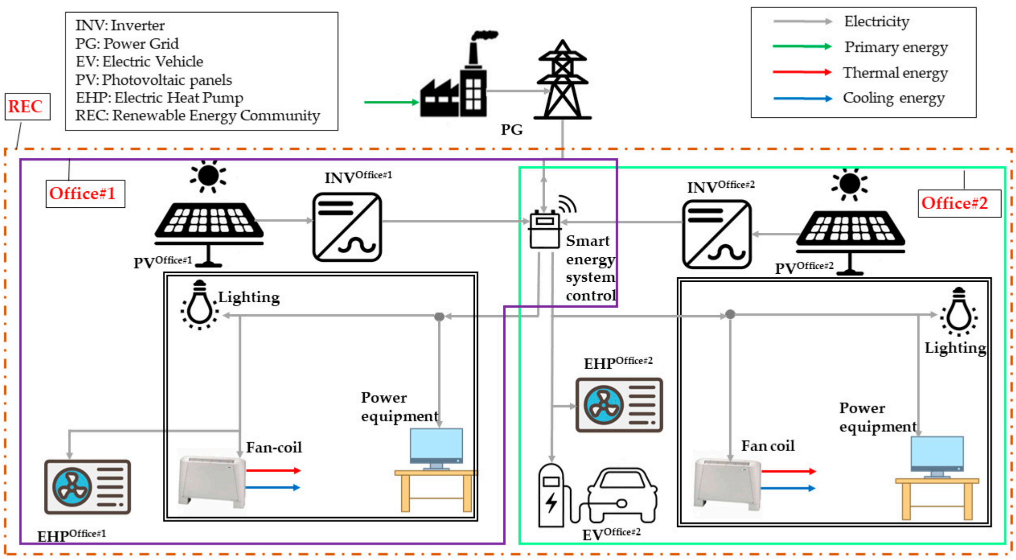

Figure 3. Schematic layout of the Renewable Energy Community (REC).

The main features of energy conversion systems installed at each office will be listed in the following bulleted points:

- Office#1: a reversible air to water heat pump (EHP$^{Office\#1}$) installed outdoors meets the space heating and cooling load of Office#1. It has a rated thermal and cooling capacity of 14.1 kW$_{Th}$ and 13.3 kW$_{Co}$, respectively, while the Coefficient of Performance (COP) amounts to 3.19 and the Energy Efficiency Ratio (EER) is equal to 3.32 (Table 2 [38]). A PV field with a peak power of 9 kW$_{El}$ is installed on the roof. The panels are arranged in 3 arrays with 12 units facing south with a tilt angle equal to 30°. The main characteristics of PV panels are reported in Table 3 [39], while the features of the Inverter (INV) are listed in Table 4 [40].

- Office#2: $EHP^{Offfice\#2}$ has the same characteristics as $EHP^{Offfice\#1}$ reported in Table 2. The PV field installed on Office#2's roof has a peak power of 14.25 kW_{El}. It is composed of 3 strings of 19 units and faces south with a tilt angle of 30°. The PV field occupies all the available roof area. The PV panels and inverter features ($INV^{Office\#2}$) are equal to those of Office#1's PV field, and they are listed in Tables 3 and 4, respectively. At Office#2, an EV charging station with a capacity of 3.3 kW_{El} and an efficiency of 0.860 is installed. The efficiency of charging systems is defined as the ratio between Direct Current (DC) power used by EV and Alternating Current (AC) or DC power required by the charging station. It is able to provide constant charging to a selected EV with a nominal electric storage of 30 kWh [41], a specific consumption of 0.173 kWh/km in Direct Current [42], and a daily distance covered of 120 km. The electric energy required to charge an EV, ensuring a daily distance of 120 km, is equal to 24.41 kWh, while 7.31 h are needed to reach the full charge. The annual electricity requested by an EV amounts to 6.84 MWh/y.

Table 2. Air to water heat pump data for both offices.

		$EHP^{Office\#1}$ and $EHP^{Office\#2}$
Heating period	Heating power (kW)	14.4
	Electric power input (kW)	4.42
	COP (-)	3.12
Cooling period	Cooling power (kW)	13.3
	Electric power input (kW)	4.12
	EER (-)	3.32

Table 3. $PV^{Office\#1}$ and $PV^{Office\#2}$ panels technical data.

Parameter	Value
Peak power (kW)	0.250
Solar panel efficiency (%)	15.28
Rated working voltage (V)	30.38
Rated working current (A)	8.29
Open circuit voltage (V)	37.1
Short circuit current (A)	8.76
Maximum power temperature factor (%/K)	−0.42
Temperature coefficient of voltage (%/K)	−0.32
Temperature coefficient of current (%/K)	0.059
Gross area (m^2)	1.64

Table 4. $INV^{Office\#1}$ and $INV^{Office\#2}$ main features.

Parameter	Value
Rated DC input power (kW)	22.75
Rated AC power (kW)	22.0
Maximum efficiency (%)	98.2

As mentioned before, both offices' plants are in parallel with PG, thus photovoltaic electricity is used to meet the electricity requested by the EHP, power equipment, lighting system, plant auxiliaries and EV (in Office#2), and the surplus/deficit of electricity could be exported to/taken from PG. Nevertheless, it is possible to share the photovoltaic electricity "produced" by both PV plants within the REC. More precisely, a smart energy control system manages the electricity flows within the REC through a strategy, reported in the following, aimed at maximizing the self-consumed electricity within the REC. If in some instances the $PV^{Office\#1}$ plant cannot cover in whole or in part the electricity load of Office#1, the smart energy control system checks if there is a certain quantity of electricity available from the $PV^{Office\#2}$ plant. If yes, the surplus electricity of the $PV^{Office\#2}$ plant is used to meet in whole or in part the remaining electric load of Office#2. Any remainder is balanced by taking electricity from PG. On the contrary, if there is surplus electricity "produced" by the $PV^{Office\#1}$ plant, the smart energy control system finds out whether an "electricity request" from Office#2 occurs; otherwise, it allows the electricity to be exported to PG.

The same control strategy is followed for electricity "generated" by the $PV^{Office\#2}$ plant.

The offices are equipped with low temperature terminals and fan-coils to cover the heating and cooling requests, ensuring an indoor comfort air temperature of 20 ± 0.5 °C in the heating period and 26 ± 0.5 °C in the cooling period. Ten fan-coils are installed in each office. The rated data of the selected fan-coils model are listed in Table 5 by accounting for the mean value of fan velocity [43]. The EHPs switching ON/OFF is managed by a chronothermostat in each office according to the occupancy schedule and the indoor temperature.

Table 5. Rated fan-coil features.

	Heating Mode *	**Cooling Mode ****
Capacity [kW]	1.51	1.22
Electric power fan [W]	22	22
Water flow rate [l/h]	210	210
Air flow rate [m^3/h]	220	220

* water inlet temperature of 50 °C. ** water inlet temperature of 7 °C.

2.3. Model Description

TRNSYS 17 has been employed to model and simulate both the office buildings and the plants [32]. It is an extensively used tool in the scientific community to assess the dynamic behaviour of building+plant systems activated by fossil or renewable sources. Each component is modelled by means of a subroutine called "type" describing its performance through experimentally validated mathematical models. The types belong to the TRNSYS library or Thermal Energy Systems Specialists (TESS) library [44]. Following a methodology common in the literature review, the whole system is considered validated if all components are defined through models validated by means of experimental, manufacturers' or literature data [34,45–47]. Thus, this approach has also been adopted in this work. Hereinafter, there are brief notes on the models of components employed in the simulation. For each of them, a reference, where the detailed description of a model can be found, is provided.

"Type 94" is used to model PV panels. It is based on a set of equations aimed at defining the "four-parameters" empirical equivalent circuit model to obtain the current-voltage curve. The mathematical model returns the curve for each module on the basis of PV panel manufacturers' data. The model is characterized by considering manufacturers' PV data [48].

The inverter has been designed through "type 48" based on a constant-efficiency model. This model takes as the input a PV panels' direct current and office electricity demand in order to send data to a smart energy system control, ensuring a right interface with PG [42]. "Type 941" models the air to water reversible EHP based on two performance maps (for cooling and heating mode) built in by manufacturers' data, including normalized heating/cooling capacity and power input [49].

The model of an air to water heat exchanger that allows heat exchange from air flow to a liquid one is used to describe the performance of fan-coils [34]. Finally, office buildings are modelled by "type 56", which defines the dynamic behaviour of a building with several thermal zones differenced by occupancy schedule, set point temperature, intended use, etc. [50].

2.4. Methods

In this section, the methodology used to evaluate the energy and environmental performances of the REC will be presented. The following analysis will be conducted with reference to two cases named as follows:

- NO_SH (NO SHaring): in this case, all the energy and environmental indices are referred to the condition in which the offices cannot share the photovoltaic electricity with each other. More precisely, the photovoltaic electricity produced by the $PV^{\mathrm{Office\#1}}$ plant can only be used to meet the electricity load of Office#1, and the same goes for Office#2. In this case, the energy and environmental analysis will be referred to as the control volume violet (for Office#1) and green (for Office#2), depicted in Figure 3.
- SH: in this case, the sharing of PV electricity between two offices is allowed, thus the energy and environmental indices are evaluated by considering the REC as a single entity that interacts bidirectionally with PG (see dashed control volume in Figure 3). In addition, in this case the individual behaviour of the Office#1 and Office#2 joined REC will be determined, too.

Obviously, the indices referring to REC will be assessed only in the SH case.

First of all, two indices aimed at defining how the renewable electricity is used are evaluated. The s index indicates the quantity of total electric load covered by PV—it is defined for Office#1, Office#2 and the REC as expressed by Equations (1)–(3), respectively. The second index, d, defines the amount of electricity used on-site with respect to the total PV electricity production. Thus, the d index can be evaluated for Office #1 (Equation (4)), Office#2 (Equation (5)) and the REC (Equation (6)).

$$s^{Office\#1} = \frac{E_{El,os}^{PV^{Office\#1}}}{E_{El}^{EHP^{Office\#1}} + E_{El}^{US^{Office\#1}}} \cdot 100 \tag{1}$$

$$s^{Office\#2} = \frac{E_{El,os}^{PV^{Office\#2}}}{E_{El}^{EHP^{Office\#2}} + E_{El}^{EV^{Office\#2}} + E_{El}^{US^{Office\#2}}} \cdot 100 \tag{2}$$

$$s^{REC} = \frac{E_{El,os}^{PV^{REC}}}{E_{El}^{EHP^{REC}} + E_{El}^{EV^{Office\#2}} + E_{El}^{US^{REC}}} \cdot 100 \tag{3}$$

$$d^{Office\#1} = \frac{E_{El,os}^{PV^{Office\#1}}}{E_{El}^{PV^{Office\#1}}} \cdot 100 \tag{4}$$

$$d^{Office\#2} = \frac{E_{El,os}^{PV^{Office\#2}}}{E_{El}^{PV^{Office\#2}}} \cdot 100 \tag{5}$$

$$d^{REC} = \frac{E_{El,os}^{PV^{REC}}}{E_{El}^{PV^{REC}}} \cdot 100 \tag{6}$$

where $E_{El,os}^{PV^{Office\#1}}$ and $E_{El,os}^{PV^{Office\#2}}$ are the photovoltaic electricity produced by the $PV^{\mathrm{Office\#1}}$ plant and the $PV^{\mathrm{Office\#2}}$ system, respectively, and consumed on-site, while $E_{El}^{PV^{Office\#1}}$ and $E_{El}^{PV^{Office\#2}}$ are the total electricity produced by PV plants installed on the roof of Office #1 and Office #2. $E_{El}^{EHP^{Office\#1}}$ and $E_{El}^{EHP^{Office\#2}}$ are the electricity requested by the EHP of Office#1 and Office#2, respectively. $E_{El}^{US^{Office\#1}}$ is the electricity requested by Office#1 user (US) and it includes no HVAC electricity requests including plant auxiliaries—the same goes for $E_{El}^{US^{Office\#2}}$ with reference to Office#2. In addition,$E_{El}^{EV^{Office\#2}}$ is the electricity needed to charge the EV through the charging station installed at Office#2. The electricity flows assigned to the REC ($E_{El,os}^{PV^{REC}}$, $E_{El}^{EHP^{REC}}$, $E_{El,os}^{PV^{REC}}$,$E_{El}^{PV^{REC}}$) are the sum of their respective quantities referred to Office#1 and Office#2.

The energy performance of REC^{SH} has been determined by means of the calculation of Primary Energy (PE), as indicated in Equation (7). It is the ratio between the electricity taken from the grid (*fg*) and the Italian efficiency of fossil fuels and renewable-based power plants (η_{El}^{PP}).

$$PE^{REC^{SH}} = \frac{\sum_{j=1}^{m}\left(E_{El,j}^{EHP^{REC}} + E_{El,j}^{US^{REC}} + E_{El,j}^{EV^{Office\#2}}\right)_{fg}}{\eta_{El}^{PP}} = \frac{E_{El,fg}^{REC^{SH}}}{\eta_{El}^{PP}} \quad (7)$$

where the index j is the time-step and m is the whole number of time-steps for the accomplished dynamic simulations. Thus, the energy flows in Equation (7) are the sum of the respective quantities in each time-step. The numerator of Equation (7) expresses the amount of electricity needed by EHPs, US and EV covered by the power grid and not met by PV plants. It can be synthetically expressed by $E_{El,fg}^{REC^{SH}}$.

The environmental analysis is performed by the evaluation of carbon dioxide (CO_2) emissions due to the electricity taken from the grid by REC^{SH} (Equation (8)).

$$CO_2^{REC^{SH}} = E_{El,fg}^{REC^{SH}} \cdot \alpha \quad (8)$$

In particular, α is the electricity CO_2 emission factor for Italian electricity production by fossil fuels and renewable-based power plants.

In addition, PE and CO_2 have been evaluated with reference to two scenarios defined as follows:

- Scenario_AI (Average Indicators): the average annual values for efficiency and environmental indicators of Italian Powee Plant (PP) have been adopted in the calculation. In particular, both η_{El}^{PP} and α are considered constant all year long and they are equal to 0.655 and 360 gCO_2/kWh_{El} [42]. These indicators are referred to the whole Italian electricity production from fossil fuels and RESs.
- Scenario_HI (Hourly Indicators): Italian efficiency and environmental indicators (η_{El}^{PP}, α) for Italian PP vary hour by hour on the basis of the actual electricity-production mix referred to in 2017. These indices have been evaluated by the authors in a previous work [33].

3. Results and Discussion

In this section, the results of dynamic simulations elaborated following the methodology described in the previous subsections will be presented and discussed. Figure 4 shows the electricity flows, *s* and *d* indices with reference to Office#1, Office#2 and REC control volume (see Figure 4) in the NO_SH and SH cases. In Figure 4 and in the following figures the electricity exported to PG will be indicated as a negative flow in order to stress the different versus of energy vector compared to electricity taken from the grid and consumed on-site. Referring to the NO_SH case, the electricity taken from the grid by $Office\#1^{NO\_SH}$ and $Office\#2^{NO\_SH}$ ($E_{El,fg}^{Office\#1}$, $E_{El,fg}^{Office\#2}$) amounts to 4.93 MWh/y and 5.19 MWh/y, whereas the photovoltaic electricity exported to PG by Office#2 ($E_{El,tg}^{PV^{Office\#2}}$, 9.47 MWh/y) is significantly higher than that exported by Office#1 ($E_{El,tg}^{PV^{Office\#1}}$, 6.53 MWh/y).

This is due to the fact that the photovoltaic electricity available from the $PV^{Office\#2}$ plant is greater thanks to its bigger size, even if the presence of the EV at $Office\#2^{NO\_SH}$ increases the $Office\#2^{NO\_SH}$ electric load. However, the $PV^{Office\#2}$ plant covers 32.70% (2055 MWh/y) of the total EV request. Figure 5 shows the $PV^{Office\#2}$ electricity contribution to the EV electricity request on a monthly basis. It is higher in intermediate months with respect to summer months because in that period no space heating and cooling demands occur; in addition, in winter months the poor availability of photovoltaic electricity results in a poor contribution to EV electricity demand, too.

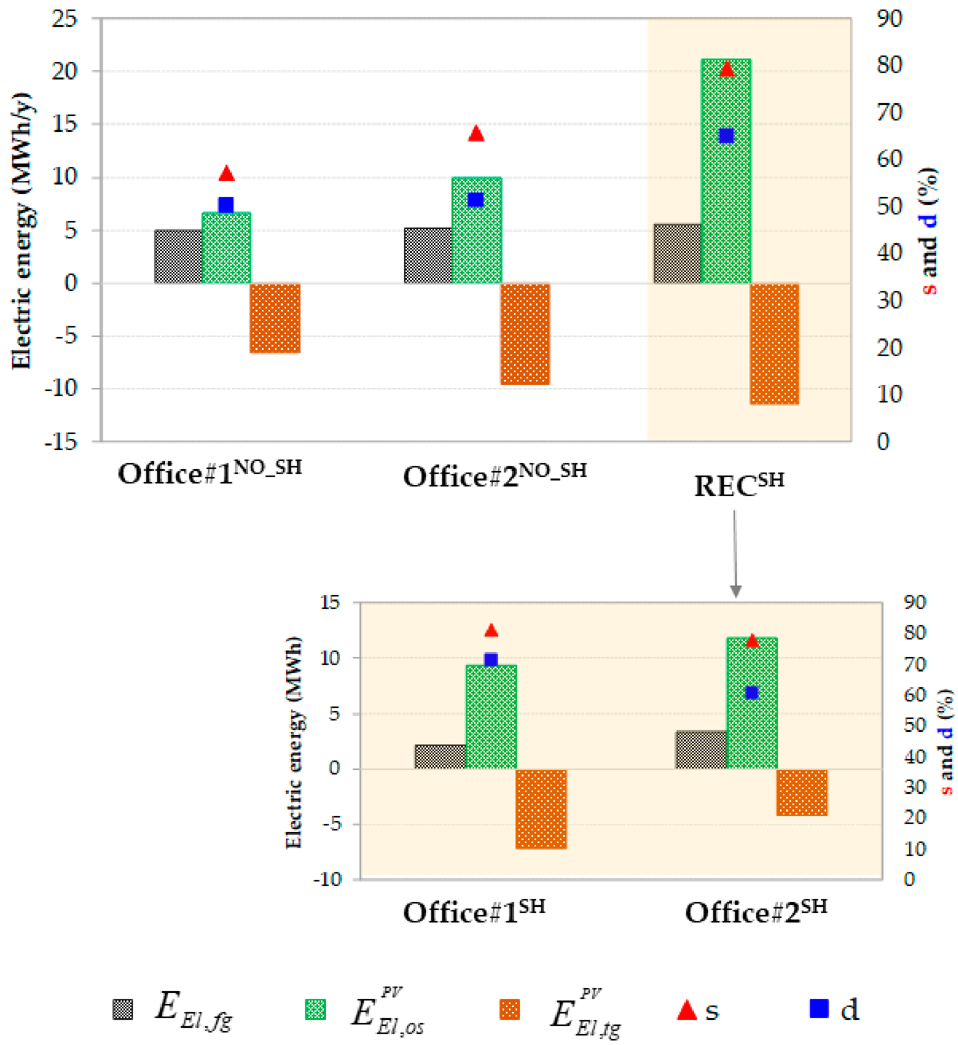

Figure 4. Electricity flows, s and d indices, for Office#1, Office#2 and REC in NO_SH (NO Sharing) and SH (sharing) cases.

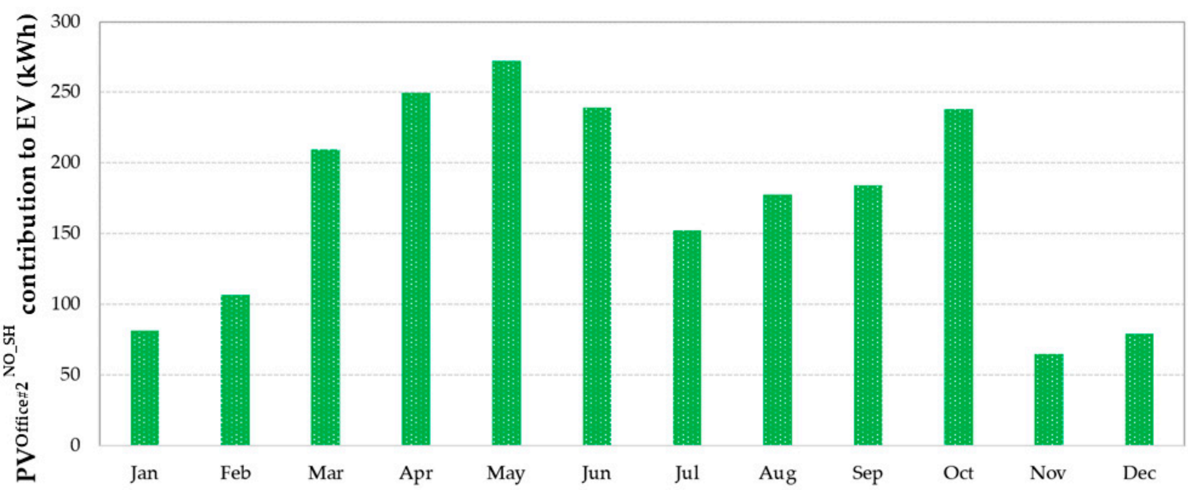

Figure 5. $PV^{Office\#2}$ electricity contribution to electric vehicle (EV) on a monthly basis in NO_SH case.

Referring to whole systems in NO_SH cases (Figure 4), 57.17% (equal to *s* index) of the Office#1 electric load is covered by photovoltaic electricity "produced" by the $PV^{Office\#1}$ plant, while this quantity increases up to 65.76% if $Office\#2^{NO\_SH}$ is considered. In addition, the d index reaches 50.24% and 51.25% for Office#1^{NO_SH} and Office#2^{NO_SH} in no sharing cases, evidencing that there is the opportunity to improve the results. Indeed, by considering the SH case, in which photovoltaic electricity sharing between two offices is allowed, the s and d indices referred to in the individual offices within the community increase. The s index grows up to 81.27% for Office#1^{SH} and 77.84% for Office#2^{SH}, while the d index rises up to 74.41% and 60.67% for Office#1^{SH} and Office#2^{SH}, respectively. By analysing the results referred to in REC^{SH}, as a single entity interacting with PG, it has been noticed that the electricity sharing within the community allows a reduction of the amount of electricity exported to PG by up to 11.40 MWh/y (in the NO_SH case, the sum of $E_{El,tg}^{PV^{Office\#1}}$ and $E_{El,tg}^{PV^{Office\#2}}$ amounted to 16.00 MWh/y). The same trend occurs for the electricity taken from the grid that for REC^{SH} is equal to 5.52 MWh/y (in the NO_SH case, the sum of $E_{El,fg}^{Office\#1}$ and $E_{El,fg}^{Office\#2}$ was 10.12 MWh/y). Definitely, the possibility to share photovoltaic electricity reduces the perturbations on PG, promoting the on-site consumption of photovoltaic electricity and leading to the s index for REC^{SH} reaching 79.32%.

More precisely, Figure 6 shows the energy flows for Office#1 (Figure 6a) and Office#2 (Figure 6b) in the NO_SH and SH cases on a monthly basis. A comparison among the electricity exported, imported and consumed on-site in the two cases is also reported by means of the difference percentage between the corresponding energy flows in the NO_SH and SH cases for both offices. For both offices, the transition from the NO_SH case to the SH case determines an increase in electricity consumed on-site ($E_{El,os}^{PV}$) and a decrease in electricity imported from the grid ($E_{El,fg}$) and exported to the grid ($E_{El,tg}^{PV}$) in each month. In particular, the greatest difference percentage in electricity consumed on-site between the NO_SH and SH cases is recorded for Office#1, which benefits from the large availability of photovoltaic electricity from the PV$^{Office\#2}$ plant that has a larger size. Thus, the electricity consumed on-site for Office#1 in the SH case reaches an increase percentage varying from 35.44% in May to 53.17% in November. Indeed, even if in May there is a greater availability of photovoltaic electricity thanks to the weather conditions, the electricity demand is lower because in intermediate months EHP$^{Office\#1}$ is switched off.

In addition, Office#2 (Figure 6b) takes advantages from electricity sharing too, even if the "profit margin" on electricity consumed on-site is inferior compared to Office#1, since the PV$^{Office\#1}$ plant has a lower size. Nevertheless, the increase percentage in $E_{El,os}$ going from the NO_SH case to the SH case ranges from 13.80% in August to 26.30% in March. By referring to both electricity taken and imported to/from the grid, again Office#1 reaches the greatest benefits from electricity sharing. The amount of electricity imported from the grid for Office#1 decreases up to 63.80% in July and that exported to the grid up to 51.93% in January with respect to the NO_SH case. For Office#2, the percentage changes are smaller but they always record an improvement in electricity use. More precisely, by comparing the NO_SH and SH cases for Office#2, the greatest decreasing change in electricity imported from the grid amounts to 42.20% in March, while it is equal to 33.72% in November, referring to electricity exported to PG.

Figure 7 points out the monthly results with reference to the REC (dashed control volume in Figure 3). As mentioned before, the REC exists only in the SH case, where electricity sharing is allowed.

It can be seen that even if the photovoltaic electricity "produced" by both PV$^{Office\#1}$ and PV$^{Office\#2}$ plants is greater than the REC's electricity load, especially in the months with a large solar energy availability, the amount of electricity taken from the grid is not null, as well as the amount of electricity exported to the grid. This is due to the fact that there is a mismatch between the period in which the photovoltaic electricity is available and when the electricity is requested. In order to improve these results, it could be useful to evaluate the possibility of introducing an electric energy storage. However, the REC configuration in the actual layout ensures the great exploitation of photovoltaic electricity consumed on-site, which is always more than double that exported to the power grid in each month.

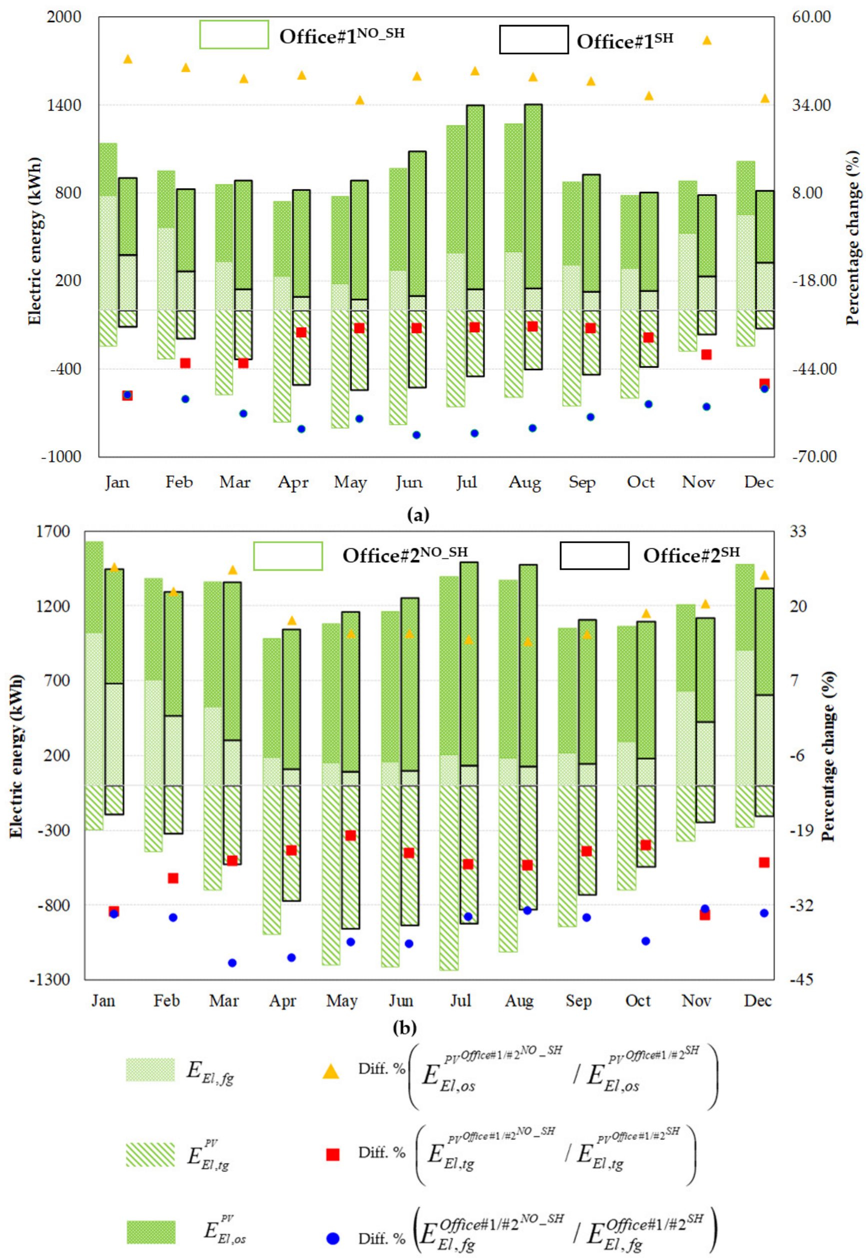

Figure 6. Comparison of energy flows for Office#1 (**a**) and Office#2 (**b**) in SH and NO_SH cases on a monthly basis.

Figure 8 schematically represents the yearly electricity balance for Office#1, Office#2 and the REC in the SH and NO_SH case. In the NO_SH case, 57% of Office#1's electricity load is covered by electricity "produced" from the PV$^{\mathrm{Office\#1}}$ plant (Figure 8a); if it is also allowed to use surplus electricity from PV$^{\mathrm{Office\#2}}$ to meet Office#1's electric load, the aforementioned percentage increases to 81% (SH case) and only 19% of the electric load is satisfied by electricity taken from PG in the SH case Figure 8c). As a consequence, the amount of electricity produced by the PV$^{\mathrm{Office\#1}}$ plant and exported to PG decreases from 6.53 MWh/y (NO_SH case) to 4.20 MWh/y (SH case). By considering Office#2, the share of electric load covered by photovoltaic electricity goes from 66% (NO_SH case, Figure 8b) to 78% (SH case, Figure 8d), and the amount of exported electricity drops to 7.20 MWh/y (it is 9.47 MWh/y in the NO_SH case) thanks to the exploitation of surplus electricity within the community. Finally, looking at the results for the whole REC$^{\mathrm{SH}}$ (Figure 8e), it has been noticed that only 11.40 MWh/y is exported to the grid, ensuring a rate of self-consumption of 79% within the community.

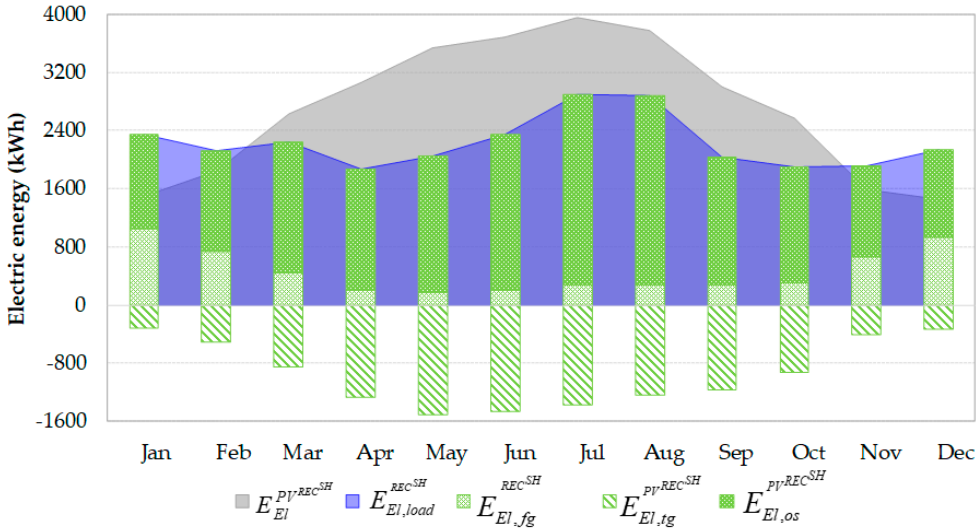

Figure 7. Electricity flows, photovoltaic electricity and electric load for REC^{SH}.

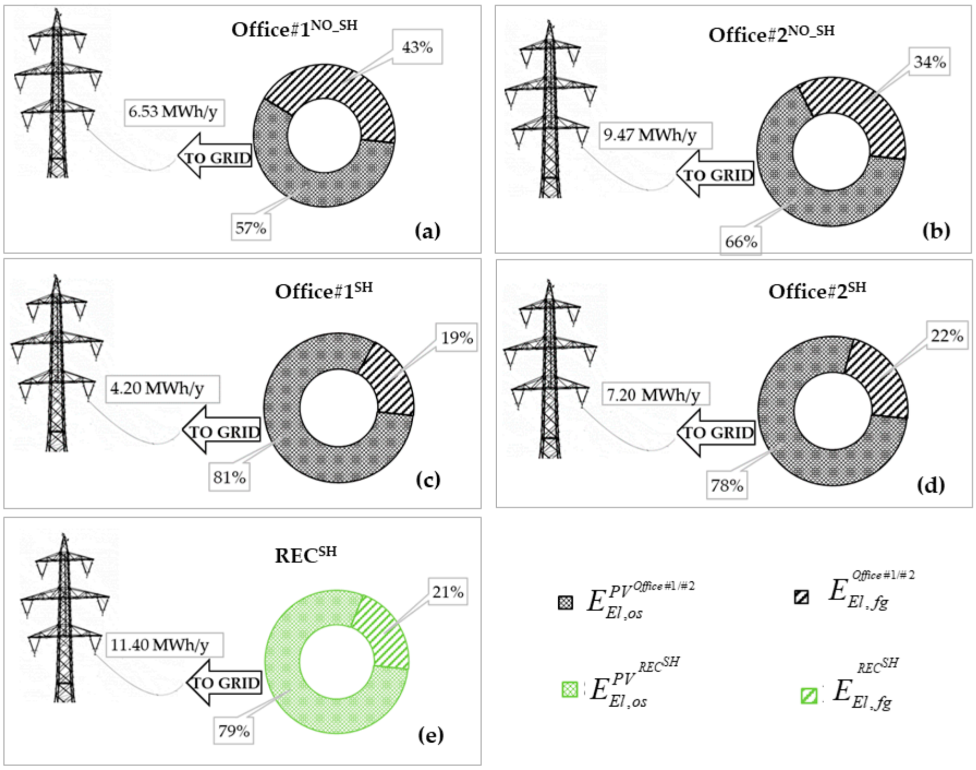

Figure 8. Annual electricity balance for Office#1^{NO_SH} (**a**), Office#2^{NO_SH} (**b**), Office#1^{SH} (**c**), Office#2^{SH} (**d**), REC^{SH} (**e**).

Hereinafter, the energy and environmental analysis results will be discussed, following the methodology introduced in the previous subsections. The outcomes will be referred to REC^{SH} in Scenario_AI (average values for efficiency and environmental indicators) and Scenario_HI (hourly-varying indicators). Figure 9 shows the *PE* demand for REC^{SH} on an annual basis (Figure 9a) and a monthly basis (Figure 9b) for both scenarios. The primary energy demand of the REC is evaluated according to Equation (7)—8.76 MWh/y in Scenario_AI and 7.15 MWh/y in Scenario_HI—resulting in a percentage decrease between the two scenarios of 18%. The variation in the results achieved by using average and time-varying.

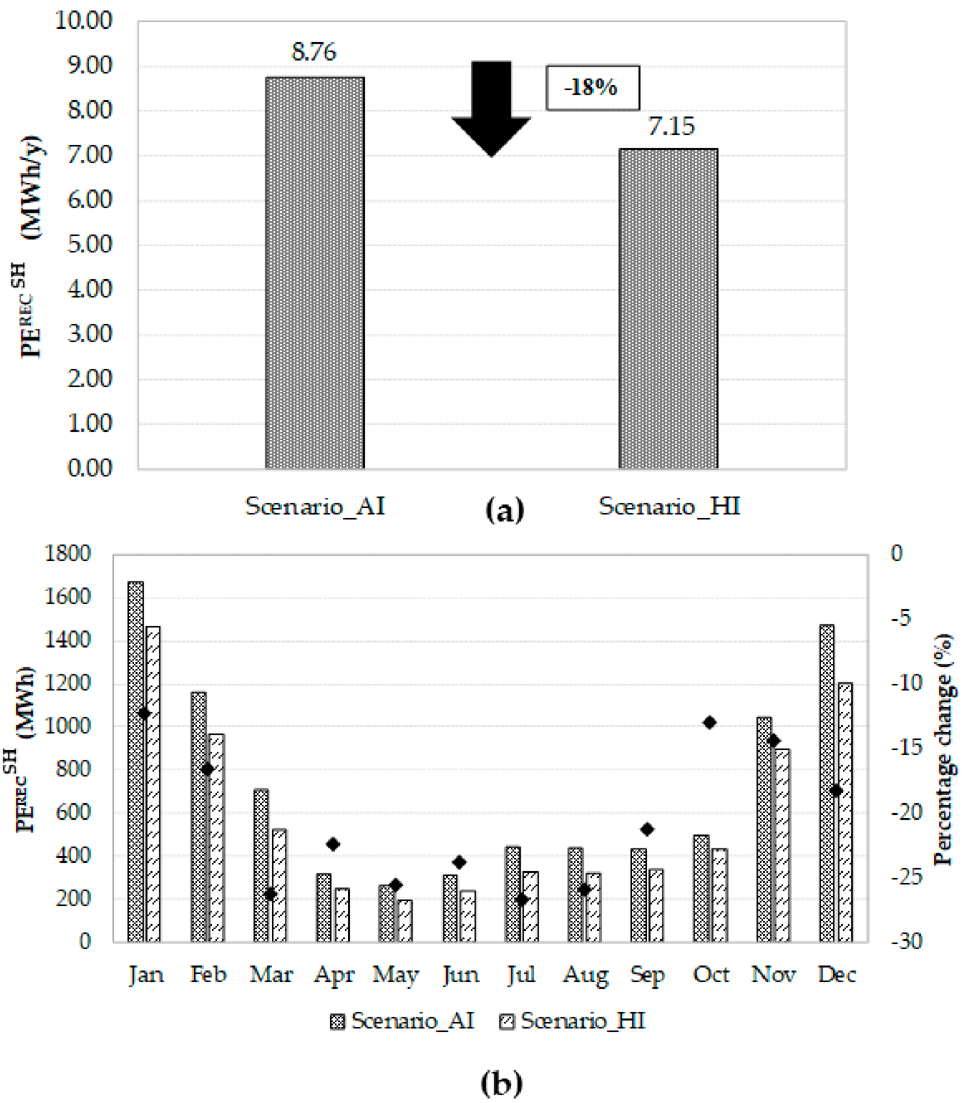

Figure 9. Energy analysis results on an annual (**a**) and a monthly (**b**) basis for REC^{SH}.

η_{El}^{PP} is more evident on a monthly basis (Figure 9b); indeed, the percentage change between PE on a monthly basis in two scenarios varies from -12.31% in January to 26.71% in July. Indeed, the penetration of photovoltaic electricity in the electricity production mix results in a higher η_{El}^{PP} calculated on an hourly basis with respect to the average values of the efficiency indicators, especially in summer months. This fact determines an overestimation of the PE demand of the REC if it is evaluated without accounting for η_{El}^{PP} fluctuations on an hourly basis. Similarly, Figure 10 reports CO_2 emissions for REC^{SH} in Scenario_AI and Scenario_HI on an annual (Figure 10a) and a monthly basis (Figure 10b). The outcomes of environmental analysis follow those obtained by energy analysis: the use of the time-dependent emission factor for electricity (α, Scenario_HI) leads to lower CO_2 emissions for REC^{SH} by up to 12% with respect to Scenario_AI, on an annual basis. The difference percentage between two scenarios increases to -21.12% in July for the analysis on a monthly basis (Figure 10b).

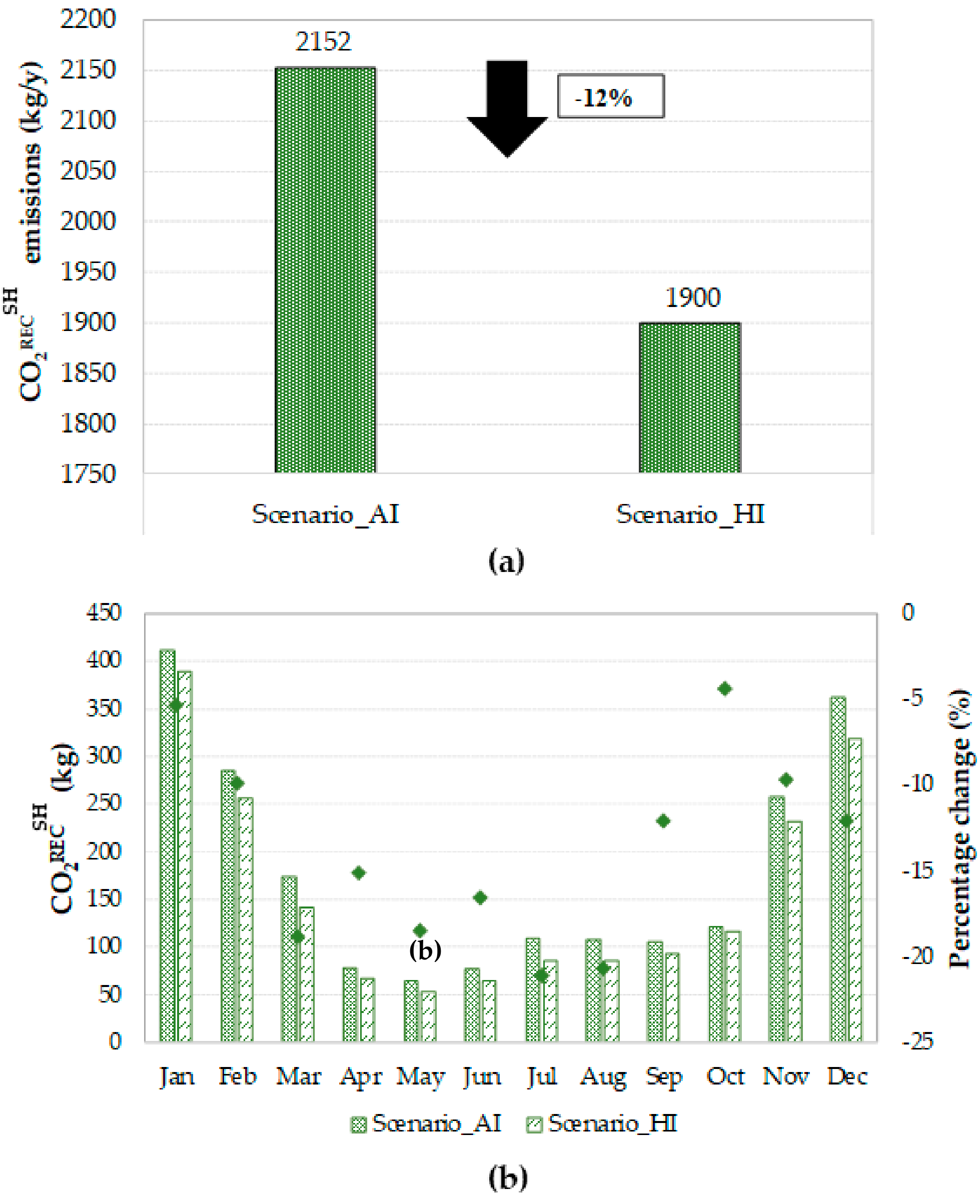

Figure 10. Environmental analysis results on an annual (**a**) and a monthly (**b**) basis for REC^{SH}.

The outcomes of this study suggest food for thought and discussion at different levels: community, regulatory and future works. More precisely, they can be summarized as in the following bulleted lists:

- Community: it is clear from the previous results that the share of electricity within the community leads to a better photovoltaic electricity exploitation, reducing the amount of electricity exported to the power grid. This fact brings advantages both to the community and to the power grid. Indeed, the community's electricity bill reduces and the quality of electricity distribution through the power grid can be improved by reducing losses and by postponing network investments.
- Regulatory: the recent Clean Energy Package pushes for the diffusion of RECs as it sets the foundation for energy communities under the EU legislative framework. However, the full transposition of the European Clean Energy Package regulations into national laws will be critical from different points of view. First of all, it is necessary to develop a business model which is able to support the diffusion of RECs in the longer term. Nowadays, the quick development of community-based projects can be largely imputable to policy support schemes supporting investments on RES-based

technologies, as it has already occurred in the past for all the innovative solutions. The results of this study suggest that business models as well as the evaluation of environmental and energy benefits achieved thanks to RECs cannot be based on static indicators, since the real nature of RESs is variable and intermittent. Thus, it is necessary to study remuneration and efficiency evaluation mechanisms that respond to real cost-efficiency and sustainability signals of RECs that cannot, regardless of the variability of parameters (η_{El}^{PP}, α) used to calculate them.
- Future works: regarding this study, it could be interesting to evaluate the results in the cases in which a battery storage is added to the REC layout or the EV is used as "vehicle to building technology" in order to use the EV battery as storage for office buildings. In addition, as soon as the EU package is fully transposed in Italian laws and the economic framework is delineated, the investigation could be extended with an economic analysis. Moreover, it will be possible to extend the REC, including other type-users (residential users, hospitals, schools, hotels, etc.).

4. Conclusions

This work analyses the energy and environmental performance achieved by a renewable-based community located in Naples (South of Italy). The renewable-based community is composed of two office buildings, each one equipped with a photovoltaic plant (9 kW_{El} and 14.25 kW_{El} peak power) installed on the roof. The heating and cooling demand of offices is satisfied by means of two reversible air to water heat pumps, and the office equipped with the largest size photovoltaic plant is furnished with a constant charging station for an electric vehicle charged during working hours. The office buildings are connected through an electric microgrid to share the electricity "produced" by the photovoltaic plants, and they are in parallel with a power grid, too. The buildings and plants have been modelled and simulated in the dynamic simulation software TRNSYS 17. The simulation results have been used to compare the electricity flows (exported, imported to/from the power grid and consumed on-site) in the case in which electricity sharing is allowed and in the case in which it is denied. The outcomes evidence that the amount of electricity exported to the grid significantly reduces and the quantity of electricity consumed on-site increases a lot when the buildings are connected within the community. In addition, the primary energy demand and carbon dioxide emissions of the renewable energy community have been evaluated by considering fixed and time-varying efficiency and environmental indicators for electricity production. The outcomes reached in two scenarios are very different, and in particular, the use of average indicators leads to an overestimation of the primary energy demand and carbon dioxide emissions imputable to the renewable energy community. Thus, it is necessary to use variable indicators to evaluate the performance of such systems that for their nature are based on intermittent and variable sources, such as renewable energy communities.

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Abbreviations

COP	Coefficient Of Performance (-)
CO_2	Carbon dioxide emissions ($kgCO_2$)
d	Ratio between the photovoltaic electricity consumed on-site and the total photovoltaic electricity available (%)
E	Electricity (kWh)
EER	Energy Efficiency Ratio (-)
PE	Primary Energy (kWh)
s	Ratio between the photovoltaic electricity consumed on-site and the total electricity request (%)
Greek Symbol	
α	Carbon dioxide emission factor for electricity (gCO_2/kWh_{El})
η	Efficiency (-)
Subscripts	
Co	Cooling
El	Electric
fg	From Grid
os	On-site
tg	To Grid
Th	Thermal
Superscripts and Acronyms	
AC	Alternating Current
DC	Direct Current
EHP	Electric Heat Pump
EU	European Union
EV	Electric Vehicle
HVAC	Heating, Ventilation and Air Conditioning
IEMD	Internal Electricity Market Directive
INV	Inverter
NO_SH	Referred to as the NO_SH case, in which photovoltaic electricity sharing is not allowed within the community
PG	Power Grid
PP	Power Plant
PV	Photovoltaic
RED II	Recast of Renewable Energy Directive
REC	Renewable Energy Community
RES	Renewable Energy Source
Scenario_AI	Referred to as the scenario in which average Italian values for efficiency and environmental indicators for PP are used.
Scenario_HI	Referred to as the scenario in which hourly varying efficiency and environmental indicators for PP and referring to Italy are used.
SH	Referred to as the SH case, in which photovoltaic electricity sharing is allowed within the community
US	User

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