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The Impact of Energy Community Composition on Its Technical and Economic Performance

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Abstract: European policies are promoting energy communities and energy sharing to decarbonize the energy system through increased penetration of renewables thereby reducing European energy dependency. However, the implementation of energy communities takes place following different patterns, and it is not entirely clear how the composition may affect community performance. This research evaluates and compares different energy-sharing scenarios at technical and economic levels. Several possible energy community solutions are evaluated. Analyses are conducted by combining the monitored electricity consumption of industries, services, and residential buildings with simulated photovoltaic production and heating consumption. The results highlight the conflict between the economic goal and the objective of maximizing the self-sufficiency of the energy community. The Italian incentive scheme currently makes it possible to double the economic value of the energy fed into the grid if physical self-consumption and shared energy reach 90% of the energy produced.

Keywords: energy communities; renewables; PV; residential profiles; industry profiles

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1. Introduction

The European Commission proposes reducing buildings' CO_2 emission by at least 55%, as part of the 2030 Climate Target Plan [1], by combining energy efficiency measures, electrifying building energy consumption, and harnessing renewable energy sources [2–4]. As a result, the Renewable Energy Directive RED II [5] raised the minimum share of renewable energy consumption to at least 32% by 2030. Not only is this deadline tight, but the target is also hardly achievable even in a scenario of increased availability of renewable sources due to a time mismatch between power generation and consumption. The timing mismatch could result in frequent exchanges of energy between buildings and the electrical grid, which could lead to a grid overload with stability and quality issues. According to Luthander et al. [6], the time mismatch can be reduced with either energy storage (e.g., batteries or water tanks) or through demand-side management (DSM) (e.g., peak shaving and appliance scheduling). However, these solutions are expensive or hardly applicable in residential buildings. Hence, promoting energy sharing is one of the important goals to be achieved.

Italian law [7], which enacts the European directive [8], promotes the development of renewable energy communities (REC) to increase the self-consumption of renewable energy. Energy sharing involves numerous benefits, environmentally [9], socially [10], and even economically. Environmental benefits include increasing renewable generation by minimizing grid losses and maximizing PV yield through centralized management. As early as 2015, the social innovation given by the development of RECs in Europe was mentioned to engage local communities [11,12]. The social and environmental benefits of RECs have been studied by many authors in Italy, such as [13]. Ancona et al. [14] also studied the benefit economically by exploiting the incentive tariff on shared energy, stating a reduction of 11% in primary energy demand and 12% in consumption.

The interest in REC has increased in the last few years as highlighted by the number of papers in the literature analyzing real and simulated case studies about energy sharing. Fina et al. [15] studied a renewable energy community of ten single-family dwellings, half of which were equipped with a photovoltaic system. The energy sharing allows an increase in the percentage of electric load covered by PV up to 23%. Similarly, Franzoi et al. [16] that the renewable share can be further increased with rule-based control and load shifting. Long et al. [17] simulated an energy-sharing community of 100 apartments with a 40% prosumer ratio. The authors found that self-sufficiency increases by 20%. Lode et al. [18] compared the design phase of seven communities (ECs) in Europe, combining different stakeholders. For example, Eslamizadeh [19] analyzed the importance of increasing the awareness of industries regarding the benefits of sharing energy.

However, most of the test cases evaluated in these studies used a fixed set of community configurations, whereas there are several ways in which REC can be implemented. The extent to which REC design affects economic, self-dependence, or environmental goals is little investigated in the literature. Similarly, it is still unclear which composition of users is more suitable for achieving REC goals. Griego et al. [20] analyzed the extent to which microgrid sizes and prosumer–consumer ratios affect self-consumption and self-sufficiency rates. They found optimal results for prosumer-to-consumer ratios within 40–60%. However, the optimal ratio only considers self-sufficiency while neglecting economic issues.

Additionally, according to [21], many papers in the literature have seldom addressed the fundamental aspects of complementarity, such as heterogeneous energy conversion units and demand profiles. Nonetheless, the REC configuration has an impact on community energy flows and, consequently, on cash flows.

This study aims to raise awareness about the advantages and disadvantages of different REC configurations in view of the greater spread of REC in the future. Different REC configurations are investigated considering residential, industrial, and service load profiles. The analysis is carried out in hybrid mode by combining real measured profiles, with synthetic probabilistic profiles and dynamic energy simulations. The main configurations of RECs are then evaluated and compared with reference to self-consumption, self-sufficiency, and economic indicators as the ratio of prosumer to consumer changes.

In the following sections, simulated consumption profiles for residential buildings and measured consumption profiles for industrial utilities and the library are initially described. After describing the simulation of PV production (Section 2.4), the different energy community composition scenarios (Section 2.5) and performance indicators used in the analyses are introduced (Section 2.6). Finally, in Section 3, the results obtained in terms of self-consumption, self-sufficiency, and economic value of energy are presented for each energy community composition considering the different heat pump penetration scenarios.

2. Materials and Methods

This work focuses on the test case of the city of Trento, located in the Italian Alpine region and characterized by a heating-dominated climate. Trento is the main city in the region, covering 22% of the region's 538,223 inhabitants and 2% of its 6207 km^2. The region's energy demand in 2016 was quantified at 15,435 GWh, 47% of which was caused by heating while 20% was related to electric consumption excluding heat pumps and electric vehicle charging [4]. Although the region is characterized by high electricity production from hydropower plants, 76% of the heating is combustion-based, thus with a total annual consumption of 5502 GWh.

The paper analyzes four different REC scenarios by evaluating self-consumed energy by prosumers and shared energy within the community. The scenarios are designed to represent the most frequent types of existing or emerging RECs in the area, based on the expressions of interest in the establishment and registration of energy communities in the regional register. Based on the type and promoter, local RECs can be classified into:

- Residential, which are established by a committee of citizens who own or rent the homes and act either as prosumers or consumers.
- Mixed, with industrial or farm prosumers and residential consumers.
- Public, in which the government provides the roofs of public buildings for PV installation and creates a REC with citizens.

The analysis combines measured consumption profiles (Sections 2.2 and 2.3) with simulated or stochastically created consumption patterns for both household appliances and air-conditioning systems (Section 2.1). Different building types are considered, namely residential apartments in multi-family buildings, single-family houses, two medium-sized industries, and a university library.

A custom Matlab code was developed to analyze the consumption profiles described in Sections 2.1–2.3, compare them with the simulated PV production profiles (Section 2.4), and evaluate prosumers' physical self-consumption and shared energy in the REC (Section 2.6). The prosumer physical self-consumption is calculated as the instantaneous power produced from renewable sources directly consumed by the prosumer system, evaluated by closing the energy balance every minute. Excess production is fed into the grid and shared with other REC users whenever possible, thus becoming shared energy. This contribution is evaluated with an hourly energy balance in accordance with the current national rules [7]. Finally, the code estimates the economic values of shared energy by using average prices in the Italian electricity market and current incentives.

The following sections define the sources of the data, the characteristics of the dynamic energy simulations, and how both were used for the analysis.

2.1. Residential Load Profiles

In residential buildings, typical electrical loads are related to household appliances and HVAC systems in buildings equipped with heat pumps.

The electricity consumption patterns of the heat pump system are obtained through a dynamic simulation [16,22]. Both single-family houses [22] and apartments in medium and large multifamily buildings [16] were simulated in Trnsys with a timestep of 1 min. Apartments in the medium (i.e., 12) and large (i.e., 36) condominiums are equipped with an independent heating and hot water system and therefore were added to the single-family building, resulting in 49 electrical consumption patterns. Moreover, different envelope characteristics are assumed based on the three building periods considered, which include approximately 28% of the residential buildings in the Trentino stock:

- Class V5 for buildings built between 1981–1990
- Class V6 for buildings built between 1990–2005
- Class V7 for buildings constructed or renovated after 2005.

The distribution of the annual electrical consumptions of the heat pumps operating in heating and domestic hot water production is shown in Figure 1 according to the different construction periods.

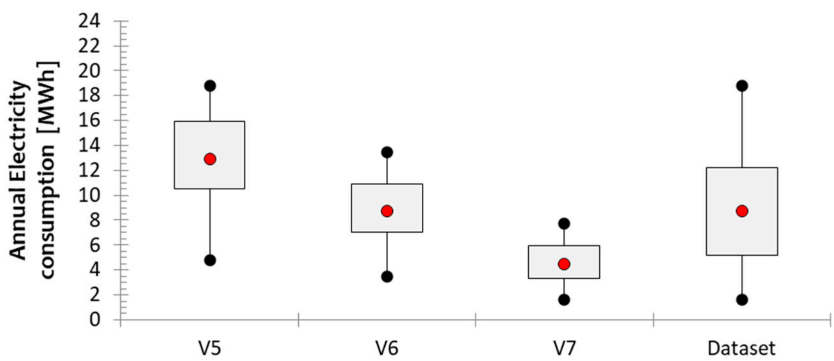


Figure 1. Distribution of heat pump electricity consumption for heating and domestic hot water production.

The analysis is limited to classes V5, V6, and V7 since heat pumps can ensure a reasonable performance in these buildings. However, not all these buildings will be equipped with heat pumps. By analyzing the dataset of air conditioning systems in the Trentino building stock [23], the most common heat generators for heating and domestic hot water are the gas-fired boiler (73.3%), the oil boiler (8.6%), and wood biomass boilers (11.7%). Only 4.97% of the buildings have a heat pump system. This distribution was also assumed in the analyses performed and described in the following sections.

The electrical absorption profiles of the appliances were also simulated using a stochastic approach by means of a custom code written in MATLAB. The code starts from the activation probability distributions of large household appliances described in [24] and the consumption profiles measured in [22]. Once the profiles are created, compliance with the contracted power contract limit is checked according to the statistics shown in Table 1 for low-voltage customers.

Table 1. Nominal power contract for Italian residential buildings (source [25]).

Nominal Power Contract [kW]	Available Power [kW]	Share of Residential Contracts
3	3.30	90%
4.5	4.95	6%
6	6.60	4%

Checks were performed according to nominal power with a 10% tolerance as usual in Italian utility contracts with no time limit. Whenever the power exceeds this available power, there is an additional 27% threshold for a period not exceeding 2 min. If this threshold is also exceeded for more than two minutes, the electric power supply is interrupted. These thresholds have been considered in the generation of the withdrawal profiles and determine the eventual time shift in the switching on of one of the turned-on appliances.

2.2. Industrial Load Profiles

Two different industrial consumption profiles are employed in the analyses and refer to a food industry and medium-sized mechanical industry, respectively. According to the chamber of commerce data, Trentino's industrial sector is 73.2% composed of companies with less than 50 employees hired primarily in the mechanical (33%) and food (15%) sectors. These two sectors thus represent very frequent and characteristic types of industry in the area. Moreover, while the mechanical industry is characterized by a regular production cycle throughout the year, the food industry is affected by the seasonality of products, which therefore has an impact on the energy withdrawal from the grid. The choice of these two types allows an assessment of the extent to which industrial load characteristics impact the profitability of the REC.

The patterns of energy consumption were obtained by gathering actual data from the energy meter during the year 2021. The two industries are characterized by a rather similar annual consumption, which is primarily affected by process loads. In fact, the food industry consumes 802.48 MWh annually while the mechanical industry has an annual consumption of 875.38 MWh. Nevertheless, the time profiles are very different (Figure 2). The mechanical engineering industry has a 5-day operation schedule (Figure 2a), and the processing load is the same throughout the year, except, of course, for closure periods. The food industry, on the other hand, has a seasonal profile that is affected by different processing and production. The processing load is concentrated in 3 days from January to May (Figure 2b), increases to 5 days in the summer months (Figure 2c), and decreases to 4 days in the last months of the year (Figure 2d).

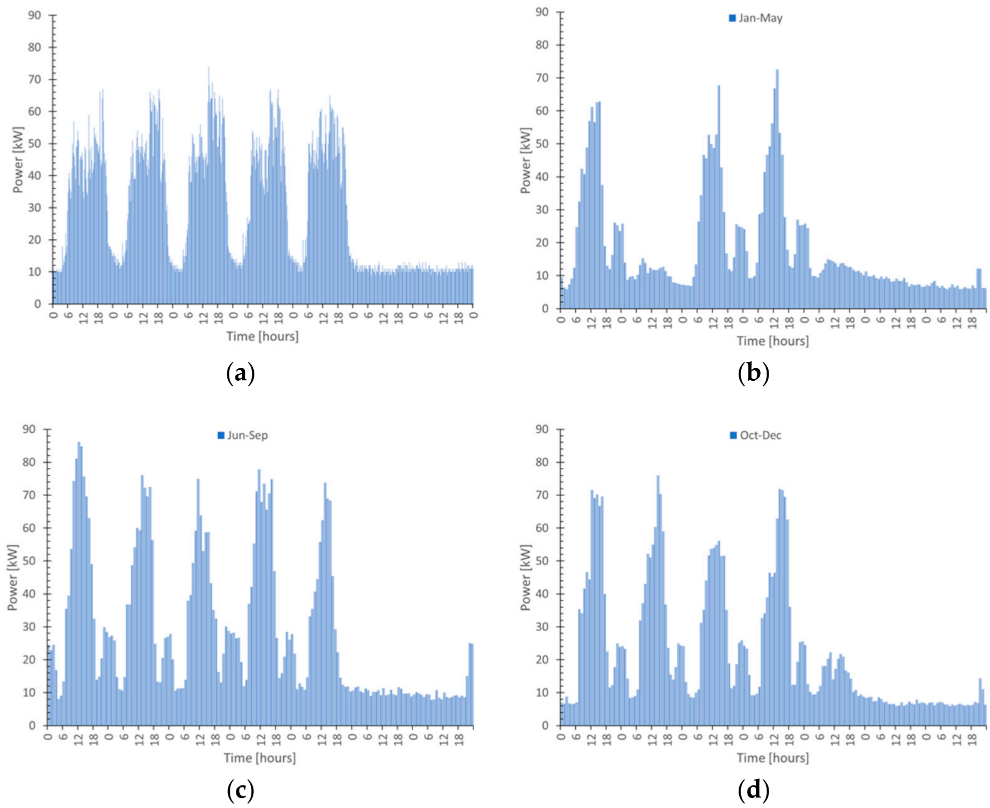


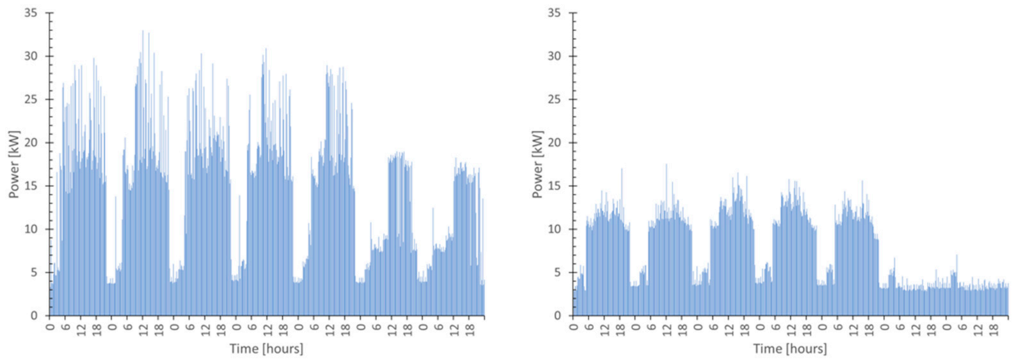
Figure 2. Weekly consumption profile of the mechanical industry (**a**) and the food industry (**b**–**d**).

2.3. Library Load Profiles

The last profile employed in the analyses concerns the electrical absorption of a public building, particularly the Trento University Library. The building is equipped with geothermal and air-to-water heat pumps for the operation of the air-conditioning system.

A monitoring system was purposely constructed for this experimental activity. Data were collected every 5 min by two Schneider PM 3255 energy meters via the Modbus protocol. One of the energy meters was dedicated to measuring the electrical absorption of the air-conditioning system, while the other one collected measurements of plug loads and lighting. The energy meters belong to class C according to EN 50470 [26] and thus have an accuracy better than 0.5% on active power and class 2 according to the EN/IEC 62053 [27] standard for reactive power measurement.

The weekly profile is almost constant for 5 out of 7 days, while during the weekend, the plug loads are nearly zero and the system consumption is substantially reduced (Figure 3). The profile is obviously affected by the seasonality of the heating/cooling demand, especially for the magnitude of peaks. During the monitored year, the air conditioning system consumed 362.08 MWh, while the electricity consumed for plug loads and lighting is 259.48 MWh. Altogether, the library's electricity consumption is 621.56 MWh, approximately 22–28% less than the consumption of the two industries.



(**a**) (**b**)

Figure 3. Weekly consumption profile of the library: Overall consumption (**a**) and consumption for plug loads and lighting (**b**).

2.4. Production Profiles from Photovoltaics

Production profiles from renewable sources are obtained by dynamic simulation of photovoltaic systems. The installation of photovoltaic modules on a 20° tilted surface facing south was assumed. Photovoltaic arrays are obtained by connecting them in series and parallel modules with a peak power of 420 W_p (Table 2). The power output was obtained from the simulation in Trnsys by type 94 using the test reference year of the city of Trento. Type 94 emulates the performance of the PV array through a "four-parameter" equivalent circuit.

Table 2. Technical specifications of the simulated PV module.

Variable	Value	Units
Short circuit current (Isc)	9.76	A
Open circuit voltage (Voc)	40.0	V
Current at max power point	9.27	A
Voltage at max power point	32.9	V
Cell Temperature coefficient of Voc	−0.12	V/K
Cell Temperature coefficient of Isc	0.005	A/K

2.5. The Renewable Energy Community Configuration

Different REC configurations are constructed starting from the profiles described in the previous sections. The analysis focuses on four different scenarios representative of residential, mixed, and public RECs.

Scenario 1 (S1): Energy sharing takes place between residential users only. There is a specific number of prosumers, i.e., 10, and an ideal number of consumers. Prosumers have a PV system with a standard size of 2.94 kW_p (as usual for residential users).

Scenario 2 (S2): Due to constraints on PV installation or suboptimal exposure, residential utilities are not equipped with PV systems. Thus, only a nonresidential user, i.e., either the mechanical (S2m), the food industry (S2f), or the library (S2l), is the prosumer. Residential users then participate in the REC as consumers. In this scenario, the photovoltaic system size is assumed to be 750 kW_p in accordance with the available roof area of the prosumers' buildings.

Scenario 3 (S3): This scenario is similar to the previous one with an additional user participating in the REC with the role of a renewable energy producer only. This represents, for example, the case of agrivoltaic solar farms. The PV system is divided between the two producers while maintaining the overall size of 750 kW_p. A 445 kW_p PV system is installed on the roof of the mechanical industry while the remaining 305 kW_p is attributed to the agrivoltaic solar farm.

Scenario 4 (S4): The two industries and the library are the three prosumers of the REC each with a PV system of 750 kW_p with a total PV peak power of 2.25 MW_p.

For each scenario, three different cases are assumed regarding the demand profiles of residential buildings joining the REC. In the first case (R1), buildings have only electrical consumption due to household appliances. Alternatively, the heat pump electrical demand is also considered assuming the current HP penetration level of 4.95% (R2). Finally, the ideal case is considered in which all buildings belonging to V5, V6, and V7 are equipped with heat pumps (R3).

2.6. Key Performance and Economic Indicators

Energy sharing is evaluated through the self-consumption factor (SCF) and load coverage factor (LCF). While the latter gives an indication of energy self-sufficiency, the SCF describes the fraction of on-site renewable energy that is self-consumed by the REC. SCF is defined as the ratio of the sum of annual physical self-consumption plus annual shared energy to the annual REC's renewable production.

LCF is defined as the ratio of the same numerator to the total annual REC's electricity demand. Hence, if LCF equals SCF, then the denominators will also be equal. In this case, therefore, over the year, the REC will produce an amount of renewable energy equal to its annual consumption. This condition was used as the first target in the optimal configuration of a REC.

Obviously, this does not imply exclusive use on site of the renewable energy, which is achieved only when the REC self-consumes the entire amount of renewable energy produced. For this reason, a second target has been defined in which the composition of the REC is able to guarantee a SCF value conventionally set at 90%.

Finally, the economic benefits are also analyzed to evaluate the best REC scenarios. The reference case involves the sum of the individual prosumers' economic remunerations for energy fed into the grid in the absence of RECs. This is evaluated by considering the prices, of which the trend for northern Italy is shown in Figure 4. An average annual selling price of 110 €/MWh for the year 2021 and 340 €/MWh for 2022 can be derived by assuming a typical profile of energy fed into the grid according to the seasonality of energy consumption and production.

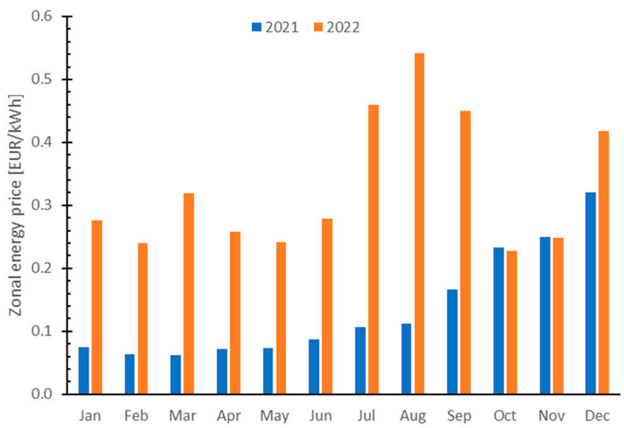


Figure 4. Monthly price trend of energy fed into the grid for the years 2021 and 2022.

This reference case is then compared with the economic value in the case of REC. The latter considers both the Italian economic incentive and the remuneration of any excess fed into the grid. In Italy, the Manager of Electricity Services (GSE) incentives energy communities by providing an economic contribution based on shared energy. The incentive consists of two grants:

- Refund on low-voltage transmission and utilization tariffs and avoidance of grid losses. This contribution is currently quantified as 8 €/MWh.
- Ministry of ecological transition's incentive for the promotion of RECs, currently equal to 110 €/MWh.

Both incentives are paid for 20 years and are in addition to economic remuneration for the additional surplus fed into the grid and not consumed by REC members.

3. Results

Our analysis compares the performance of RECs both in terms of self-consumption and energy self-sufficiency and in terms of economic remuneration of the renewable energy not physically self-consumed by producers. The following sections show the key performance indicators for the four scenarios analyzed as the number of residential consumers in the REC increases. The purpose is to evaluate the optimal ratio of prosumer users to consumer users in different REC scenarios. The economic analysis primarily aims to assess the impact of the economic incentive on the economic value of the energy shared and sold to the grid.

3.1. Scenario 1

Figure 5a shows the trends of SCF and LCF as the number of consumers increases while keeping the 10 prosumers fixed. Heat pumps are beneficial at increasing the overall self-consumption of PV energy through the increased energy shared in the REC.

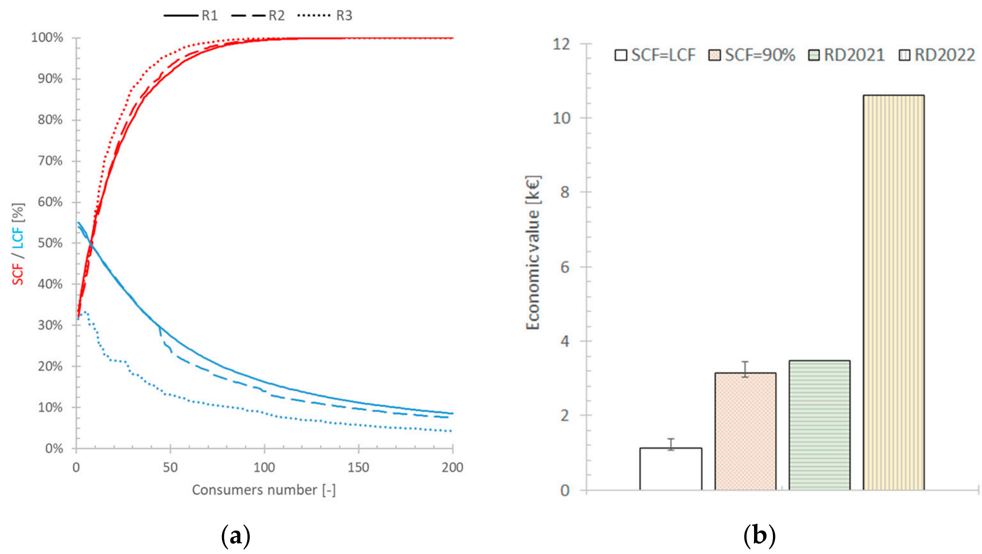


Figure 5. KPI for Scenario 1. SCF and LCF as a function of the number of consumers (**a**) and economic value of energy (RD) and incentives for R2 case (**b**). Error bars indicate the incentives for R1 and R3 cases.

This especially allows a high SCF to be achieved with fewer consumers. Increasing the energy demand for heating and domestic hot water, however, causes an inevitable reduction in self-sufficiency. In the case of the individual management of prosumers' PV systems, the overall self-consumption and load coverage factors are equal to 26% and 39%, respectively. On the other hand, a self-consumption of the entire PV production can be achieved with a consumer/prosumer ratio equal to 8.3, 9.8, or 10.3, respectively, in the cases of R3, R2, and R1.

Figure 5a highlights the absence of an intersection point between SCF and LCF in case R3. This means that the annual production of PV systems never equals the annual consumption of household appliances in the case of deep penetration of heat pumps. In contrast, PV production balances energy consumption with 3.7 kW_p/consumer (approximately eight consumers) in cases R1 and R2. Analyzing the self-consumption target of 90% of production, this target is achieved with a ratio of PV peak power to REC consumers of 0.65 kW_p/consumer (46 consumers), 0.69 kW_p/consumer (43 consumers), and 0.87 kW_p/consumer (34 consumers) for R1, R2, and R3, respectively.

Figure 5b shows the economic value of incentives at points where SCF equals LCF or the 90% target with current heat pump penetration (R2 case). Additionally, the economic values of energy fed into the grid (RD) are shown considering the price trend of the years 2021 and 2022. The value of the incentive is important since it represents the economic advantage of energy sharing compared to the case without RECs, considered business as usual. The incentive is one-third or approximately equal to the 2021 economic value in the case of self-consumption equal to self-sufficiency or SCF equal to 90%, respectively. The rising cost of energy, on the other hand, greatly reduces the impact of incentives, which are 10% and 30% of the value of energy fed into the grid. The incentive bar error in Figure 5b highlights the impact of different heat pump penetrations on shared energy and thus on the incentive. While the case with only appliances has a negligible reduction in the incentive value, the installation of heat pumps in all buildings where it is technically feasible leads to incentive increases of 21% and 10%, respectively, when SCF equals LCF or 90%.

3.2. Scenario 2

In this scenario, production is concentrated in non-residential users, and for this reason, the energy available for sharing also depends on the characteristics of non-residential patterns. The impact of the different profiles can be assessed by analyzing the case where the PV systems are not part of any REC but are intended for the building in which they are installed. Although they have the same peak power, self-consumption and self-sufficiency vary greatly. Self-consumption increases from 29% to 39% and 41% from the library to the mechanical industry and the food industry while self-sufficiency decreases from 60% to 46% and 53%, respectively. Thus, not only the magnitude of consumption but also its temporal distribution impacts the energy that can be exchanged and thus the profitability of the REC. Figures 6–8 show the trends of KPIs in the case of the mechanical industry, food industry, and library load profile, respectively. Regarding self-consumption and self-sufficiency, the graphs show how increasing the number of consumers improves self-consumption by obviously reducing LCF.

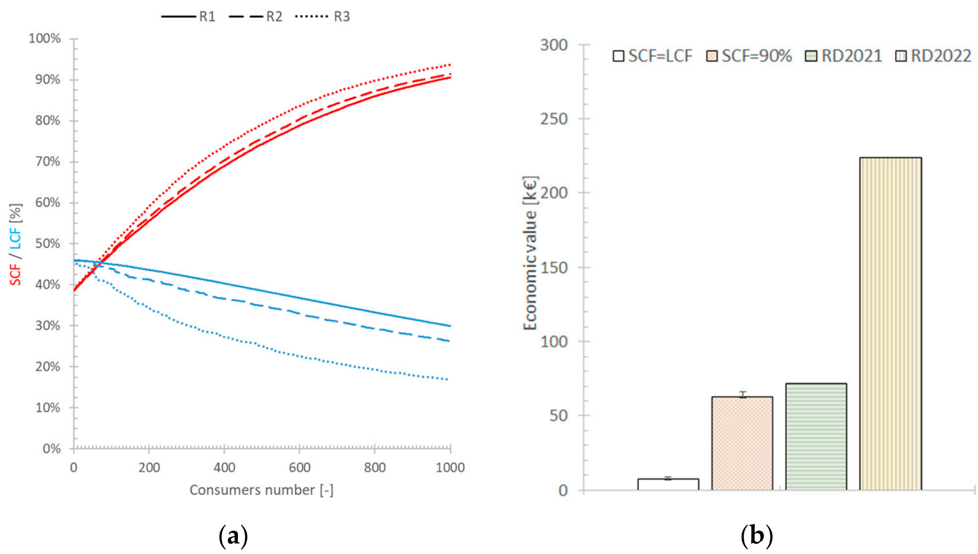
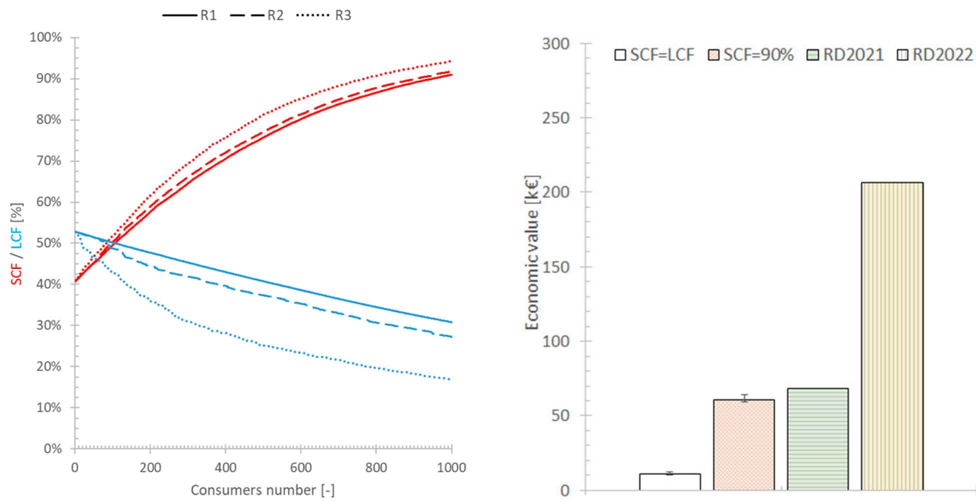
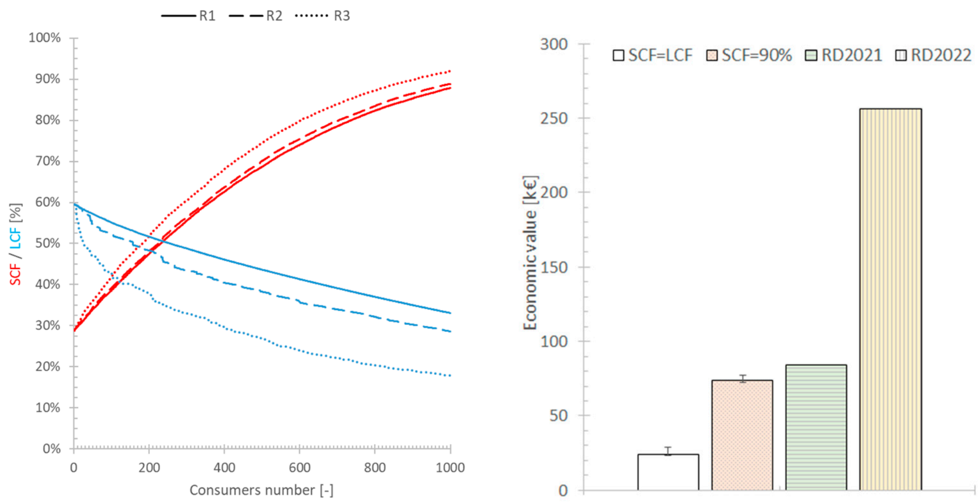


Figure 6. KPI for Scenario 2 and Mechanical Industry Prosumer. SCF and LCF as a function of the number of consumers (**a**) and economic value of energy (RD) and incentives for R2 case (**b**). Error bars indicate the incentives for R1 and R3 cases.



(**a**) (**b**)

Figure 7. KPI for Scenario 2 and Food Industry Prosumer. SCF and LCF as a function of the number of consumers (**a**) and economic value of energy (RD) and incentives for R2 case (**b**). Error bars indicate the incentives for R1 and R3 cases.



(**a**) (**b**)

Figure 8. KPI for Scenario 2 and Library Prosumer. SCF and LCF as a function of the number of consumers (**a**) and economic value of energy (RD) and incentives for R2 case (**b**). Error bars indicate the incentives for R1 and R3 cases.

For all three cases, we also see a smaller increase in SCF than a decrease in LCF when heat pump penetration increases. Table 3 shows the ratio of peak power to REC-connected consumers able to achieve the targets in the KPIs. The number of buildings that can be connected to the REC is greater in the library compared to the other buildings given the greater availability of shareable energy. Note that the ratios of peak powers to the number of consumers to achieve the target KPIs increase compared to scenario 1 but less than the prosumers' energy surplus. Indeed, the peak powers are similar in the case of the library, 2.2 and 3 times larger in the case of the food and mechanical industries, whereas the prosumer's surplus is between 20 and 24 times that of scenario 1. This is due to the presence of an industrial or utility-related load profile that is significantly different from residential profiles. In fact, process loads have characteristics and time distribution that are best suited to the physical self-consumption of PV power. Additionally, prosumer's loads are a considerable share of the REC energy needs in Scenario 2.

Table 3. kW_p/consumer for configurations to achieve target KPIs.

Case	SCF = LCF			SCF = 90%		
	R1	**R2**	**R3**	**R1**	**R2**	**R3**
S2m	10.3	12.3	16.0	0.8	0.8	0.9
S2f	7.1	8.2	16.0	0.8	0.8	1.0
S2l	3.2	3.7	7.4	0.7	0.7	0.8

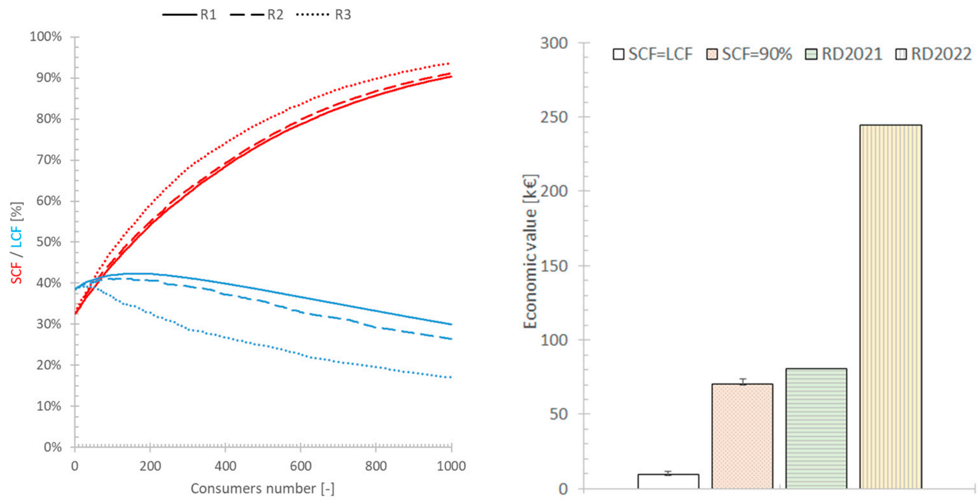
The economic analysis (Figures 6b, 7b and 8b) reflects the trend of shared energy. In the three scenarios in which SCF equals LCF, the incentive is worth 10% to 29% of the economic value of energy fed into the grid with 2021 price trends and decreases to between 3% and 9% using 2022 prices. The variations thus show the importance of load characteristics, which, however, is largely reduced when SCF reaches the 90% target. In fact, in this configuration, the incentive varies between 87% and 89% of the economic value of RD2021 and between 28% and 29% of the value of RD2022. The scenarios with the three different prosumers are also characterized by very similar sensitivities to the presence of heat pumps in consumers joining the REC. As in Scenario 1, consumers with only appliances lead to a negligible reduction in economic benefit compared to the reference case. In contrast, higher penetration of heat pumps can lead to increased incentives of 19%, 16%, and 19% in the case of the mechanical, food industry, or library, respectively.

Although the industrial utilities have a much greater physical self-consumption than the residential prosumers in Scenario 1, the energy surplus is greater due to the higher PV power installed. While the PV production surplus in scenario 1 is 30.4 MWh per year, it is 637.6 MWh, 616.3 MWh, and 740.5 MWh in cases S2m, S2f, and S2l, respectively. This explains the increase in the number of users needed to maximize the shared energy. Note then that although the three prosumers have different amounts of shareable energy. the graphs in Figures 6b, 7b and 8b are very similar to each other. Thus, this shows that the limitation in energy sharing is not related to the profiles of prosumers but rather to those of residential consumers. This result highlights the importance of effectively communicating the availability of surplus energy within the REC to guide consumers to turn on their electric loads.

3.3. Scenario 3

In this scenario, the self-consumption of the mechanical industry inevitably drops to 32%, as does self-sufficiency (i.e., 39%), due to the lower peak power of the dedicated PV system. This, combined with the presence of agrivoltaics, results in a slight increase in the energy that can be shared with the REC, which is 702.3 MWh annually.

Figure 9a shows a slight shift to the right of the points at which SCF equals LCF compared with the S2m case due to a different ratio of physical self-consumption to energy shared with residential utilities. However, this difference is dampened in achieving the target related to 90% self-consumption. In fact, this target is achieved with a peak power per residential user similar to those shown in Table 3.



(**a**) (**b**)

Figure 9. KPI for Scenario 3. SCF and LCF as a function of the number of consumers (**a**) and economic value of energy (RD) and incentives for R2 case (**b**). Error bars indicate the incentives for R1 and R3 cases.

Figure 9b shows trends similar to those in Figure 6b. Nevertheless, there is a 12% and 9% increase in the economic value of energy fed into the grid with 2021 and 2022 prices, respectively. The main diversity concerns the increase in the incentive, which increases by 33% in the case of self-consumption equal to self-sufficiency and 9% in the REC, which self-consumes 90% of the renewable production. This result is related to the different time intervals used in quantifying physical self-consumption and shared energy, which actually makes Scenario 3 more cost-effective than the similar Scenario 2m.

3.4. Scenario 4

This scenario is characterized by a larger REC. The purpose is to assess whether an economy of scale exists. In the absence of REC, the three prosumers manage to self-consume a total of 37% of production from their systems by covering 50% of the loads. Figure 10a highlights the increase in SCF as the number of residential users increases; however, it also highlights how the SCF target of 90% is never reached, even in the case of higher penetration of heat pumps.

In contrast, the break-even target between SCF and annual LCF is achieved in the configuration with 6.19 kW_p/consumer, 7.33 kW_p/consumer, and 13.33 kW_p/consumer in cases R1, R2, and R3, respectively. Figure 10b shows how increasing PV production reduces the economic benefit of setting up the REC as evidenced by the lower weight of the incentive on the total economic value of prosumers' energy surplus. In fact, the incentive reaches 16% and 5% of the economic value of RD2021 and RD2022 in the case of breakeven between SCF and LCF, and it increases to 47% and 15% of the values of RD2021 and RD2022 in the case where the REC self-consumes 90% of the PV production. Even if energy exchange between industries is possible, the oversizing of their PV systems does not allow them to consume the PV excess of other users. Therefore, this result highlights the importance of sizing renewable systems according to the users joining the REC in order to maximize cost-effectiveness.

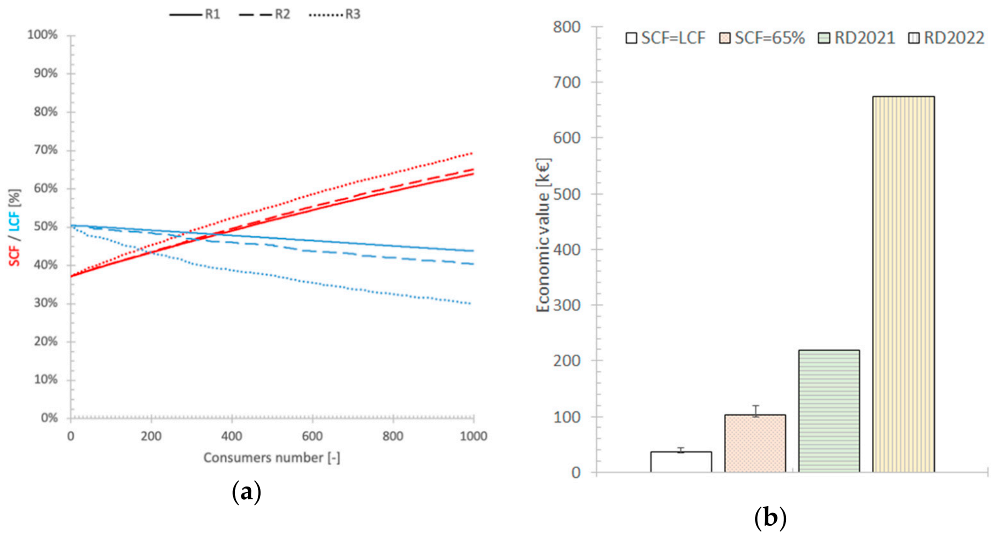


Figure 10. KPI for Scenario 4. SCF and LCF as a function of the number of consumers (**a**) and economic value of energy (RD) and incentives for R2 case (**b**). Error bars indicate the incentives for R1 and R3 cases.

4. Discussion

The increased penetration of heat pumps in residential buildings is beneficial since it reduces the minimum number of buildings required to achieve the REC performance targets, increasing energy sharing and thus the REC's economic benefit. In the future scenario where heat pumps are installed in all buildings, where such a system is compatible with the characteristics of the building itself, shared energy will increase to approximately 20 percent over the current value in RECs designed to achieve the break-even point between SCF and LCF. This is the optimal REC configuration since renewable systems generate the energy that is consumed by the REC members on an annual basis. However, greater improvement can be achieved through load-shifting techniques, which aim to decrease the time lag between heating loads and renewable generation in the REC. Therefore, it is important to have real-time communication of the energy surplus in order to vary the load in residential buildings by taking advantage of smart-grid-ready heat pumps and thermal energy storage.

This solution can also obviate the conflict between the goals of maximizing the REC's economic benefit and having a high self-sufficiency of REC. In fact, the incentive increases with increasing energy sharing and, consequently, by reaching the SCF target of 90% and above. However, this is only possible by boosting the number of users joined to the REC, with an installed peak power of 600–1000 Wp per consumer in the different scenarios analyzed. In this configuration, the economic incentive for shared energy is comparable to the economic value with 2021 prices of energy fed into the grid. Thus, the REC constitution doubles the economic value of prosumers' excess energy in all investigated scenarios in which the 90% target of self-consumption is achieved. The increased energy price in 2022, however, reduces the impact of the economic incentive to approximately one-third of the remuneration for energy fed into the grid, making it less attractive to establish a REC.

The break-even point of SCF and LCF is obviously achieved with a more balanced REC composition between installed power and loads of consumers and prosumers. In this case, the installed peak power per consumer also depends on the characteristics of the prosumers' loads. In fact, the average installed power in the scenarios analyzed is 8.2 kW_p/consumer with the current deployment of heat pumps and 14.4 kW_p/consumer with the maximum penetration currently possible. However, the peak power per consumer varies greatly in the different scenarios from a minimum of 3.7 kW_p/consumer in Scenario 1 to a maximum of 13.6 kW_p/consumer in Scenario 3. In this composition of the REC, however, economic attractiveness is limited. In fact, the incentive varies from 10% to 30%

of the economic value of the energy fed into the grid with 2021 prices and decreases to between 5% and 10% with 2022 prices.

5. Conclusions

The economic and technical viability of renewable energy communities is evaluated from measured and synthetically consumption profiles for industries, services, and residential buildings.

The results show how the goal of self-sufficiency conflicts with the economic goal. In the current incentive scheme, a large number of consumers is required to maximize the economic value of the prosumer's energy surplus, in contrast leading to a reduction in self-sufficiency. This goal is generally achieved with an installed peak power of 600 ÷ 1000 W_p per consumer in the different REC scenarios analyzed. A REC that self-consumes 90% of the renewable energy through physical self-consumption and shared energy will double the economic value of the prosumer's energy surplus through the current Italian incentive scheme. In contrast, an average peak power of 8 kW_p per consumer is able to ensure a self-sufficient REC on an annual basis. Nevertheless, this peak power may vary between 3.7 kW_p per consumer in the case of residential or service prosumers to 16 kW_p for industrial prosumers. In this configuration, however, the economic value of energy fed into the grid will only increase by between 10% and 30% due to the incentive on shared energy.

The current scenario of increasing costs of electricity paradoxically leads to making the formation of the energy community less attractive due to the reduced impact of the incentive.

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Abbreviations

The following abbreviations are used in this manuscript:

HP	Heat pump
KPI	Key Performance Indicators
LC	Large condominium
LCF	Load cover factor
MC	Medium condominium
PV	Photovoltaic
RD	Economic value of energy (€)
REC	Renewable energy community
SC	Self-consumption
SCF	Supply cover factor

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