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# Optimal ATECO-Based Clustering and Photovoltaic System Sizing for Industrial Users in Renewable Energy Communities

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**Abstract:** This paper presents a new approach to optimize the clustering of industrial users and to determine the appropriate size of photovoltaic (PV) systems in renewable energy communities (RECs). By combining data including each company's energy consumption profiles based on its ATECO classification, existing and installable PV capacity, electricity purchase and sale costs, REC incentives, and PV installation costs, the proposed algorithm identifies the optimal clustering of industrial users to form an economically efficient REC. Additionally, the optimal PV capacity for each member is evaluated, taking into account potential constraints of the available area. As a whole, the proposed algorithm can determine which cluster of companies maximizes the REC net present value ($NPV$) without compromising the payback time ($PBT$), providing a strategic framework and aid for improving the economic performance of industrial RECs, correctly sizing the community and ensuring that PV installation and investment yields the greatest possible financial and social benefits. From the analysis of the considered case studies, it appears that the proposed clustering and sizing method allows, for the REC as a whole, for an increase in the NPV from a minimum of about 25% with no change in $PBT$, up to about 75% in the case of a change in $PBT$ of up to 5 years.

**Keywords:** renewable energy communities; electricity market; design optimization; ATECO; industrial user; optimal clustering; photovoltaic systems; photovoltaic optimal sizing

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## 1. Introduction

Climate change driven by increasing anthropic greenhouse emissions is a pressing challenge, for which it is not only timely but also crucial to identify the main sources of pollution, explore mitigation opportunities, and develop innovative strategies and solutions with the aim of alleviating the problem and fostering environmental sustainability.

Figure 1 provides the distribution of estimated greenhouse gas (GHG) emissions across economic sectors in 2019, when global emissions reached 59 billion tonnes of $CO_2$eq [1]. The left column shows, for each sector, the direct emissions from owned or directly controlled sources. The right column, on the other hand, shows indirect emissions, where emissions from electricity and heat production are reallocated to the sectors where energy transmitted through these vectors is, in fact, consumed.

A notable remark is the prominent role of the electricity and heat sector, particularly within the energy reallocated to the industry and building sectors, which accounts for 43% and 46.9%, respectively. The evaluation of indirect emissions reveals that the industry sector remains the largest emitter, accounting for 34% of total emissions, followed by agriculture, forestry, and other land uses (AFOLU) with 22%, building (16%) and transportation (15%). The remaining portion is related to other energy systems and fugitive emissions, which, globally, account for 12% of GHG emissions. From this overview, it is clear that a successful decarbonization cannot rely on isolated efforts but requires a coordinated and synergetic approach involving all sectors. On this basis, the European Union has set specific targets and pathways for different sectors to drive the transition to a zero-emission future. In particular, the Green Deal Industrial Plan emerges as a pivotal initiative within the European Green Deal, offering a strategic framework designed to integrate environmental sustainability with economic growth in the industrial sector [2].

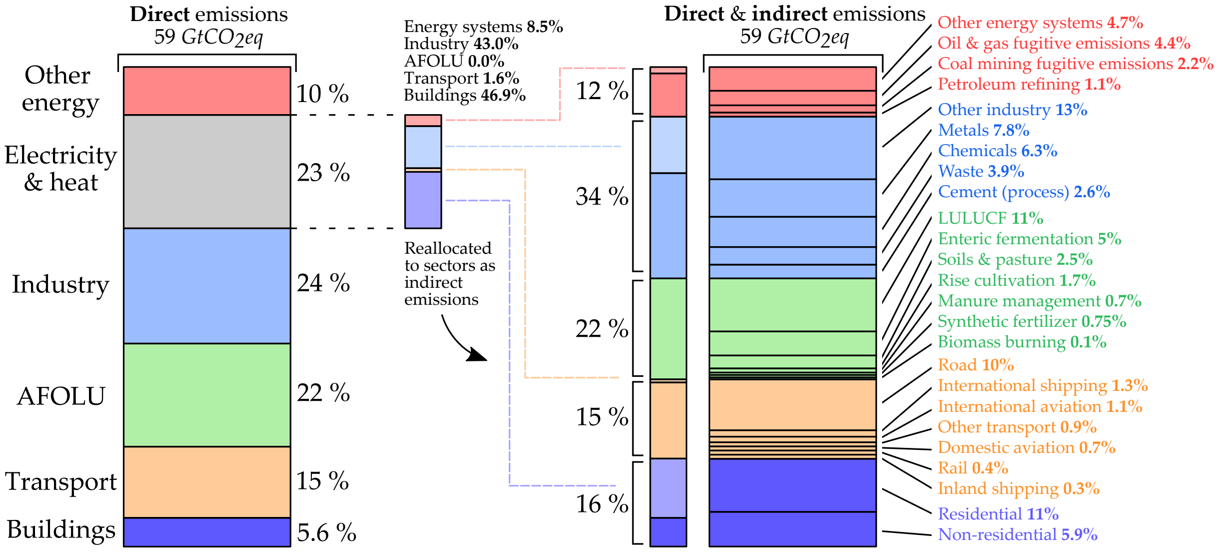


**Figure 1.** Comparisonof direct and indirect global GHG emissions: global GHG emissions in 2019 split by sector (**left**) and share of global emissions following the reallocation of indirect emissions (**right**).

The key components of the Green Deal Industrial Plan involve improving energy efficiency, decarbonizing industrial processes, and advancing clean energy technologies, including renewable energy sources, to mitigate carbon emissions from industrial operations. Several studies in the literature have examined these elements from multiple points of view, yielding novel solutions to advance the decarbonization of the industrial sector [3–5]. Although tackling direct emissions from production processes can be challenging and requires a level of technological advancement that is not always readily available, addressing indirect emissions from the electricity sector can be quicker to achieve. This can be achieved by integrating renewable energy sources, such as photovoltaic (PV) systems, which offer an easy and quick solution compared to other technologies [6]. In particular, industrial zones are typically filled with several buildings, whose rooftops can be ideally used to install PV systems without additional land use [7].

Despite the economic convenience arising from self-implemented energy systems, companies often face significant challenges such as space constraints, construction difficulties, or issues in collecting the funds for the initial costs. In these cases, renewable energy communities (RECs) offer an attractive alternative, allowing the adoption of a collective, comprehensive approach to address and overcome these obstacles. The concept of an REC is straightforward: prosumers (individuals or entities that both produce and consume energy) often generate surplus energy, particularly when utilizing non-dispatchable renewable energy sources such as PV systems or wind turbines. Traditionally, excess energy from prosumers is fed back into the distribution system, typically at low buyback prices. However, within the framework of an REC, this surplus energy takes on a new significance.

Instead of merely selling their excess energy back to the grid, prosumers within an REC can choose to share this surplus with other community members, which happen to be in need of additional energy due to higher consumption or lower production. The emergence of energy communities represents a shift in how energy is managed and valued, which supports an extended concept of local self-consumption and, in turn, helps in relieving the distribution system of the excessive burden due to load and generation unbalance. In Europe, RECs are economically supported by means of a different incentive mechanism in different countries: notably, the Italian system grants economic subsidies based on the concept of REC-shared energy [8], while other countries opt for indirect support through reduced taxes, reduced interest on loans, or economic compensation [9–12]. By promoting the exchange of locally produced renewable energy, these financial supports help to accelerate the adoption of sustainable energy practices, reducing the community's reliance on fossil fuels and lowering carbon emissions. Moreover, the collaborative nature of energy communities fosters social cohesion, as members work together to achieve common goals, such as energy independence and environmental management, as outlined by recent European directives [13,14].

A similar but distinct concept is represented by jointly acting renewable self-consumer groups, which are RECs including only users physically located in the same building who join to collectively produce, consume, and manage energy, typically through renewable sources installed on shared properties. In a residential setting, this could involve neighbours in an apartment complex pooling their resources to install a shared PV system to meet their individual household needs. Any surplus energy generated by the group can either be stored for later use, shared among members, or fed back into the grid. Concerning this last concept, several works have contributed to the current literature, analysing the operation, the investment, the profitability and the environmental impact of different solutions including the optimal sizing of a PV-BESS system [15] and the development of energy management systems (EMSs) in order to optimally manage energy flows [16] of PV-based systems for jointly acting renewable self-consumer groups. Furthermore, the effects of electric vehicle (EV) charging have been studied [17,18], with future possibilities to include Vehicle-to-Grid (V2G) systems [19,20] and flexibility services [21].

The potential benefits of RECs in general have also been examined in depth in the recent literature. In [22], an optimization model to aid energy experts and urban planners in REC capacity sizing and flow management under Italian regulations in introduced. Specifically, physical and virtual power-sharing models are compared in centralized and decentralized setups, possibly including storage devices. Findings show that virtual sharing in a centralized setup enhances economic benefits, reduces carbon emissions by up to 34%, and can support low-income families, lowering energy poverty. On the other side, while the current policies make virtual power sharing more profitable, it should be recognized that its benefits rely on economic incentives [23], which are currently granted only for a limited time. Especially in cases where the potential REC members are physically close, or where a group of jointly acting renewable self-consumers is considered, a physical power-sharing model [24], possibly realized by a DC system including multiport converters [25], exhibits several possible advantages, including improved power quality and reliability. Additionally, in [26], an optimization model to support REC investment decisions regarding renewable generation portfolios and electricity sharing is proposed. The model analyses costs, revenues, and sensitivity to solar and wind resources, highlighting key factors influencing optimal investment decisions and the benefits of RECs for renewable energy deployment. A hydrogen production system can also be employed to address the temporal mismatch between renewable energy generation and consumer usage within a residential REC, as shown in [27]. Furthermore, in [28], a hydrogen-based

Power-to-Power (PtP) system to improve the self-sufficiency of users in an REC has been discussed. The system involves two RECs: the first generates renewable energy and stores excess energy as hydrogen, while the second uses that hydrogen for power. Despite its low efficiency, the system significantly increases energy self-sufficiency, but remains economically unsustainable due to high costs. The study conducted by [29] investigates a biomass-based REC with an integrated thermal heating network, showcasing the economic viability of an REC centred on wood biomass and emphasizing the expansion potential of renewable technologies beyond PV systems. The study in [30] develops an optimal dispatch strategy utilizing Model Predictive Control (MPC), which considers different price dynamics and uncertainties, and is tested on a real REC pilot project in Austria. In addition, several papers studied the performance of RECs in ports and marinas to improve the level of decarbonization and sustainability [31,32].

Conversely, few studies have thoroughly examined RECs within industrial contexts. In [33], the benefits of establishing an REC in an industrial area are assessed. The findings indicate a significant increase in self-sufficiency and a notable reduction in $CO_2$ emissions and operating costs. Nonetheless, this analysis was conducted based on a European directive that was not fully adopted and on fixed incentives for REC-shared energy. As of 2024, these incentives have been permanently revised and are now variable depending on the current energy price, as discussed in [34]. Additionally, the study examines only a limited number of scenarios, considers just two companies, and does not account for any restrictions on the installation of renewable energy solutions. In addition, the impact of non-residential users in RECs is discussed in [35], focusing on the evaluation of technical performance under different scenarios, but without developing an algorithm for choosing users to be included in the REC and without evaluating the economic aspect. Another clustering method is studied in [36], where, however, once again the focus is on clustering based on purely technical aspects such as the energy characteristics of the users and is without any economic evaluation. In addition, neither of these two works proposes a valid algorithm for evaluating the appropriate oversizing of REC generation plants in order to maximize the economic return.

In general, from an economic and environmental perspective, it is always advisable to carefully select users (both residential and non-residential) to be included in an REC. An optimal grouping of users maximizes shared energy and is in line with the key objectives of European directives, which emphasize the importance of RECs in addressing environmental (the promotion of renewable energy production), economic (cost reduction), and social (the inclusion of users in economic or energy poverty) benefits. It is clear that grouping users with very similar load profiles is not always beneficial, as they are unlikely to share energy effectively. Instead, identifying users with complementary characteristics that maximize shared energy and thus achieving the above goals can significantly improve the efficiency and impact of the REC.

Generally speaking, the potential industries to be included in an REC can vary significantly in terms of constraints such as the available space for installing PV systems, their energy consumption profiles, and the nature of their economic activities. Specifically, in Italy, companies and industries are classified using specific codes called ATECO codes, which are short for "ATtività ECOnomiche" (Economic Activities). These codes are part of a standardized classification system managed by the Italian National Institute of Statistics (ISTAT) [37] and are used to categorize businesses based on their primary economic activities. The ATECO system aligns with the European NACE classification but includes additional levels of detail tailored to the Italian economy.

It is therefore valuable to explore how companies with diverse characteristics and specific energy consumption patterns can be grouped within an REC to reduce both economic and environmental costs while supporting the local economic fabric. Based on the aforementioned concepts, this study aims to identify the optimal clustering of companies within a specific geographical area to form an REC, and to determine the most suitable PV capacity to be installed at the REC establishment. This, in turn, requires us to identify the most suitable companies for membership, based on factors such as economic costs, pre-existent PV systems, the available area for additional PV capacity, and ATECO classification. On the basis of companies' ATECO codes, it is possible to estimate their energy consumption profiles and assess the best combinations to optimise the REC performance. In addition, the optimal additional PV capacity is evaluated, for each user, to improve energy self-consumption and sharing within the community.

To the best of the authors' knowledge, no previous research in the context of RECs has specifically explored clustering methods of industrial users based on the association of ATECO codes and load profiles, and evaluating both technical and economic aspects. Furthermore, the proposed algorithm provides the correct sizing of the PV plants of each user, for any combination of users included in an REC, to improve collective REC performance indexes (and not those of single users), which to the best of our knowledge is a further original contribution.

The paper is structured as follows: Section 2 delves into the specifics of the energy generation units, load profiles, and the economic parameters that influence the proposed analysis. Section 3 details the methodology behind the proposed algorithm for the optimal clustering of industrial users and sizing of PV systems within RECs. Section 4 provides an overview of the case study and describes the datasets of industrial companies used for the validation. Section 5 presents the findings and the analysis of the results obtained from the proposed method. Finally, Section 6 collects the conclusions, implications and future developments of the study.

## 2. Generation Units, Loads, Available Data and Economic Incentives

In this section, the general structure of the system considered for the potential establishment of an REC by the optimal selection and clustering of its members will be outlined. This includes a detailed description of the possible companies that may be part of the community, their connection to the distribution grid and the parameters and constraints of the PV systems used for energy production. The energy consumption profiles of the companies will be described according to the specific type of economic activity they perform, as defined by their industrial classification and their ATECO codes. In addition, this section will provide an overview of the costs associated with the purchase and sale of electricity to the grid, along with a discussion of the new incentive systems introduced by the latest regulations, which aim to promote the creation of new RECs. In addition, in this study, all power profiles are based on hourly sampling.

A general overview of the industrial users considered in this study is illustrated in Figure 2. Without a loss of generality, the analysis focuses on a set of $N$ industries characterized by different production activities. It is assumed that each of these industries is independently connected to the AC distribution network, while sharing the same primary substation, according to the European regulatory requirements for RECs.

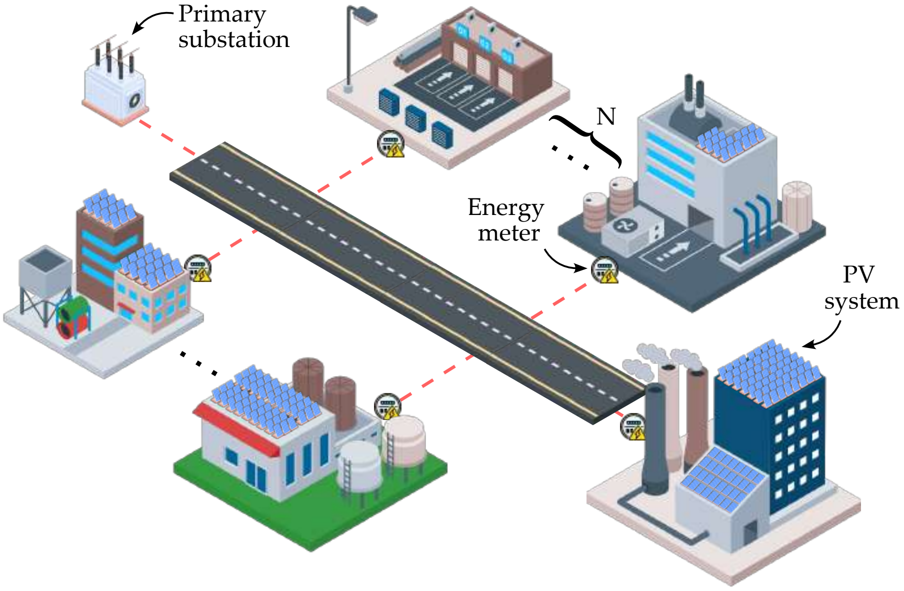


**Figure 2.** A general example of "N" industrial users connected to a public AC distribution system through the same primary substation (designed with resources from www.flaticon.com and www.freepik.com (accessed on 25 January 2025)).

### *2.1. PV System Description*

The primary objective of the PV system is to supply energy to the companies, with the aim of covering a significant part of their energy needs. This reduces their dependence on the electricity grid and minimises the absorption of energy from external sources whenever possible. One of the main objectives of this work is to determine the optimal size of the PV system for each member in order to maximise the economic benefits of the REC.

It is assumed that the PV system is designed using modules with a nominal power of 450 Wp and an efficiency of 22.2% [38]. As a result, the minimum capacity increase of the PV system is equivalent to the nominal power of a single module. Each company participating in the REC has a maximum area available for the installation of a PV system, and this available space is used as an input parameter for the optimisation process. Where companies already have PV systems, only the remaining usable area will be considered for the further expansion of PV capacity.

In order to model the energy production of these systems, hourly profiles of solar irradiance and ambient temperature were obtained from an online database [39]. These datasets were used to generate the annual PV energy production profile for each company, allowing an estimation of their potential energy production under varying environmental conditions [40]. This ensures that the design of the PV system is adapted to the specific company, maximising energy production within the limits of the available space. Also, it is assumed that all the PV systems are installed with optimal azimuth and tilt angles for the considered latitude.

### *2.2. ATECO-Based Load Profiles*

The energy consumption profile of each company in this study is defined based on its ATECO code. This provides a standardized classification for economic activities, enabling the assignment of typical energy consumption patterns associated with each sector.

To model these consumption profiles, a dataset of regression-based electricity load profiles, proposed in [41], was used. This publicly available database provides, for each ATECO code, yearly load profiles normalized with respect to the company's yearly consumptions.

In this paper, for each company, the corresponding load profile was selected on the basis of the company's ATECO classification, which provide insight into the variations in energy demand throughout the day, capturing both the typical operational behaviour of each company and the fluctuations driven by their industry-specific activities. The load profiles are also characterized by weekly and seasonal fluctuations in energy demand, reflecting the typical patterns of activity during weekdays and weekends. For instance, the profiles account for reduced activity or shutdowns during weekends and public holidays, as well as significant changes in energy consumption during periods of vacations.

Figure 3 presents these profiles for each ATECO (AT) code over a representative week of the year. The primary goal of this figure is to provide a general overview of the consumption patterns without focusing on specific numerical values. These profiles will be then adjusted and scaled to match each company's annual energy consumption.

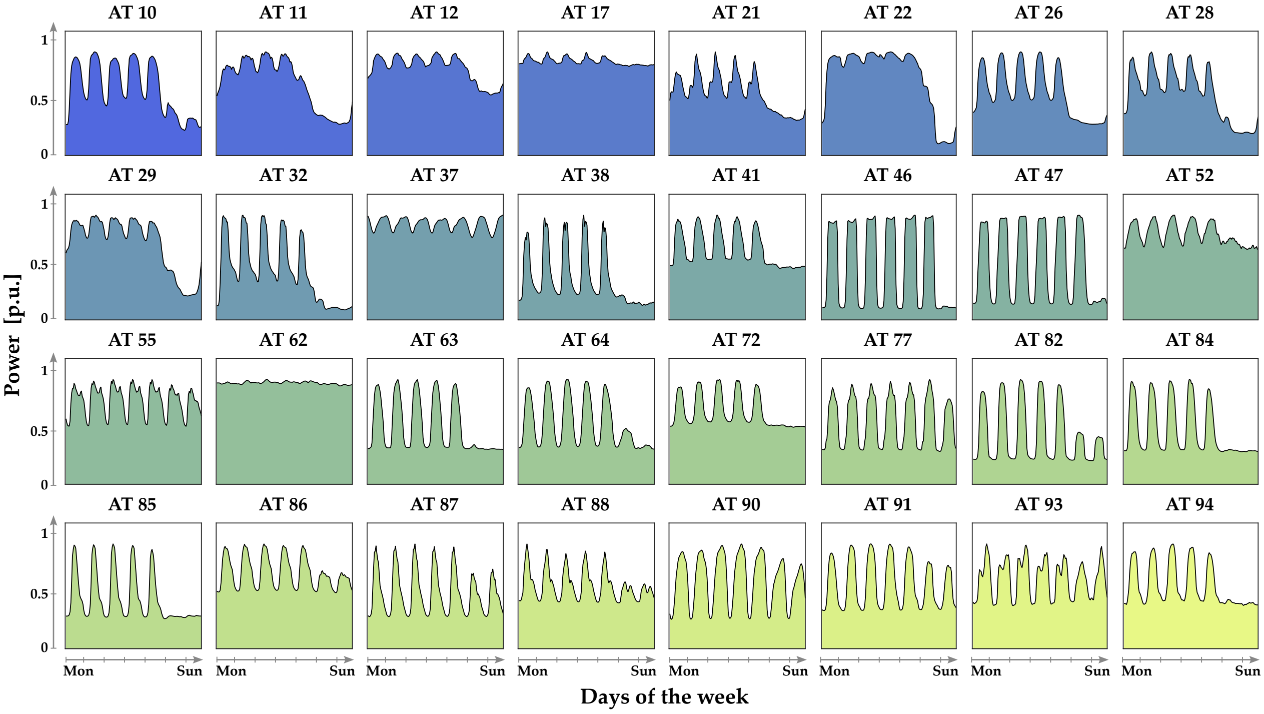


**Figure 3.** Load profiles representing the typical energy consumption patterns of different ATECO codes. Each subplot highlights the unique power profile in p.u. over one sample week associated with a specific economic activities.

As noted, some sectors like AT 10, 11, 26, 28, 29, 32 and 41 demonstrate regular rhythmic fluctuations throughout the week. These profiles exhibit high energy consumption during working hours, followed by sharp declines during the evenings and weekends. Such patterns are typical of industries like manufacturing or construction where operations are concentrated during standard work shifts, with machinery and production lines operating predominantly during weekdays. The clear peaks indicate that these industries follow a structured schedules with high energy demands during operational hours.

On the other hand, other sectors like AT 12, 17, 37, 52 and 62 show more flat and steady energy profiles with little variation across days, suggesting continuous operation. These profiles are characteristic of industries where energy consumption remains consistent due to 24/7 operational needs. Such industries often require stable power for running their facilities that operate around the clock, regardless of weekends or holidays.

Moreover, other sectors exhibit pronounced daily cycles, with sharp peaks and valleys in energy usage. These sectors may include processes that operate cyclically, with high energy use during active production periods and lower demand during the night. These activities range from waste management and trade to the provision of IT, administrative, educational, health, cultural and association services, and often exhibit such cyclic energy patterns, where consumptions are intermittently switched on and off based on demand or production schedules. These pattern can be seen in sectors like AT 38, 46, 47, 63, 77, 82, 84, 85, 87, 90, 91 and 94.

In contrast, sectors like AT 21, 32 and 93 show irregular energy consumption patterns with high variability within days, suggesting industries with less predictable energy demands. This could be reflective of creative industries, research and development, or specialized manufacturing, where energy needs vary based on specific projects, deadlines, or intermittent operations. These industries may not have regular schedules, and their energy consumption can fluctuate based on the requirements of specific tasks or projects.

The above-mentioned characteristics are significant in designing an energy management strategy for the REC and its economic evaluation, as they influence the overall energy consumption and the interaction with the PV generation.

### 2.3. Economic Parameters of the REC

The economic evaluation of RECs implies a comprehensive examination of all relevant costs, including those related to the implementation and operation of PV systems, the financial aspects of buying and selling electricity, and the incentives associated with participating in RECs. From an economic point of view, maximizing on-site energy consumption remains the most advantageous strategy for REC participants, as self-consumed energy is effectively "free" after the initial expenditure for the PV system, avoiding the need to purchase electricity at higher prices from the grid. However, the REC model also presents an interesting opportunity for economic benefit through energy sharing. If consumption and generation patterns within an REC are aligned in such a way that a significant portion of energy can be shared between members, the financial benefits of shared energy incentives can be substantial.

One of the key aspects of the economic modelling of RECs is the cost of energy transactions. The energy generated by PV plants and fed into the distribution grid is sold at a fixed price of 4.6 c€/kWh [42]. In contrast, the cost of electricity purchased by industrial users follows a more dynamic pricing model, based on a two-tier time-of-use tariff. During peak hours (8 a.m. to 7 p.m.), the tariff is higher, at 30.5 c€/kWh, to reflect the higher demand on the grid, while during off-peak hours (7 p.m. to 8 a.m.) a slightly lower tariff of 28.5 c€/kWh applies [42]. In addition to these variable costs, the industrial users must also take into account fixed costs related to network infrastructure, system operating expenses, as listed in Table 1, and the applicable value added tax (VAT), which is set at 22% for industrial consumers.

**Table 1.** Power and fix fees as a function of the contractual power range for the considered study [42].

| Power Range | Power Fees [€/(kW year)] | Fix Fees [€/year] |
|---|---|---|
| $P \leq 100\,\text{kW}$ | 31.79 | 436.88 |
| $100\,\text{kW} < P < 500\,\text{kW}$ | 28.55 | 393.20 |
| $P \geq 500\,\text{kW}$ | 25.04 | 379.90 |

In addition to direct energy costs, RECs benefit from specific incentives to promote the shared generation of renewable energy. One important mechanism is the financial incentive provided based on the amount of energy shared among community members. Shared energy is calculated as the hourly minimum between (a) the amount of energy generated by the REC's renewable sources and fed into the grid and (b) the amount of energy taken from the grid by the REC members. This system ensures that the incentive supports optimal energy sharing within the community, encouraging both energy producers and consumers to effectively balance their loads.

Remarkably, starting in 2024, the new regulatory changes introduce a revised incentive structure to further support RECs [8]. According to the new guidelines, the traditional fixed incentive (previously 110 €/MWh, with minor compensation for avoided grid losses) is replaced by a more variable incentive structure, known as the Premium Incentive Tariff ($TIP$). The $TIP$ is designed to better reflect market conditions and the specific characteristics of renewable energy production and it is calculated according to the following Equation (1):

$$TIP = \begin{cases} \min(80 + \max(0; 180 - P_z); 120) & \text{if } P \leqslant 200, \\ \min(70 + \max(0; 180 - P_z); 110) & \text{if } 200 < P \leqslant 600, \\ \min(60 + \max(0; 180 - P_z); 100) & \text{if } P \geqslant 600. \end{cases} \quad (1)$$

where $P$ [kW] represents the installed capacity of the renewable energy generator for each member and $P_z$ [€/MWh] indicates the zonal electricity price, reflecting the hourly price fluctuations. This tiered structure ensures that larger systems with a higher capacity have a gradual reduction in the financial incentive.

For PV plants, in particular, the $TIP$ is further adjusted according to geographical location, with plants in central Italy receiving an additional bonus of 4 €/MWh and those in northern Italy receiving a larger bonus of 10 €/MWh. This geographic differentiation recognizes regional disparities in solar irradiation and energy production capacity, incentivizing investments in areas where the energy yield might otherwise be less competitive.

The proposed algorithm for optimal sizing and clustering is based on the calculation of the Net Present Value ($NPV$), a metric that reflects the return on investment over its lifetime. This is calculated according to Equation (2), which depends on the variation of cash inflows and outflows calculated through Equations (3) and (4), respectively, as shown below:

$$NPV = -(OCS \cdot P_n) + \sum_{k=1}^{N_{PV}} ICF_k \cdot \frac{(1+g)^k \cdot (1+e)^k}{(1+i)^k} - \sum_{k=1}^{N_{PV}} OCF_k \cdot (1+g)^k \quad (2)$$

$$ICF_k = \left\{ E_0 \cdot P_n \cdot \left[ P_{uf} \cdot sc + FiT \cdot (1 - sc) \right] + R_{TIP} \right\} \cdot \left[ 1 - \frac{d_r \cdot (k-1)}{100} \right]. \quad (3)$$

$$OCF_k = OCS \cdot P_n \cdot FO\&MC \quad (4)$$

where $N_{PV}$ is the PV system's expected life, $OCS$ [€/kWp] is the overnight capital cost, $ICF_k$ [€] is the input cash flow in the k$^{th}$ year, $g$ [%] is the inflation rate, $e$ [%] is the energy inflation rate, $i$ [%] is the interest rate, $OCF_k$ [€] is the output cash flow in the k$^{th}$ year, $E_0$ [kWh/kWp] is the yield of the plant over the first year of operations, $R_{TIP}$ is the revenue due to incentives on shared energy [€], $d_r$ [%] is the PV module degradation rate, $P_{uf}$ [c€/kWh] is the electricity price, $FiT$ [c€/kWh] is the feed-in tariff for the energy sold to the grid, $sc$ [-] is the self-consumption, $FO\&MC$ are the fixed operation and maintenance costs [%] and $P_n$ [kWp] is the nominal power of the PV plant.

Moreover, the $PBT$ is calculated by the first year in which the cumulative cash flow ($ICF_k - OCF_k$) becomes positive and the initial cost is fully recovered.

A summary of all economic parameters used for the economic evaluation of the REC with its values is shown in Table 2.

**Table 2.** Parameters used for the economic evaluation of the REC.

| Parameter | Value | Parameter | Value |
|---|---|---|---|
| $N$ | 30 [years] | $d_r$ | 0.25% |
| $OCS$ | 1000 [€/kWp] | $g$ | 1.96% [43] |
| $E_0$ | 1311 [kWh/kWp] | $e$ | 2.16% [42] [1] |
| $FO\&MC$ | 2% | $i$ | 3.6% |
| $P_{uf}$ | 30.5–28.5 [c€/kWh] | $FiT$ | 4.6 [c€/kWh] |

[1] Average value from 2014 to 2024.

## 3. Proposed Algorithm for Optimal REC Member Clustering and PV Sizing

In this section, the proposed algorithm for optimal REC member clustering and PV sizing is described. In particular, each one of the following subsections addresses one step in the proposed algorithm, and includes a detailed description of the used data, equations, and any action required from the user. The proposed algorithm was developed using Matlab 2022a as the development environment and an overview of the complete procedure is presented in Figure 4.

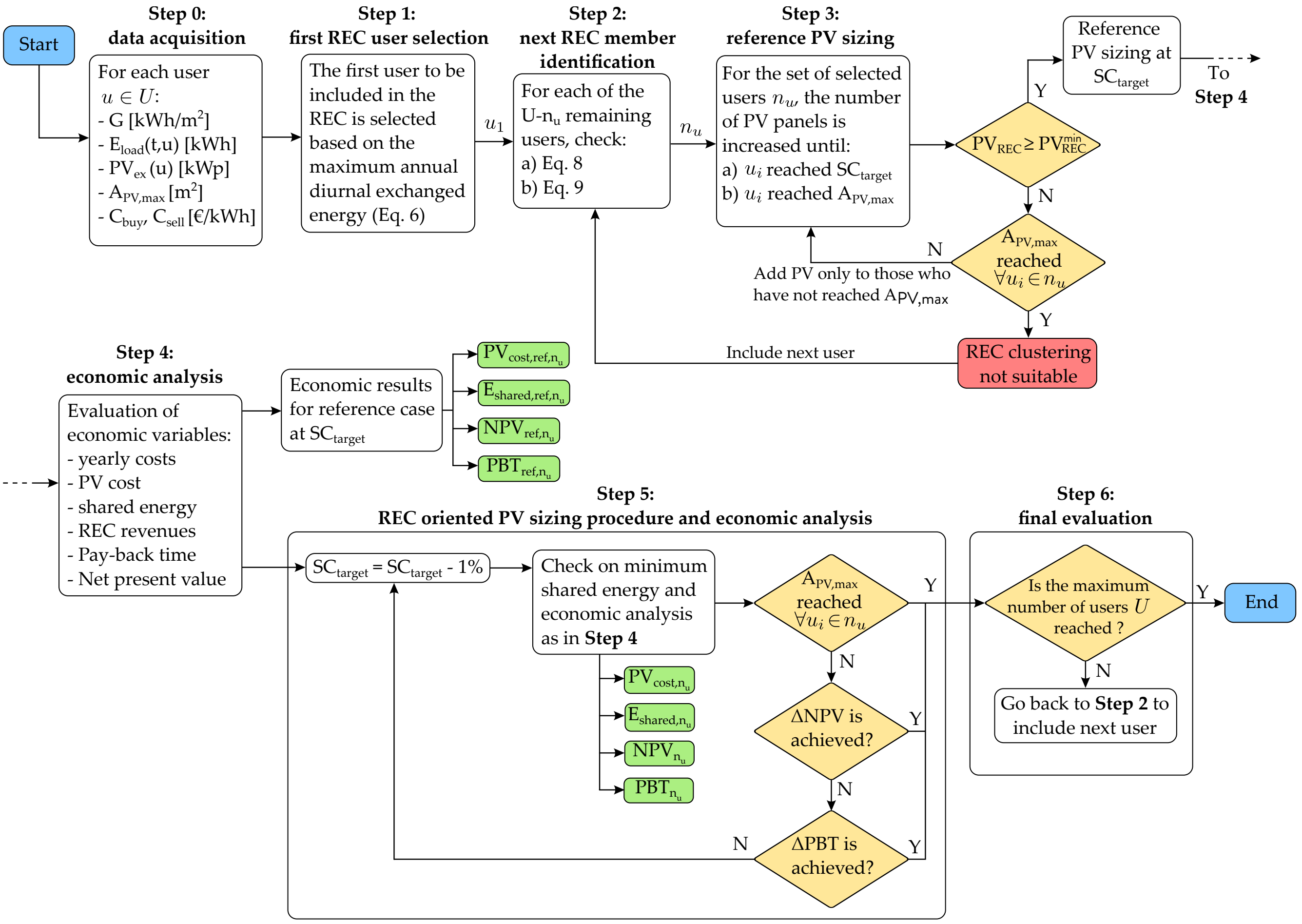


**Figure 4.** A flowchart of the complete procedure for the proposed optimal REC member clustering and PV sizing.

### 3.1. Step 0: Data Acquisition

During this preliminary step, the necessary data are acquired and loaded into the workspace. These include relevant data for each user $u \in U$ potentially interested in joining the REC, namely:

- The hourly irradiance profile of the year—$G(t,u)$ [kWh/m$^2$];
- The hourly ATECO-based consumption profile of the year—$E_{load}(t,u)$ [kWh];
- The capacity of pre-existing PV systems, if any—$PV_{ex}(u)$ [kWp];
- The available area for increasing each user's PV capacity, if any—$A_{PVmax}(u)$ [m$^2$];
- The hourly energy buying and selling price profiles—$C_{buy}(t,u)$ and $C_{sell}(t,u)$ [€/kWh].

On the basis of this information, the following quantities are evaluated:

- The hourly PV generation profile of a single PV panel over one year—$E_{PV}(t)$ [kWh] [40]
- The hourly PV generation profile of each user over one year—$E_{PV}(t,u)$ [kWh];
- The hourly energy exchange profile for each user $E_{POD}(t,u)$ [kWh], including pre-existing PVs, if any, and evalauted as:

$$E_{POD}(t,u) = E_{load}(t,u) - E_{PV}(t,u); \tag{5}$$

- The yearly energy cost for each user $C_E(u)$ [€], including the income from pre-existent PVs, if any.

### *3.2. Step 1: First REC User Selection*

In the Italian case, the only allowed model for REC energy exchange is the so-called virtual exchange model [22], where energy is physically exchanged through the DSO electrical grid. Under this condition, the criteria for the selection of possible REC users are based on the following considerations:

1. Traditional self-consumption provides the maximum economic benefit;
2. Shared energy, thanks to the current economic incentives, provides a significant economic income, but is not as relevant as self-consumption;
3. Sold energy provides minimal economic income.

As a consequence, the maximum economic performance is obtained by maximizing self-consumption and shared energy, which can be obtained only by selecting users with large diurnal consumptions.

The first user to be included in the REC is hence selected on the basis of their yearly diurnal energy consumption $E_{POD,dy}(u)$ [kWh], which is evaluated, for each user, as the sum of the energy consumed while solar irradiance is not null, namely:

$$E_{POD,dy}(u) = \sum_{t=1}^{N} [E_{POD}(t,u) \cdot X_{PV}(t,u)] \tag{6}$$

where:

$$X_{PV}(t,u) = \begin{cases} 1 \text{ if } E_{PV}(t,u) > 0 \\ 0 \text{ otherwise} \end{cases} \tag{7}$$

The potential REC members are then ordered on the basis of their yearly diurnal energy consumption $E_{POD,dy}(u)$, and the user exhibiting the maximum diurnal consumption is selected as the first potential REC member.

### *3.3. Step 2: Identification of the Next REC Member*

This step is used to identify the next member to be added to the REC and can be executed in two cases:

(a) When only the first REC member has been selected in Step 1, and the second REC member is to be identified;

(b) When a number of REC members have been selected, and the successive one is to be identified.

In both cases, during this step, the former REC member list is not modified. For the same reasons discussed in Step 1, the next REC member is selected in order to maximize the REC's yearly diurnal energy consumption $E^{CER}_{POD,dy}(u)$ [kWh]. Note that, in general, this cannot be carried out on the basis of the data from Step 1 due to the effect of pre-existing PV systems.

The maximum REC yearly diurnal energy consumption $E^{CER}_{POD,dy}(u)$ is hence evaluated considering each possible REC member not yet included in the REC, toghether with the current REC members, according to:

$$E^{CER}_{POD,dy} = \sum_{t=1}^{N} \left[ \left( \sum_{u=1}^{n_u} E_{pod}(t,u) \right) \cdot X_{PV}(t,u) \right] \tag{8}$$

where $n_u$ is the number of considered users. Additionally, for each potential REC composition, it is necessary to evaluate the minimum PV capacity considering that, in order to constitute an REC in Italy, the pre-existent generation capacity cannot be more than 30% of the overall REC generation capacity, so that:

$$\sum_{u=1}^{n_u} PV_{ex}(u) \leqslant 0.30 \cdot PV_{REC} \rightarrow PV^{min}_{REC} = \frac{10}{3} \cdot \sum_{u=1}^{n_u} PV_{ex}(u) \tag{9}$$

must hold. The resulting minimum PV capacity must be recorded and included in the CER PV constraints later on.

The combination of previous REC members and a new potential REC member exhibiting the highest yearly diurnal energy consumption is hence identified, and the successive REC member and the corresponding minimum PV installation constraint are selected accordingly.

### 3.4. Step 3: Reference PV Sizing

The aim of this step is the definition of a reference PV sizing for each REC member, which should:

- Be consistent with common PV installation practices;
- Serve as a reference for the evaluation of the economic benefits of establishing an REC, with respect to having each user install a PV capacity tailored to their own needs, without considering a possible REC.

To this end, it is necessary to set a target self-consumption $SC_{target}$, which is typically between 70% and 80%. Each user PV capacity is then evaluated by incrementally increasing the number of installed PV panels and evaluating the resulting self-consumption $SC(u)$, until at least one of the following conditions is reached:

1. The user's self-consumption becomes equal to or smaller than the target self-consumption, namely $SC(u) \leqslant SC_{target}$;
2. The number of PV panels installed reaches the maximum available area, namely $A_{PV}(u) \geqslant A_{PVmax}(u)$.

Once each user's PV installations is compliant with at least one of the aforementioned conditions, if the REC PV capacity is greater than the minimum value obtained from (9), the reference PV sizing at $SC_{target}$ is obtained. If not, it is necessary to increase each user's capacity until the minimum REC PV capacity constraint is reached. If all users reach their maximum PV capacity constraint, but the REC does not reach its minimum PV capacity constraint, then the combination of users under consideration is not suitable for establishing an REC and the next best combination of users identified in Step 2 should be considered.

### 3.5. Step 4: Economic Analysis

Based on the PV system sizing determined in Step 3, the main quantities of interest are recorded for each combination $n_u$, namely:

- $PV_{cost,ref,n_u}$
- $E_{shared,ref,n_u}$
- $NPV_{ref,n_u}$
- $PBT_{ref,n_u}$

where $PV_{cost,ref,n_u}$ is the reference PV system cost, $E_{shared,ref,n_u}$ is the amount of energy shared within the REC, $NPV_{ref,n_u}$ is the reference Net Present Value and $PBT_{ref,n_u}$ is the reference Payback Time.

Specifically, $NPV$, is calculated using the Equation (2) taking into account the discounted cash flows over the period of operation of the system. Equation (3) describes the components of the cash inflow generated during the life of the system, including energy cost savings and REC revenue contributions, while Equation (4) captures the cash outflows mainly due to plants maintenance.

### 3.6. Step 5: REC-Oriented PV Sizing Procedure and Economic Analysis

The optimal sizing of an REC is obtained by increasing the PV capacity of REC members in order to increase the REC-shared energy, thereby pursuing the ideal REC aim of promoting local self-consumption and obtaining an economic revenue due to current incentives on shared energy. However, this increase in PV capacity leads to an increase in both $NPV$ and $PBT$; as a consequence, it is necessary to identify a trade-off between these two economic indicators. To this aim, a maximum allowed increase in $PBT$ and a minimum required increase in $NPV$ are defined in Equations (10) and (11), respectively, as:

$$\Delta_{PBTmax} = PBT_{n_u} - PBT_{ref} \tag{10}$$

$$\Delta_{NPVmin} = NPV_{n_u} - NPV_{ref} \tag{11}$$

These quantities are to be considered design parameters that are preliminarilyy agreed upon by potential REC members (i.e., users are assumed to accept an increased initial cost and longer $PBT$ if a certain $NPV$ increase is obtained).

The additional PV capacity is homogeneously shared among REC members, thereby keeping each member's self-consumption equal as long as possible. This is obtained, for each REC member who has not reached the maximum PV capacity, by slightly reducing (i.e., few percent points) their reference self-consumption and re-evaluating each member's PV capacity and economic performance indexes by means of the same algorithms used in Steps 3 and 4. This process is repeated iteratively until one of the following conditions is reached:

(a) All users reach their maximum PV capacity;
(b) The target $NPV$ increase is reached;
(c) The maximum allowed $PBT$ is reached.

If condition (b) is reached, the desired REC PV capacity is obtained. If condition (a) or (c) are reached, the obtained solution is limited by problem constraints and cannot be improved unless the constraint on the maximum acceptable $PBT$ increase is relaxed.

### 3.7. Step 6: Final Evaluation

If there are other possible users to be included in the REC, the next user to be included in the REC is selected according the procedure in Step 2, and Steps 3 to 5 are repeated until all the possible REC members have been considered. Once all possible REC members have been considered, the main quantities of interest are recorded for each combination $n_u$, namely:

- $PV_{cost,n_u}$
- $E_{shared,n_u}$
- $NPV_{n_u}$
- $PBT_{n_u}$

which are defined for each combination $n_u$.

## 4. Case Study and Company Dataset Description

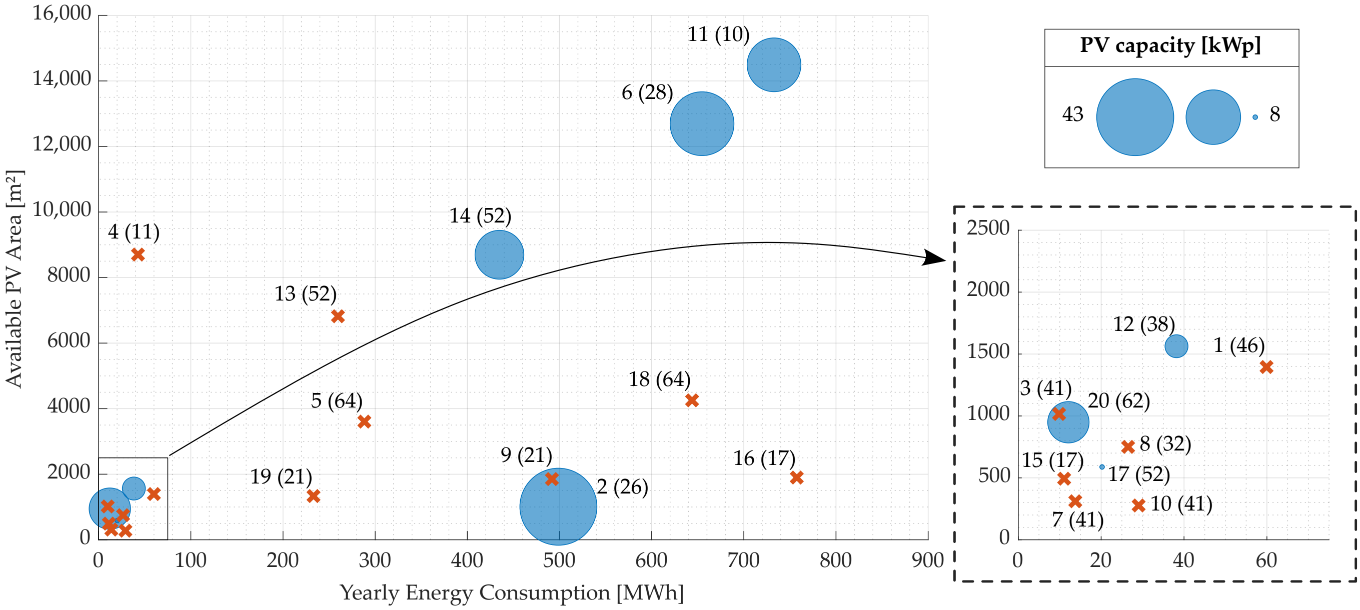
As shown in the previous section, the algorithm requires a set of input data to identify the optimal combination of companies to be included in the REC. In this section, we will provide a detailed description of the characteristics of the companies examined to validate the algorithm's operation and analyze the final results. In particular, we will examine two different datasets with different characteristics, both including 20 economic activities of different natures (i.e., different ATECO codes) located in the industrial area of Trieste, Italy. In order to collect all data, a survey was conducted in 2023, which included the ATECO code, the yearly energy consumption, the capacity of existing PV plants and the area available for potential new PV installations.

Both Figure 5a,b map the companies included in the related dataset with their yearly energy consumption and available PV area. Each of them is marked with a blue bubble, where its size represents the existing PV capacity [kWp], if any, or a red cross, where there is no existing PV capacity. In addition, each company is described by its ID and ATECO code within the brackets—e.g., 14(52) denotes company number 14 with ATECO code 52.

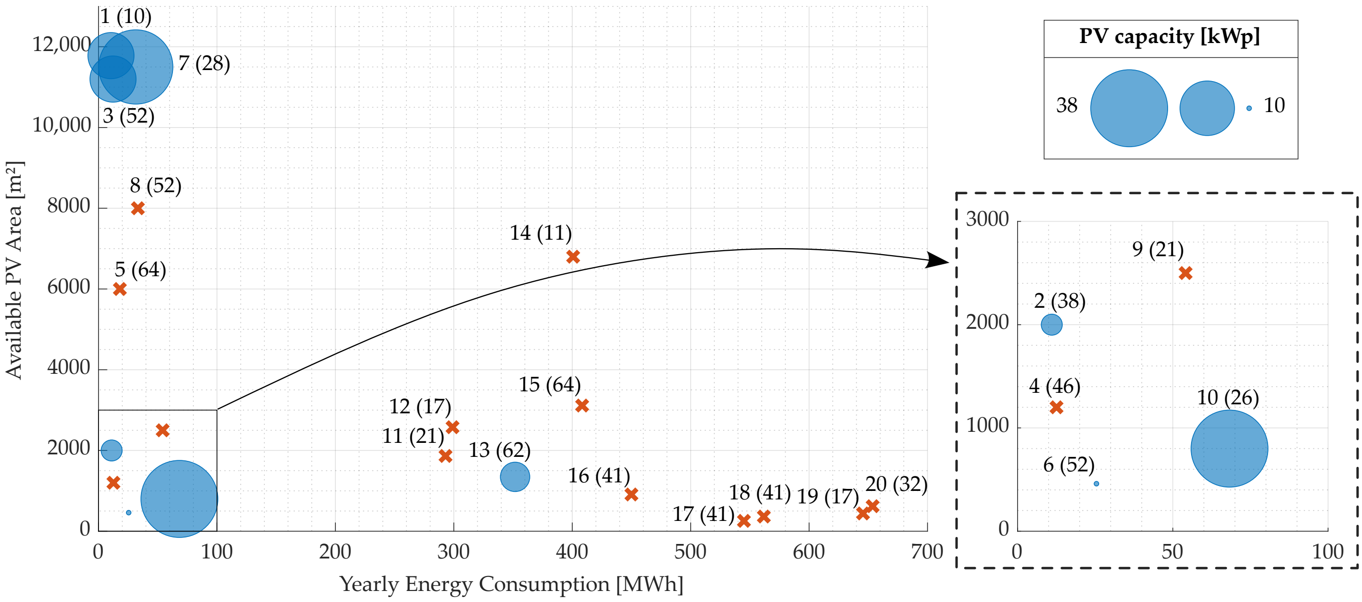
In Figure 5a, related to dataset A, the companies show a wide range of yearly energy consumption, spanning two orders of magnitude. The dataset includes users ranging from small companies consuming 9.84 MWh per year to large energy consumers, with the highest consumption reaching over 757.4 MWh per year. Most of the companies in the dataset have no installed PV capacity at all, with the exception of a few companies with relatively modest PV systems. The area available for future PV systems also varies widely, with companies reporting areas from as small as 277 $m^2$ up to as large as 14,491 $m^2$. As expected, a clear correlation between higher energy consumption and available PV area is recognized. However, some significant exceptions suggest that energy needs and space do not always correlate directly.

Considering the now-installed PV capacity, the larger blue bubbles indicate existing PV plants reaching up to 43 kWp, while smaller bubbles represent lower-capacity installations with a minimum of 8 kWp. Red crosses denote companies without PV installations, highlighting opportunities for future PV deployment based on the corresponding company available area. The inset zoomed-in view in the lower right corner provides further insight into companies with low amounts of energy consumption (below 60 MWh) and limited amounts of available PV area (under 2000 $m^2$). As shown, the majority of the companies in these ranges have not invested in PV installations and only three of them have existing PV systems.

Conversely, Figure 5b shows the same information extracted from dataset B. Also in this case, a wide range of available PV areas is noticeable, with values spanning from smaller areas around 256 $m^2$ to much larger ones reaching up to 11,700 $m^2$. Regarding yearly energy consumption, values also vary significantly, ranging from as low as 10.47 MWh to a peak of 653.6 MWh. This difference in energy consumption showcases the different energy needs of the companies represented, reflecting a wide range of operational scales and energy needs within the dataset. In addition, most companies do not have any PV capacity despite the high annual energy demand. In these cases, it is worth observing that most companies do not have high PV installation potential due to the limited amount of available PV area. Existing PV systems, on the other hand, range from a minimum of 10 kWp to a maximum of 38 kWp, which is not much different from dataset A. To enhance the visibility of the companies with low amounts ofenergy consumption and smaller available areas, a zoomed-in section appears in the lower right corner. This inset focuses on companies with energy consumption levels below 100 MWh and PV areas under 3000 m$^2$.



(**a**) Dataset A



(**b**) Dataset B

**Figure 5.** Scatter plots illustrating the relationship between available PV area [m$^2$] and yearly energy consumption [MWh] for companies in dataset A (**a**) and B (**b**). Blue bubbles represent companies with PV installations, where bubble size corresponds to PV capacity [kWp], while red crosses denote companies without PV installations. An zoomed-in view shows companies with lower amounts of energy consumption and PV areas, providing a detailed view of companies with smaller operational sizes.

A key observation is related to the distribution pattern of energy consumption relative to available area, which does not show the direct correlation recognized in dataset A. Indeed, some companies with significant PV areas have relatively low energy requirements, suggesting that while they have the capacity to support large PV systems, their actual energy needs may not require high amounts of PV capacity or they have not invested in PV installation at all in the past. In contrast, companies with moderate amounts of available areas show a high range of energy demands but unfortunately are limited in their ability to install PV systems.

The analysis of the collected data makes it possible to assess the potential of each company within the energy community and to identify the best opportunities for mutual collaboration between the various entities involved, maximising the economic benefits for the entire community.

## 5. Results

The clustering algorithm proposed in Section 3 has been applied, separately, for datasets A and B presented in Section 4. For each dataset, two families of REC designs have been developed by running the proposed algorithm with different target results.

First, a modest minimum required increase in $NPV$ (e.g., $\Delta_{NPVmin}$ = 25%) and minimal allowed increase in $PBT$ (e.g., $\Delta_{PBTmax}$ = 0–1 years) have been considered. This allows for the identification of the configurations providing the desired increase in $NPV$ with minimal additional $PBT$ (e.g., the iterative procedure occurring during Step 5 of the proposed algorithm is interrupted by reaching the target $NPV$ increase, and not other constraints).

Second, a much larger minimum required increase in $NPV$ (e.g., $\Delta_{NPVmin}$ = 100%) and a modest allowed increase in $PBT$ (e.g., $\Delta_{PBTmax}$ = 0–5 years) have been considered. This allows for the identification of the configurations providing the maximum increase in $NPV$ which can be achieved by the maximum allowed $PBT$ and the available surface constraints (e.g., the iterative procedure occurring during Step 5 of the proposed algorithm is interrupted by reaching the maximum $PBT$ constraint, the maximum available surface constraint, or a combination of both, but not by the increase in the target $NPV$).

The results obtained from the processing of datasets A and B are reported, separately, in the following subsections.

### *5.1. Dataset A*

First, let us consider, as a reference, the results in terms of $NPV$, $PBT$, shared energy and PV cost obtained by installing PV systems in a community of users selected from dataset A. This is obtained during Step 3 and 4 of the proposed algorithm, where, in this case, the target self-consumption $SC_{target}$ has been set equal to 80% for all users.

Figure 6 shows economic and energetic aggregated performance indexes, evaluated for the different combinations of users provided by the proposed clustering algorithm. In particular, Figure 6a reports the trend of the community $NPV$ [M€] as a function of the number of members, simply evaluated as the sum of each user’s $NPV$, the REC’s $NPV$ [M€] as a function of the number of members, evaluated as the sum or each user’s $NPV$, including the economic incentive on shared energy obtained by the REC. Additionally, Figure 6a reports the percentage variation in the $NPV$ obtained due the economic incentive on shared energy (i.e., the percentage variation between the two curves in Figure 6a). Analogously, Figure 6b reports the community-aggregated $PBT$ [years] as a function of the number of members, the REC-aggregated $PBT$ [years], evaluated including the economic incentive on shared energy, as a function of the number of members, and the $PBT$ variation due to the economic incentive on shared energy (i.e., the percentage variation between the two curves in Figure 6b). Lastly, Figure 6c reports the shared energy $E_{shared}$ [MWh] as a function of the number of members, while Figure 6d reports the aggregated PV cost [M€] as a function of the number of members.

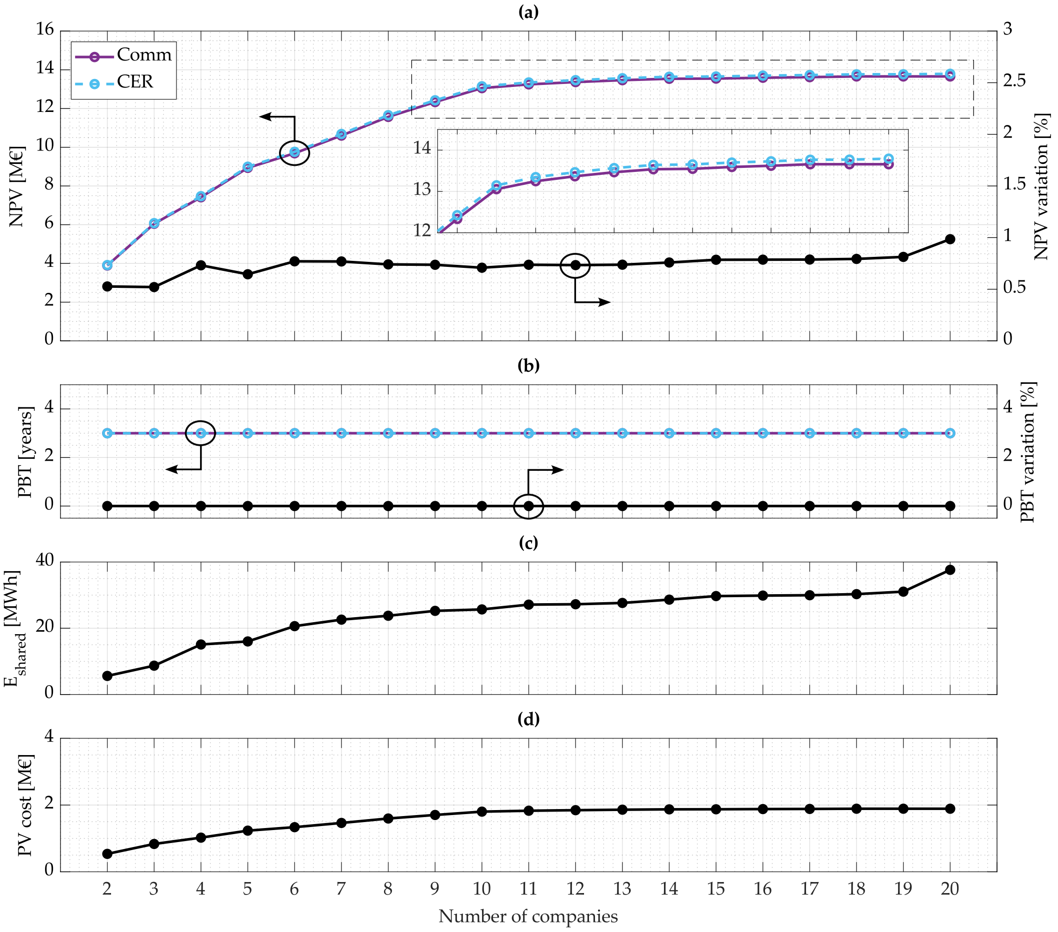


**Figure 6.** Results for dataset A in the reference case for different numbers of members, when self-consumption is equal to 80% for each member: (**a**) $NPV$ values [M€] at the community level and for the REC, and their $NPV$ variation [%] (black line), (**b**) $PBT$ values [years] at the community level and for the REC, and their $PBT$ variation [%] (black line), (**c**) shared energy [MWh], and (**d**) cumulative PV cost [M€].

Considering Figure 6a, it can be observed that both $NPV$ curves are monotonously increasing as the number of members of the community increases, yet the increase in $NPV$ resulting from the addition of a new member to the community significantly decreases for more than ten members. Additionally, it is possible to appreciate that the increase in $NPV$ related to the establishment of an REC (i.e., due to the economic incentive on shared energy) is minimal, around 0.6% for most cases and, generally, on the order of one percent. The $PBT$ obtained with 80% target self-consumption is equal to three years, both considering the simple aggregation of users and the establishment of an REC, as depicted in Figure 6b. Now, considering Figure 6c,d, it can be observed that both shared energy and PV cost are monotonously increasing as the number of members of the community increases. Additionally, it is worth noting that the amount of shared energy is limited to a few tens of MWh over a year, which, considering that dataset A includes users with yearly energy consumptions up to several hundreds of MWh, justifies the marginal economic impact of the establishment of an REC. This is a result of the specific shapes of the load profiles of the users included in dataset A, which leaves little space for shared energy when PV systems are traditionally designed to obtain high self-consumption levels in the pursuit of shorter $PBT$ values.

Overall, it can be stated that, considering the addition of PV systems to the users included in dataset A with a target self-consumption equal to 80%, the investment provides significant economic performances (i.e., a 30-year $NPV$ that is roughly seven times larger than the initial investment, and a 3-year $PBT$), which is only marginally increased if an REC is established. This makes the establishment of an REC marginally attractive from a strictly economical perspective, but not so much to discourage its establishment for other, typically social, purposes.

It is now worth analysing the possible economic benefits which can be obtained by the establishment of an REC with a purposefully designed PV capacity. This is performed during Step 5 of the proposed clustering algorithm, which provides the PV capacity satisfying the minimum $NPV$ increase, the maximum $PBT$ and the maximum available area constraints, as well as the corresponding energetic and economic performance indexes. As mentioned, a modest minimum required increase in $NPV$ (e.g., $\Delta_{NPVmin}$ = 25%) and a minimal allowed increase in $PBT$ (e.g., $\Delta_{PBTmax}$ = 0–1 years) have been considered first, in order to identify the configurations providing the desired increase in $NPV$ with minimal additional $PBT$. The resulting $NPV$, $PBT$, shared energy and PV cost are reported in Figure 7. Specifically, Figure 7a reports the trend in the REC $NPV$, as a function of the number of members, for different combinations of target $NPV$ increases and maximum $PBT$ increases. Additionally, Figure 7a shows the percentage variation of the $NPV$ between the current case with an increased PV capacity and the reference case obtained with 80% target self-consumption, shown in Figure 6a. Analogously, Figure 7b reports the REC $PBT$, as a function of the number of members, for different combinations of target $NPV$ increases and maximum $PBT$ increases, and the $PBT$ variation between the current case with an increased PV capacity and the reference case obtained with 80% target self-consumption, shown in Figure 6b. Lastly, Figures 7c and 7d report, respectively, the shared energy $E_{shared}$ and aggregated PV cost, as functions of the number of members, for different combinations of target $NPV$ increases and maximum $PBT$ increases, as well as the shared energy and PV cost from the reference case.

Considering Figure 7a,b, it can be observed that $NPV$ curves are practically superimposed and monotonously increasing as the number of members of the community increases. The increase in $NPV$ resulting from the addition of a new member to the community still decreases significantly for more than ten members, yet it is possible to appreciate that, when no increase in $PBT$ is allowed, the increase in $NPV$ with respect to the reference case is slightly larger than 25% for any number of members except $n_u$ = 3. The $PBT$ is equal to three years when no increase in $PBT$ is allowed, and reaches four years only for the case of $n_u$ = 3. This increase in the allowed $PBT$ allows for reaching the desired 25% increase in $NPV$ for the case of $n_u$ = 3 members, too.

Now, considering Figure 7c,d, it can be observed that both shared energy and PV cost are monotonously increasing as the number of members of the community increases, and they exhibit marginal variations for the different cases under consideration, consistent with the $NPV$ trends in Figure 7a. Additionally, it is worth noting that the amount of shared energy, still of the order of a few tens of MWh, is reduced when the PV capacity is purposefully designed for an REC. This is not bad per se, as the REC $NPV$ is significantly higher than in the reference case, yet it highlights that, when the specific load profiles included in dataset A are considered, the increase in $NPV$ is due to an increase in self-consumed energy and sold energy, and not shared energy. As a consequence, from a strictly economical perspective, the establishment of an REC is not particularly appealing.

Overall, it can be stated that, considering the addition of PV systems to the users included in dataset A with a 25% target increase in $NPV$ and a minimal allowed increase in $PBT$, the investment provides significant economic performances (i.e., a 30-year $NPV$

that is roughly six times larger than the initial investment, and a 3-year $PBT$). However, in this case, the establishment of an REC is not responsible for a significant portion of the obtained $NPV$, which makes the REC appealing only for sustainability and social purposes, as the increased PV capacity results in a significant increase in $NPV$, with almost no impact on $PBT$.

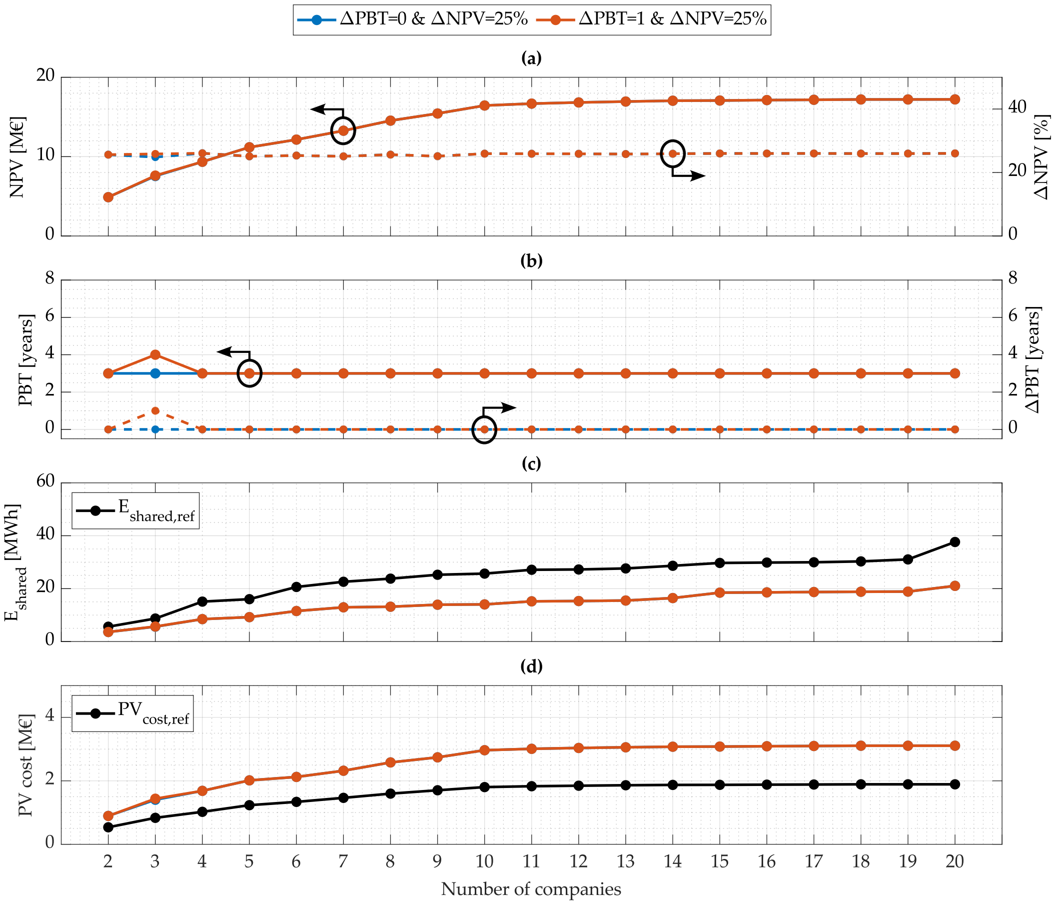


**Figure 7.** Results for dataset A when PV capacity is optimized, $\Delta NPV$ is equal to 25% with $\Delta PBT = 0$ and $\Delta PBT = 1$: (**a**) $NPV$ values [M€] (solid lines) for the REC and their $\Delta NPV$ variation [%] (dashed lines), (**b**) $PBT$ values [years] (solid lines) for the REC and their $\Delta PBT$ variation [%] (dashed lines), (**c**) shared energy [MWh] for the REC and shared energy [MWh] in the reference case, and (**d**) cumulative PV cost [M€] for the REC and the PV cost [M€] in the reference case.

Let us now examine the possible economic benefits which can be obtained by the establishment of an REC with a purposeful PV capacity design when a much larger minimum required increase in $NPV$ (e.g., $\Delta_{NPVmin}$ = 100%) and modest allowed increase in $PBT$ (e.g., $\Delta_{PBTmax}$ = 0–5) are considered. This allows for the identification of the configurations providing the maximum increase in $NPV$ which can be achieved by the maximum allowed $PBT$ and available surface constraints. The resulting $NPV$, $PBT$, shared energy and PV cost are reported in Figure 8. Specifically, Figure 8a reports the trend in the REC $NPV$, as a function of the number of members, for different combinations of target $NPV$ increases and maximum $PBT$ increases. Additionally, Figure 8a shows the percentage variation in $NPV$ between the current case with increased PV capacity and the reference case obtained with 80% target self-consumption, shown in Figure 6a. Analogously, Figure 8b reports the REC $PBT$, as a function of the number of members, for different combinations of target $NPV$ increases and maximum $PBT$ increases, and the $PBT$ variation between the current case with increased PV capacity and the reference case obtained with 80% target self-consumption, shown in Figure 6b. Lastly, Figures 8c and 8d report, respectively, the shared energy $E_{shared}$

and aggregated PV cost, as functions of the number of members, for different combinations of target $NPV$ increases and maximum $PBT$ increases, as well as the shared energy and PV cost from the reference case.

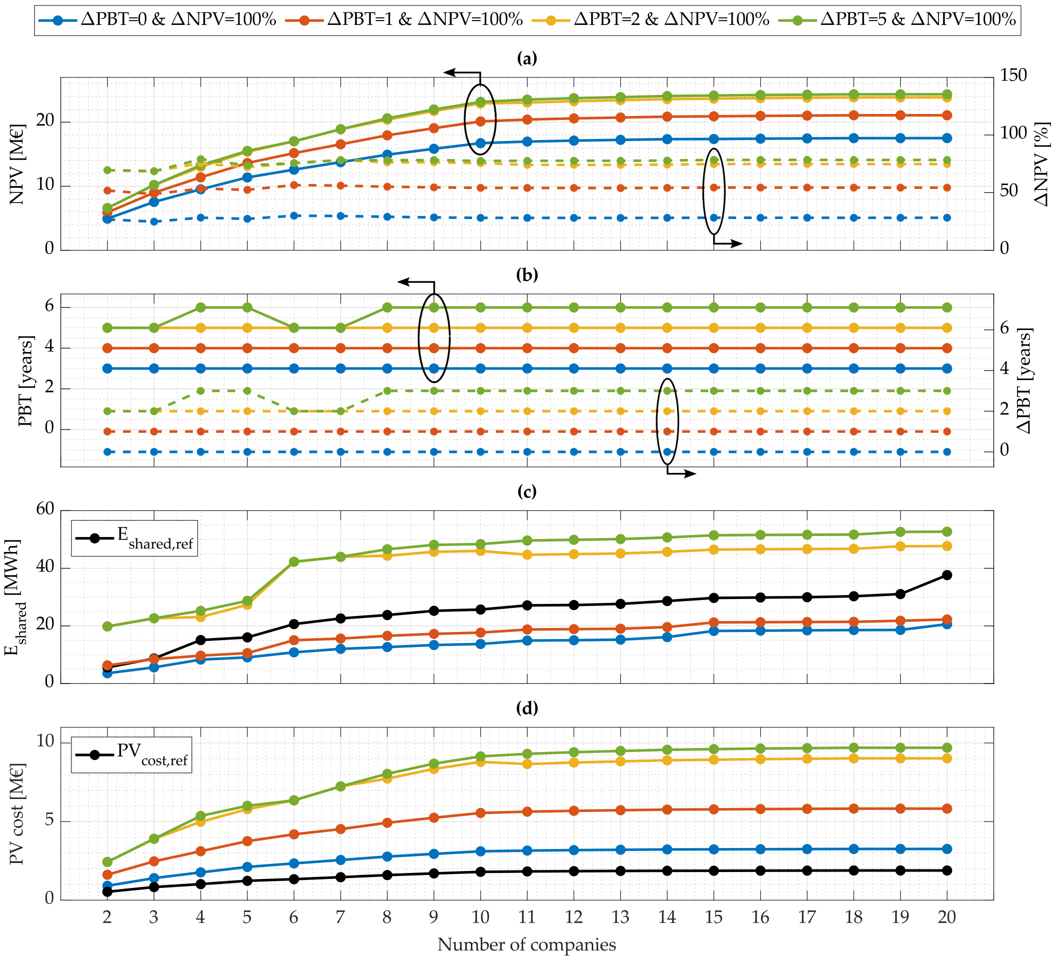


**Figure 8.** Results for dataset A when PV capacity is optimized, $\Delta NPV$ is equal to 100% with $\Delta PBT$ = 0, $\Delta PBT$ = 1, $\Delta PBT$ = 2 and $\Delta PBT$ = 5: (**a**) $NPV$ values [M€] (solid lines) for REC and their $\Delta NPV$ variation [%] (dashed lines), (**b**) $PBT$ values [years] (solid lines) for REC and their $\Delta PBT$ variation [%] (dashed lines), (**c**) shared energy [MWh] for REC and shared energy [MWh] in the reference case, and (**d**) cumulative PV cost [M€] for REC and PV cost [M€] in the reference case.

Considering Figure 8a,b, it can be observed that all $NPV$ curves are monotonously increasing as the number of members of the community increases and exhibit a similar overall trend, with $NPV$ generally being higher as the allowed $PBT$ increases. In none of the considered cases did the $NPV$ increase reach its target value, suggesting that the PV capacity is limited by the allowed $PBT$, the available area, or a combination of both, and/or the specific load profiles included in dataset A do not allow for increasing shared energy significantly, regardless of the considered PV capacity. The increase in $NPV$ resulting from the addition of a new member to the community still decreases significantly for more than ten members, and it is possible to appreciate that, when the maximum acceptable $PBT$ increase is set to 5 years, the effective $PBT$ increase which is obtained reaches only three years, suggesting that in this case the PV capacity is not limited by the constraint on the maximum $PBT$.

The $PBT$ is equal to three years when no increase in $PBT$ is allowed, and it reaches six years only when the maximum allowed $PBT$ increase is set to five years. Interestingly, the $PBT$ is constant with respect to the number of REC members for the cases when

$\Delta_{PBT} = 0$, $\Delta_{PBT} = 1$ and $\Delta_{PBT} = 2$. However, when $\Delta_{PBT} = 5$, the $PBT$ is reduced to five years for an $n_u$ equal to 2, 3, 6 and 7.

Now, considering Figure 8c,d, it can be observed that both shared energy and PV cost are monotonously increasing as the number of members of the community increases, except for the case of $\Delta_{NPVmin}$ = 100% and $\Delta_{PBTmax}$ = 2, where shared energy is slightly reduced when the number of REC members is increased from three to four, and from ten to eleven. This exception can be ascribed to the relative shapes of the load profiles of the users added as fourth and eleventh, which does not allow us to increase the shared energy over the previous REC configuration without increasing the $PBT$ by one more year. The aforementioned interpretation is easily verified by comparing the shared energy curve obtained with $\Delta_{NPVmin}$ = 100% and $\Delta_{PBTmax}$ = 2 with the shared energy curve obtained with $\Delta_{NPVmin}$ = 100% and $\Delta_{PBTmax}$ = 5, and recognizing that the latter is monotonously increasing as the number of REC members increases.

Overall, it can be stated that, considering the addition of PV systems to the users included in dataset A with the aim of maximizing the $NPV$ while allowing only a modest increase in $PBT$, the investment provides significant economic performances, with the $NPV$ ranging from roughly six times the initial investment in the case of $\Delta_{PBTmax}$ = 0, to roughly two times the initial investment in the case of $\Delta_{PBTmax}$ = 5, corresponding to an increase in $NPV$ from roughly 25% in the case of $\Delta_{PBTmax}$ = 0, to roughly 75% in the case of $\Delta_{PBTmax}$ = 5. The impact of the establishment of an REC is also significant in this case, as the shared energy increases significantly when an increase in $PBT$ of two to three years is allowed. As a consequence, in this case, the establishment of an REC is appealing not only for sustainability and social purposes, but also for economic ones, as a significant increase in $NPV$ is obtained, with a smaller impact on $PBT$.

Now, considering the selection of the best combinations of users to be included in the REC, from the present discussion, it appears that the establishment of an REC within the users included in dataset A provides significant economic advantages only if a $PBT$ increase of two to three years is allowed. Additionally, considering the trend of shared energy reported in Figure 8c, it can be observed that the maximum increase in shared energy with respect to the reference case is obtained for a number of REC members larger than six and smaller than nine. Further members can, however, be added with no economic penalty.

### *5.2. Dataset B*

Let us now consider, as a reference, the results in terms of $NPV$, $PBT$, shared energy and PV cost obtained by installing PV systems in a community of users selected from dataset B when the target self-consumption $SC_{target}$ has been set as equal to 80% for all users.

Figure 9 shows economic and energetic aggregated performance indexes, evaluated for the different combinations of users provided by the proposed clustering algorithm. In particular, Figure 9a reports the trend of the community $NPV$, the REC $NPV$ and the percentage variation in $NPV$ obtained due the economic incentive on shared energy, as a function of the number of members. Analogously, Figure 9b reports the community-aggregated $PBT$ as a function of the number of members, the REC-aggregated $PBT$ as a function of the number of members, and the $PBT$ variation due to the economic incentive on shared energy. Lastly, Figure 9c reports the shared energy $E_{shared}$ as a function of the number of members, while Figure 9d reports the aggregated PV cost as a function of the number of members.

Considering Figure 9a, it can be observed that both $NPV$ curves are monotonously increasing as the number of members of the community increases, yet the increase in $NPV$ resulting from the addition of a new member to the community significantly decreases for more than ten members. However, it is possible to appreciate that the increase in $NPV$

related to the establishment of an REC is, on average, modest, in the order of 5 %. Additionally, the $NPV$ variation rises when a further member is added up to seven members, remains constant between seven and fifteen members, and rises again significantly for more than fifteen members.

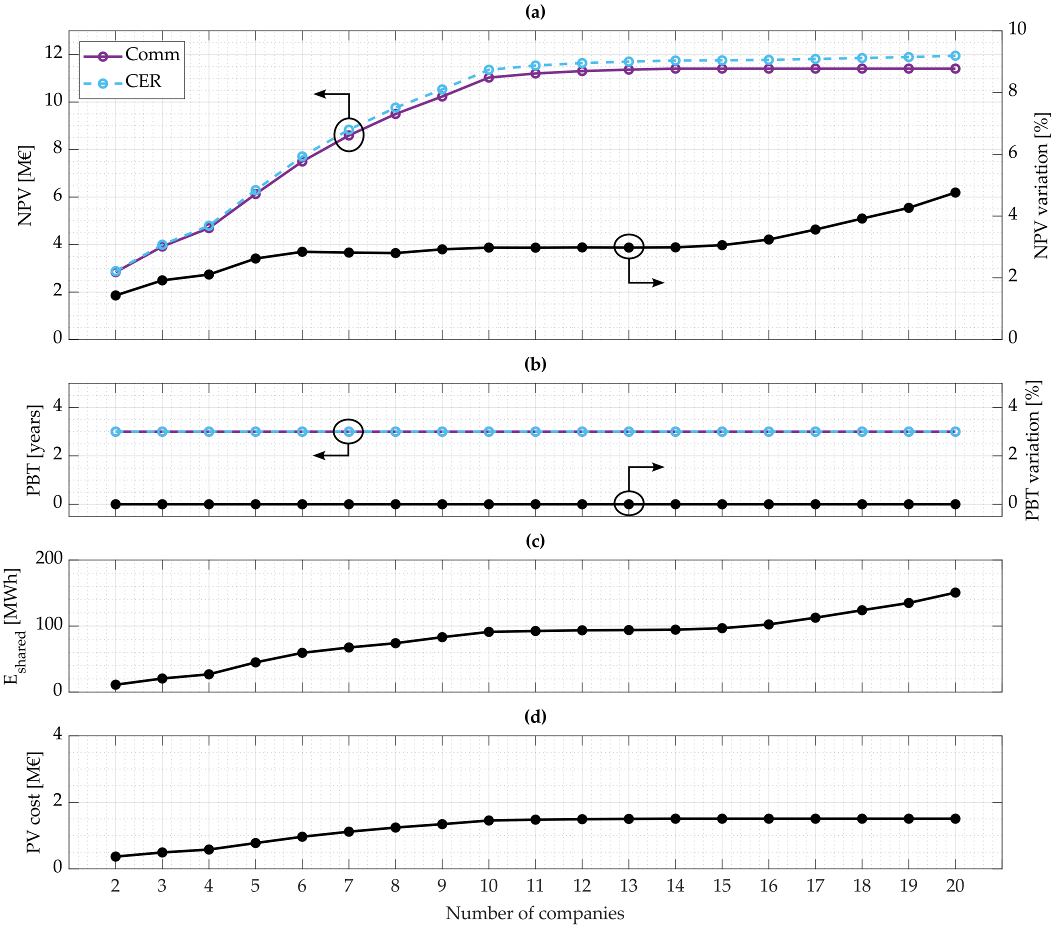


**Figure 9.** Results for dataset B in the reference case for different numbers of members, when self-consumption is equal to 80% for each member: (**a**) $NPV$ values [M€] at the community level and for the REC and their $NPV$ variation [%] (black line), (**b**) $PBT$ values [years] at the community level and for the REC and their $PBT$ variation [%] (black line), (**c**) shared energy [MWh], and (**d**) cumulative PV cost [M€].

The $PBT$ obtained with 80 % target self-consumption is constant and equal to three years, both considering the simple aggregation of users and the establishment of an REC, as depicted in Figure 9b. Now, considering Figure 9c,d, it can be observed that both shared energy and PV cost are monotonously increasing as the number of members of the community increases. Additionally, it is worth noting that the amount of shared energy, in a similar fashion to the variation in $NPV$ between aggregated users and REC, rises when a further member is added up to ten members, remains constant between ten and fifteen members, and rises again significantly for more than fifteen members. This is a result of the specific shapes of the load profiles of the users included in dataset B, which allows for reaching significant levels of shared energy even with PV systems traditionally designed to obtain high self-consumption levels in the pursuit of shorter $PBT$ values.

Overall, it can be stated that, considering the addition of PV systems to the users included in dataset B with a target self-consumption equal to 80%, the investment provides significant economic performances (i.e., a 30-year $NPV$ that is roughly six times larger than the initial investment, and a 3-year $PBT$), which is increased by roughly 5 % if an

REC is established. This makes the establishment of an REC quite attractive both from an economical and a social perspective.

Let us now analyse the possible economic benefits which can be obtained by the establishment of an REC with a purposefully designed PV capacity, considering a modest minimum required increase in $NPV$ (e.g., $\Delta_{NPVmin}$ = 25%) and a minimal allowed increase in $PBT$ (e.g., $\Delta_{PBTmax}$ = 0–1 years) first.

The resulting $NPV$, $PBT$, shared energy and PV cost are reported in Figure 10. Specifically, Figure 10a reports the trend in the REC $NPV$, as a function of the number of members, as well as the percentage variation in the $NPV$ between the current case with the increased PV capacity and the reference case obtained with 80 % target self-consumption. Analogously, Figure 10b reports the REC $PBT$, as a function of the number of members, and the $PBT$ variation between the current case and the reference case. Lastly, Figures 10c and 10d report, respectively, the shared energy E$_{shared}$ and aggregated PV cost, as functions of the number of members, as long as the shared energy and PV cost are from the reference case.

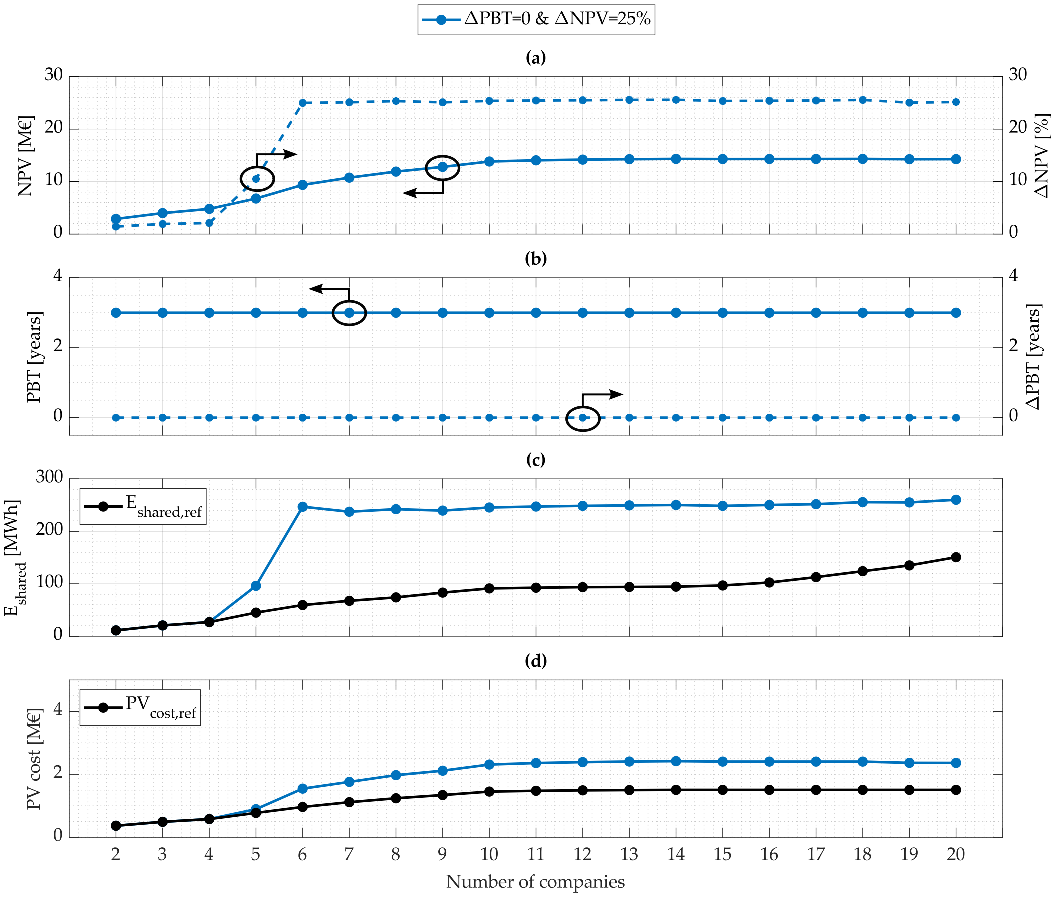


**Figure 10.** Results for dataset B when PV capacity is optimized, $\Delta NPV$ is equal to 25% with $\Delta PBT$ = 0: (**a**) $NPV$ values [M€] (solid lines) for the REC and their $\Delta NPV$ variation [%] (dashed lines), (**b**) $PBT$ values [years] (solid lines) for the REC and their $\Delta PBT$ variation [%] (dashed lines), (**c**) shared energy [MWh] for the REC and shared energy [MWh] in the reference case, and (**d**) cumulative PV cost [M€] for the REC and PV cost [M€] in the reference case.

Considering Figure 10a, it can be observed that the $NPV$ curve is monotonously increasing as the number of members of the community increases, and the increase in $NPV$ resulting from the addition of a new member to the community still decreases significantly for more than ten members. Additionally, it can be observed that the percentage variation of the $NPV$ with respect to the reference case is minimal up to four members, grows fast from four to six members, where it reaches the 25 % target, and is almost constant and slightly larger than 25 % for more than six members. As a consequence, a single combination of a required increase in $NPV$ ( $\Delta_{NPVmin}$ = 25%) and an allowed increase in $PBT$ ($\Delta_{PBTmax}$ = 0 years) has been considered, as there is no reason to allow for a longer $PBT$ if the target $NPV$ is reached. Now, examining Figure 10b, it can be appreciated that the $PBT$ is constant and equal to three years for all the combinations.

Now, considering Figure 10c,d, it can be observed that both shared energy and PV cost are monotonously increasing as the number of members of the community increases up to six members, and, in accordance with the trend observed for the $NPV$, the shared energy increases strongly when adding the fifth and sixth member to the community. For more than six members, PV cost is still monotonously increasing, while shared energy is slightly reduced when the seventh member is added, and is then marginally increased for each new member added. This is not related to the amount of installed PV capacity as, by observing Figure 10d, it is possible to appreciate that the PV cost is not directly proportional to the shared energy. On the contrary, the aforementioned strong increase in shared energy is related to two factors: firstly, some users included in dataset B show a large energy consumption, associated with a small available area for PV installation. Second, the specific shapes of the load profiles included in dataset B happen to be different enough for the excess of generation from one member to be absorbed by other members. Because of these two reasons, the REC established among the users included in dataset B has a higher potential of realizing significative quantities of shared energy, resulting in increased $NPV$ and reduced $PBT$ with respect to dataset A.

Overall, it can be stated that, considering the addition of PV systems to the users included in dataset B with a 25 % target increase in $NPV$ and a minimal allowed increase in $PBT$, the investment provides significant economic performances (i.e., a 30-year $NPV$ that is roughly six times larger than the initial investment, and a 3-year $PBT$). Additionally, in this case, the establishment of an REC is responsible for a significant portion of the obtained $NPV$, which makes the REC appealing only for sustainability and social purposes, as the increased PV capacity results in a significant increase in $NPV$, with no negative effect on $PBT$.

Let us now examine the possible economic benefits which can be obtained by the establishment of an REC with a purposeful PV capacity design when a much larger minimum required increase in $NPV$ (e.g., $\Delta_{NPVmin}$ = 100%) and a modest allowed increase in $PBT$ (e.g., $\Delta_{PBTmax}$ = 0–2) are considered. The resulting $NPV$, $PBT$, shared energy and PV cost are reported in Figure 11. Specifically, Figure 11a reports the trend in the REC $NPV$, as a function of the number of members, for different combinations of target $NPV$ increases and maximum $PBT$ increases. Additionally, Figure 11a shows the percentage variation in the $NPV$ between the current case with an increased PV capacity and the reference case obtained with 80% target self-consumption. Analogously, Figure 11b reports the REC $PBT$, as a function of the number of members, for different combinations of target $NPV$ increases and maximum $PBT$ increases, and the $PBT$ variation between the current case with an increased PV capacity and the reference case obtained with 80 % target self-consumption. Lastly, Figures 11c and 11d report, respectively, the shared energy $E_{shared}$ and aggregated PV cost, as functions of the number of members, for different combinations of target $NPV$ increases and maximum $PBT$ increases, as long as the values are obtained for the reference case obtained with 80 % target self-consumption.

Considering Figure 11a,b, it can be observed that all $NPV$ curves are almost always monotonously increasing as the number of members of the community increases and that they exhibit a similar overall trend, with $NPV$ generally being higher as the allowed $PBT$ increases. However, when a one-year $PBT$ increase is allowed, a slight decrease in $NPV$ is observed for the last combination with $n_u = 20$, which suggests that allowing a two-year $PBT$ increase is necessary when this combination of REC members is selected. In none of the considered cases does the $NPV$ increase reach its target value, suggesting that the PV capacity is limited by the allowed $PBT$, the available area, or a combination of both, and/or the specific load profiles included in dataset B do not allow us to increase shared energy significantly, regardless of the considered PV capacity. The increase in $NPV$ resulting from the addition of a new member to the community still decreases significantly for more than ten members. Additionally, it has been verified that, when the maximum acceptable $PBT$ increase is set to more than two years, the effective $PBT$ increase reaches only two years, suggesting that in this case, the PV capacity is not limited by the constraint on maximum $PBT$ and that there is no need to increase the REC $PBT$ of more than two years. The percentage variation in $NPV$, reported in Figure 11a, has different behaviours depending on the maximum allowed increase in $PBT$. In particular, when no increase in $PBT$ is allowed, the percentage variation in $NPV$ is monotonously increasing up to six members and constant from there on. When a one-year increase in $PBT$ is allowed, the percentage variation in $NPV$ is monotonously increasing up to ten members and constant from there on. Lastly, when a two-year increase in $PBT$ is allowed, the $NPV$ variation is monotonously increasing, even if the variation is marginal for more than nine members. These considerations suggest that the $NPV$ is limited by the constraint on the maximum $PBT$, which also happen to affect some configurations (e.g., an REC with six to ten members) more than others.

The $PBT$ is equal to three years when no increase in $PBT$ is allowed. It is also worth observing that the $PBT$ is not always the limiting factor for $NPV$, as, when a one-year $PBT$ increase is allowed, it is effectively used only for six or more members, while when a two-year $PBT$ increase is allowed, it is effectively used only for nine or more members.

Now, considering Figure 11c,d, it can be observed that, as expected, the trend in the shared energy is almost the same as observed for the variation in $NPV$ in Figure 11a and is, in all cases, significantly larger than the one obtained in the reference case. In the meantime, PV cost is monotonously increasing as the number of members of the community increases. As far as shared energy is concerned, the same considerations drawn for the variation in $NPV$ apply. In contrast, considering the impact of increased $PBT$ on PV cost, $NPV$ and shared energy, it can be observed that allowing a one-year increase in $PBT$ produces a very significant increase in $NPV$, shared energy and cost with respect to the results obtained when allowing no increase in $PBT$ for any REC with more than six members. On the other hand, allowing a two-year $PBT$ increase is less relevant, and affects only RECs with ten or more members.

Overall, it can be stated that, considering the addition of PV systems to the users included in dataset B with the aim of maximizing $NPV$ while allowing only a modest increase in $PBT$, the investment provides significant economic performances, with the $NPV$ ranging from roughly five times the initial investment in the case of $\Delta_{PBTmax} = 0$, to roughly three times the initial investment in the case of $\Delta_{PBTmax} = 2$, corresponding to an increase in $NPV$ from roughly 30% in the case of $\Delta_{PBTmax} = 0$, to roughly 50% in the case of $\Delta_{PBTmax} = 2$. The impact of the establishment of an REC is significant in all cases, and is the maximum for a number of members ranging from six to nine.

Now, considering the selection of the best combinations of users to be included in the REC, from the present discussion, it appears that the establishment of an REC within the users included in dataset B provides significant economic advantages regardless of the constraints on $PBT$ increase. Additionally, considering the trend in shared energy reported in Figure 11c, it can be observed that the maximum increase in shared energy with respect to the reference case is obtained for a number of REC members larger than six and smaller than nine. Including a smaller number of members produces lower economic performance, while increasing the number of members to be over nine produces a marginal detrimental effect on economic performances, but can be of interest for social purposes.

In the end, it is worth pointing out that the principles behind the proposed approach are general and, in principle, are also valid for residential users. In fact, the clustering method proposed in this paper is developed for industrial users but can also be applied to residential users. The latter, like industrial users, exhibit different energy use behaviours, influenced by factors such as household size, lifestyle, and appliance use. By applying our clustering method, residential users can be grouped together to optimize shared energy and improve the overall efficiency of renewable energy communities, demonstrating the flexibility and robustness of our approach.

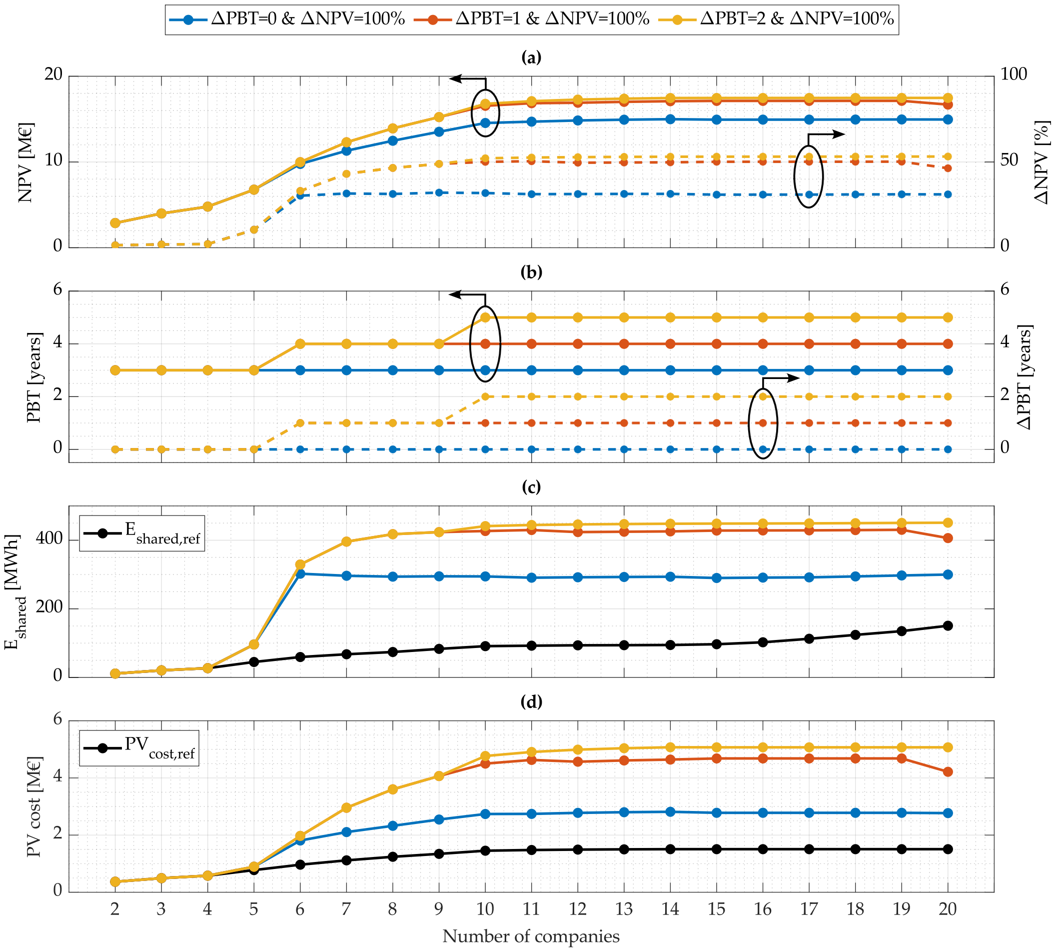


**Figure 11.** Results for dataset B when the PV capacity is optimized, the $\Delta NPV$ is equal to 100% with $\Delta PBT$ = 0, $\Delta PBT$ = 1 and $\Delta PBT$ = 2: (**a**) $NPV$ values [M€] for the REC and their $\Delta NPV$ variation [%], (**b**) $PBT$ values [years] for the REC and their $\Delta PBT$ variation [%], (**c**) shared energy [MWh] for the REC and shared energy [MWh] in the reference case, and (**d**) cumulative PV cost [M€] for the REC and the PV cost [M€] in the reference case.

## 6. Conclusions

This study introduced an innovative methodology to optimize the clustering of industrial users, evaluate the possible benefits rising from the establishment of an REC, and determine the most effective sizing of PV systems to be installed in the case that an REC is established. The proposed algorithm effectively integrates data sources, including energy consumption profiles identified by their ATECO classification, current and potential PV capacities, electricity purchase and sale costs, as well as the latest REC incentives and PV installation costs. The proposed method identifies the most beneficial cluster of industrial users to create a financially attractive REC and suggests the ideal PV capacity for each participant, all while taking into account the physical (e.g., the available space for PV installation) and economical (e.g., $PBT$) constraints. The presented results show that the proposed algorithm can successfully identify the clusters of companies which are more suitable to be included in an REC, determine the optimal number of members of the REC, assess the impact of introducing further members for other (e.g., social) reasons, and identify the PV capacity, for each member, by which the REC $NPV$ is maximized without extending the $PBT$ to unfavourable levels. This framework enables stakeholders to make informed decisions that balance the initial investment with long-term economic gains, improving the overall financial sustainability of the REC. Future work could extend this research by incorporating dynamic energy market and incentive structure conditions, examining the integration of additional renewable energy sources and storage devices, and including environmental performance indexes in the REC analysis. Such extensions would ensure the adaptability and resilience of RECs in a changing energy landscape.

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