Techno-Economic Analysis of Electric Vehicles Charging Hubs in a Renewable Energy Community

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***Abstract*—This study conducts a technical and economic assessment of a renewable energy community (REC) including multiple electric vehicle charging hubs powered by photovoltaic canopies. The analysis covers the criteria for the sizing of the photovoltaic systems, the evaluation of the energy production profiles, and the estimation of the aggregated consumption profile of the vehicle charging hubs. It provides a discussion of the technical feasibility of the proposed solution and a preliminary economic analysis, considering net present value and investment payback periods. Additionally, on the basis of a recent and comprehensive database of electric vehicles in the Italian fleet, energy flows are accurately determined considering each vehicle characteristics, and their arrival and departure patterns. As a case study, the performance of a renewable energy community comprising eleven parking lots in the city of Milan, Italy, is analysed. The presented results offer an overview of the value of RECs based on charging hubs and highlight potential challenges in their technical and economic management.**

***Index Terms*—renewable energy communities; electric mobility; energy transition; sustainability; charging hubs**

I. Introduction

Decarbonisation is a critical challenge, requiring a shift from fossil fuels to sustainable energy sources. In this context, electric vehicles (EVs) and renewable energy are promising solutions [1]. EVs can significantly reduce CO2 emissions and improve urban air quality. Moreover, advances in battery technology and the expansion of charging infrastructure are making EVs increasingly accessible and practical [2].

At the same time, renewable energy, such as solar, wind and hydroelectric power, are essential for transitioning to a low-carbon society. Among these, photovoltaic (PV) energy has grown substantially due to decreasing costs and supportive policies [3]. PV generate clean electricity from sunlight and can be installed in several locations, providing decentralised energy production. The swift expansion of PV power generation and e-mobility necessitates smart integration strategies to address potential challenges, such as the simultaneous charging of numerous vehicles in parking lots equipped with electric charging services by using optimisation strategies [4], [5]. One potential solution that efficiently reduces land use while providing space for PV systems and a protective cover for vehicles is the implementation of PV canopies, also known as PV carports. Despite their benefits, PV canopies face high capital costs [6]. Different studies have explored the economic and technical feasibility of these systems [7], [8], focusing on specific locations such as shopping malls and large parking lots [9]. Innovative designs and cost evaluations are currently aimed at the optimisation of these systems, demonstrating their potential in supporting decarbonisation efforts.

With the aim of boosting decarbonization process and promote renewable energy development, two innovative concepts were introduced by recent European directives, namely jointly acting renewable self consumers (JARSC) and renewable energy communities (RECs). JARSC groups collectively produce and use renewable energy within buildings, promoting energy self-consumption and sustainability. RECs involve local networks of individuals and organisations sharing and consuming renewable energy, enhancing energy autonomy and efficiency. Both entities offer environmental benefits, such as reduced greenhouse gas emissions, and socio-economic advantages, including new job opportunities and increased energy awareness.

Several studies have addressed different aspects of RECs, including energy management systems, optimization models [10], and techno-economic analyses [11]–[13]. These studies highlight the potential of RECs to support the energy transition not only in a residential context, but also in rural and non-residential districts, as the integration of solar energy, sustainable mobility, and energy sharing within local communities is an emerging area of interest.

This study focuses on the technical and economic assessment of the possible installation of PV canopies in Milan's parking lots. It evaluates the potential for distributed generation, EV charging stations and economic viability. The

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findings underscore the potential of local energy exchange dynamics to maximize the use of renewable energy and promote efficiency.

II. Renewable Energy Community and System Overview

This study focuses on a possible energy community consisting of eleven parking lots within the Milan city area, all managed by the local electricity distributor. Seven parking areas, located in the city's neighbourhoods and highlighted in yellow in Fig. 1, are suitable for installing PV canopies due to their outdoor, ground-level construction. The remaining four parking lots, situated in Milan central area and highlighted in red in Fig. 1, are underground or within buildings, making the installatino of PV canopies not feasible. All parking lots feature EV charging hubs, with detailed consumption profiles obtained by mergingn probability distributions of vehicles arrive and leaving times with a database of the most common electric vehicles in Italy.

From an electrical perspective, each parking lot includes the components shown in the circuit diagram reported in Fig. 2. All parking lots are connected to the public electrical grid via a medium voltage (MV) connection, enabling them to supply auxiliary loads (e.g. lighting and management services) and the EV charging points considered in this study for charging users' EVs. The parking lots which include PV systems contain all the elements within the area shaded in yellow, while parking lots including charging hubs only contain the elements included in the area shaded in red. The PV block represents the photovoltaic generator installed above the canopies, which is connected to the AC grid via a DC/AC converter with an integrated maximum power point tracking system (MPPT) to optimise photovoltaic yield. A production meter (PM) measures the PV system's output for energy and economic accounting purposes.

Each EV charging hub includes multiple charging points, the number of which is determined on the basis of the total area of the parking lot and of the EV share in the Italian car fleet. Each charging point has its own energy meter EV_n to log the energy consumption during the charging phase.

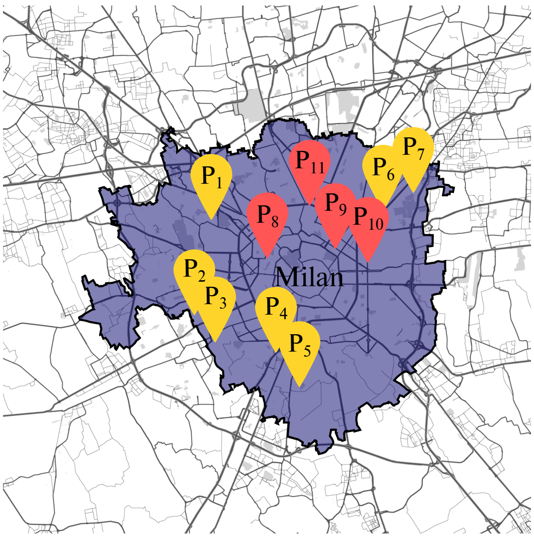

Fig. 1. Parking lots spatial distribution within the municipality area of Milan: parking lots highlighted in yellow includes both PV canopies and EV charging hub, parking lots highlighted in red includes only EV charging hub.

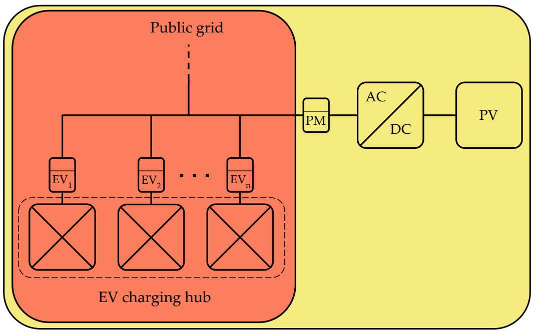

Fig. 2. Parking lot electrical scheme including PV canopies (PV) and EV charging hubs (yellow-shaded area) and with EV charging hub only (red-shaded area).

Parking lots are open 24/7, allowing all cars to be parked, with EV having reserved spots close to the charging stations.

Each parking lot has a specific total number of parking slots available for all vehicles N_{ps}, the number of which was provided by the parking lots administrator. Today, the percentage of circulating EVs in relation to the total circulating fleet in Italy is only 1% and is expected to rise to 10% in 2030. However, in Lombardy alone, the percentage of EVs is around 7.6% and is expected to rise to 13.7% by 2030. As a conservative estimate, it is assumed that a number of charging points N_{cp} equal to 13.7% of the total number of parking slots N_{ps} will be installed for each parking lot.

PV canopies are assumed to be installed over parking areas with minimal vegetation and distant from surrounding buildings to prevent external shading. Based on these criteria, the useful surface area was computed based on aerial images of the parking lots, defining a certain value of shaded ground area A_{shd}. The PV installations are restricted to the parking area itself and do not extend over internal roads used for vehicle circulation.

Each parking lot is oriented with a main direction relative to the South, determining its azimuth angle. For clarity, an azimuth angle of -90° corresponds to East, 0° to South, and 90° to West. The optimal azimuth angle for a PV system, which maximises annual energy production, varies by geographical location. However, the orientation of the PV canopies is constrained by the existing parking lot configuration, slots layout, and their alignment relative to the North-South direction. This results in sub-optimal azimuth angles and, unavoidably, lower annual photovoltaic production.

Regarding the PV canopies tilt angle relative to the horizontal plane β, an optimal angle can be determined to maximise energy production for the given azimuth angle. Although high tilt angles might improve annual solar energy production, the design of PV canopies must also consider structural constraints, wind influence, visual impact, and shadow reduction on vehicles. Consequently, due to these factors and to avoid increased costs from custom tilt designs, a standard tilt angle of 10-15° was chosen, as commonly provided by major manufacturers. In particular, the selected standard tilt angle is equal to 10°. Considering the shaded ground area and the canopies tilt angle, it's possible to calculate the available area for PV installation A_{pv} and thus the number of PV modules N_{pv} and the peak power of the PV system P_{pv}.

The PV system is organised into parallel strings, each of which includes a certain number of series-connected modules to comply with the input voltage requirements of the DC/AC converter. By examining the specifications of each PV module under standard test conditions (STC), as detailed in [11], the each parking lot power rating can be calculated.

The main parameters of the eleven parking lots considered in this work are listed in Table I. Specifically, for each parking lot suitable for PV installation (P1-P7), the azimuth angle α, the total number of parking slots N_{ps}, the total shaded area available for the installation of PV canopies A_{shd}, the number of shaded slots covered by the PV canopies N_{ss}, the total number of charging points N_{cp}, the area available on the tilted surface A_{pv}, the total number of installable PV modules N_{pv}, and the PV peak power of the entire parking area P_{pv} are defined. For the remaining parking lots (P8-P11), only the total number of parking slots and the total number of charging points are defined, as they are not suitable for installation of PV canopies. An example of PV canopy structure where the previously mentioned parameters are highlighted is depicted in Fig. 3.

It is worth emphasising that the values for A_{shd}, N_{ss} and the associated PV parameters are to be interpreted as the values that maximise the capacity of the PV system and will be used as upper-bound in the scenarios considered in Section III.

A. Generation, load and electricity price profiles

This section outlines the definition of the profiles used in the energy community model, which includes PV generation profiles for each parking lot including a PV system, consumption profiles based on the types and diffusion of specific EV models, arrival and departure EV distributions and electricity purchase prices. Each of these profiles spans a year (8760 hours) with 15-minute intervals, totalling at 35,040 samples.

1) Photovoltaic generation profiles: The National Solar Radiation Database (NSRDB) provides comprehensive solar radiation data, including global horizontal, direct normal, and diffuse horizontal irradiance, as well as meteorological information. Using quarter-hourly data for 2022 from the NSRDB, irradiance on the plane of arrays (PoA) for individual PV canopies was calculated through irradiance transposition, utilizing the pvlib toolbox. This toolbox simulates PV system performance based on input tilt and azimuth data for each canopy. The specific irradiance on the PoA is then used to calculate the electrical power generation using data from [11] and equations from [14].

2) Parking lots load profiles: Charging profiles for each parking lot are crucial for evaluating the energy and economic aspects of the REC example considered in this paper. The overall REC power consumption depends on the number of installed charging points, the type and model of cars accessing the charging service, users behavior on weekdays, and PV system energy production, which reduces grid energy purchases and boosts self-consumption and energy self-sufficiency. This section details the model components for calculating electric vehicle (EV) consumption profiles, considering a database of popular electric car brands and models in Italy in June 2023, arrival and departure distributions, cars initial state of charge (SoC), and each car model specific charging profile to determine the overall charging profile for each point.

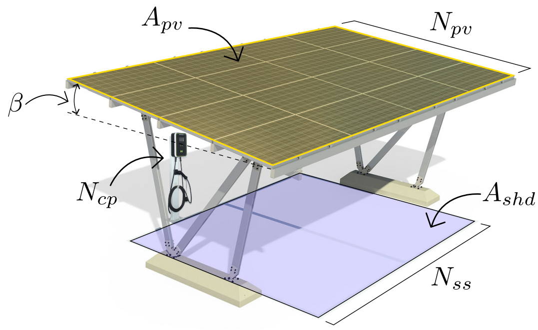

Fig. 3. PV canopy structure type considered in this work [15]

Each electric car model has distinct electrical characteristics, such as charging power from AC and DC charging points, usable battery energy, and charging power variations based on the state of charge (SoC), which typically decreases as the SoC approaches 100%. This work considers two vehicle types: BEVs (Battery Electric Vehicles) and PHEVs (Plug-in Hybrid Electric Vehicles). BEVs require high storage energy and high charging power to reduce charging times, while PHEVs, which are supported by internal combustion engine, have lower storage capacity and charging power.

The statistical considerations on which the loads profile are built rely on a database provided Quattroruote Professional, a leading automotive magazine in Italy, which includes brands, models, electrical characteristics, and number of circulating vehicles for approximately 500 types of electric vehicles, categorized into BEVs and PHEVs, providing a comprehensive view of the EV fleet in Italy as of June 2023 [16].

By using probability distributions for arrivals, departures, and initial SoC, a simulation can hence realistically represent the behaviour of the parking and charging system. This method allows for an accurate assessment of charging point performance, service availability, and overall electrical load impact. To model vehicle flow within the parking lot, prob-

TABLE I
MAIN PARAMETERS OF THE ELEVEN PARKING LOTS CONSIDERED IN THIS WORK.

Park	$\boldsymbol{\alpha}$ [°]	$\mathbf{N_{ps}}$ [-]	$\mathbf{N_{cp}}$ [-]	$\mathbf{A_{shd}}$ $[m^2]$	$\mathbf{N_{ss}}$ [-]	$\mathbf{A_{pv}}$ $[m^2]$	$\mathbf{N_{pv}}$ [-]	$\mathbf{P_{pv}}$ $[kWp]$
P1	53.2	1830	251	7580	606	7696	4572	1788
P2	-16.1	1810	248	3890	311	3950	2295	918
P3	-21.6	134	18	1660	123	1563	908	363
P4	83.6	245	34	1820	146	1848	1074	430
P5	-86.5	150	21	1500	120	1500	871	348
P6	42.2	530	73	2400	192	2437	1416	566
P7	-47.9	138	19	1330	106	1350	785	314
P8	n.d.	331	45	n.d.	n.d.	n.d.	n.d.	n.d.
P9	n.d.	700	96	n.d.	n.d.	n.d.	n.d.	n.d.
P10	n.d.	943	129	n.d.	n.d.	n.d.	n.d.	n.d.
P11	n.d.	426	58	n.d.	n.d.	n.d.	n.d.	n.d.

ability distributions for arrivals and departures are derived from historical driver behaviour data from [17]. The algorithm for generating the load profile for each charging point is straightforward. First, the probability of the arrival of an electric vehicle is determined. If this happens, the charging process begins and the charging point appears to be busy and no longer available until it is vacated. At this point, depending on the probability of departure, the vehicle could leave either before or after reaching 100% of the SoC, freeing the charging point again for a new arrival.

Fig. 4 shows the typical profiles of the system in a particular week of the year in the optimal scenario defined in Section III. The first seven plots show the power profiles of P1-P7, which include both photovoltaic production and power demand due to vehicle charging. Plots P8-P11 only show the load profile of aggregated electric vehicles, as they do not have any installed PV systems. The last plot in Fig. 4 shows the trend of potential shared power within the REC,which is subject to economical incentives .

B. Economic parameters, costs and REC incentives definitions

The economic assessment of the REC involves defining the costs and revenues associated with the PV system, electricity purchase and sale, and incentives from the shared energy.

The cost of the photovoltaic system, including the canopy support, is assumed to be equal to 1600 €/kWp. In addition, it is assumed to use 22 kW charging stations for all charging points, and a cost of 899 € is foreseen for all charging stations.

The energy fed into the distribution system is sold at a fixed price of 4.6 c€/kWh. However, the cost of purchased energy follows a two-hourly tariff structure: 30.5 c€/kWh from 8 a.m. to 7 p.m., and 28.5 c€/kWh from 7 p.m. to 8 a.m. The electricity price profiles used in this study include base prices, VAT (standard 22% in Italy), and additional fees.

If a REC is created, an incentive is provided based on the REC shared energy, which is defined as the hourly minimum of the energy supplied to the grid by the REC's renewable generators and the energy drawn from the grid by the REC members. Shared energy is rewarded with an incentive of 11 c€/kWh, in addition to a compensation of approximately 1.15 c€/kWh for avoided grid losses and distribution fees.

Common economic parameters and details on economic calculations used in this work can be found in [11], [18].

III. Definition of simulation scenarios

In this study, various simulation scenarios are analyzed to assess the economic implications of the REC. The scenarios differ in the sizing of the PV plant, which allows for a comprehensive analysis of the impact on both general economic and energy community-specific variables. In particular, we define:

- "Optimal" scenario (*Opt*): in this scenario, it is assumed that each of the seven parking lots installs the optimal PV capacity depending on their individual demands. This is based on the load profile determined by the number of charging points and the distribution of arrival and departure times. The goal is to achieve a self-consumption close to 80%, as common practice to ensure that most of the energy generated is used on site, granting favourable economic performances.

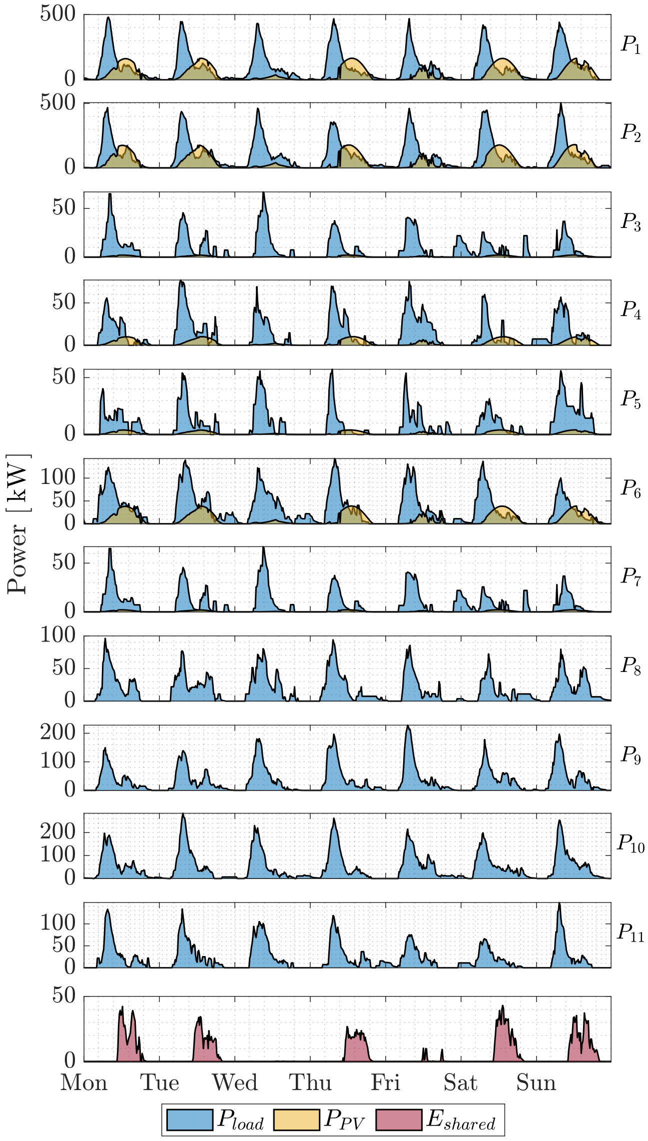

Fig. 4. Power profiles of parking lots during a typical week of operation with PV systems sized to reach 80% of self-consumption. The bottom plot represents the potential shared energy of the REC, if established.

- "Maximum" scenario (*Max*): it is assumed that each of the seven parking lots installs the maximum possible PV capacity listed in Table I. This scenario represents the upper limit of PV energy generation, and, possibly, the maximum REC shared energy.
- Scenarios "$s_1 ... s_8$": these intermediate scenarios are derived by considering the optimal (*Opt*) and maximum (*Max*) scenarios as lower and upper limits for PV sizing. Afterwards, the range between these two bounds is divided into eight equidistant sizings, for a total of ten considered scenarios. This allows exploring a wide spectrum of possible PV capacities and their corresponding impact on the REC.

For all the considered scenarios, system operation is simulated for a period of one year and the establishment of a REC is considered. This simulation provides insight into how different PV sizings influence the performance of the energy community, including economic performance. As a consequence, the trade-offs and benefits associated with different levels of investment and utilisation of PV systems are better understood, and the variation of economic parameters such as Net Present Value (NPV) and Payback time (PBT) at both the individual user level and the entire community level are investigated.

IV. Results and discussion

In this section, the main results of the study are presented and discussed in detail, on the basis of the scenarios defined in Section III.

First, the yearly average self-consumption of the seven parking lots that have the possibility to install the PV system (P1-P7) is reported in Fig. 5 for the ten considered scenarios. By design, in the *Opt* scenario, the self-consumption for all parking lots is close to 80%, as discussed in Section III. It can also be appreciated that, keeping the EV load profile for each parking lot unchanged, as the PV capacity increases linearly from the *Opt* scenario to the *Max* scenario, the self-consumption decreases monotonously, yet in a non-linear way (the difference in self-consumption between scenarios *Opt* and s_1 is much larger than the difference between scenarios s_1 and s_2, and so on), as the self consumed energy is limited by the available electrical load.

The variation in self-consumption due to a change in PV capacity is also strictly related to the available shared energy, the values of which are shown, aggregated for the whole REC and for each scenario, in Fig.6. It is worth noting that in the *Opt* scenario, where the self-consumption is higher, shared energy is lowest, at approximately 100 kWh/year, yet it increases considerably as PV capacity increases, up to a maximum of 500 kWh/year in the *Max* scenario. However, it can be seen that the growth of shared energy as PV capacity increases tends to reduce towards a saturation level, which is related to overall REC available electrical load. Indeed, as the energy generated by the PV system increases, the consumed energy from the parking lots remains unchanged and does not contribute to a proportional increase in shared energy, which constitutes an upper limit for energy sharing.

The main economic [11], [12] (net present value - NPV [k€] - and payback time - PBT [years]) parameters for the present analysis were computed considering a charging hub lifetime of 20 years. Fig.7 shows the NPV for each of the seven parking lots, for each scenario. It is possible to appreciate a similar, increasing trend for all parking lots, which is justified by the increasing revenues caused by the sale of energy generated by the PV system and not self-consumed to the electricity grid according to the prices defined in Section II-B. These values, in absolute terms, these are proportional to the maximum installable PV capacity as defined in Table I. In addition, it should not be neglected that by increasing indiscriminately the PV capacity, the NPV grows roughly proportionally to the PV capacity, yet the initial costs also increase considerably, leading to a corresponding increase in payback times.

The PBT of the individual parking, for each scenario, is reported in in Fig. 8. It can be readily appreciated that PBT increases considerably as the PV capacity increases, starting from 3 years for the *Opt* scenario for all the parking lots, and progressively growing even up to 7 years for parking lots P3, P4, P5 and P7 for the *Max* scenario.

As a REC is, however, an aggregation of prosumers, it is more relevant to evaluate the aggregated economic results shown in Fig.9 and Fig.10 for the NPV and PBT, respetively. In both figures, each vertical bar with uniform color indicates the aggregate value of the individual NPV and PBT values of the parking lots without considering the incentives related to the energy community, while the texture filled areas indicate the aggregate increase in NPV and PBT due to the incentives collected from the establishment of the REC. Moreover, the values above each vertical bar indicate the percentage change in NPV and PBT in the two cases.

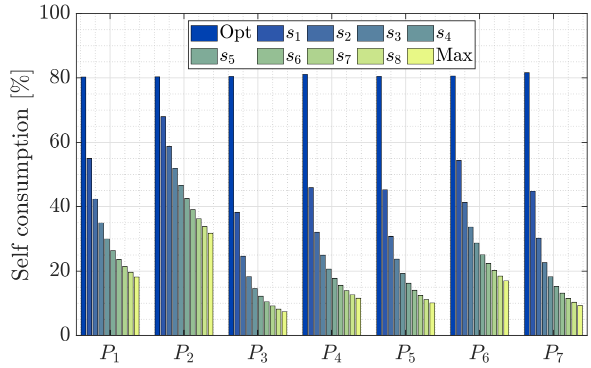

Fig. 5. Yearly self consumption values of parking lots P1-P7, for all the considered scenarios.

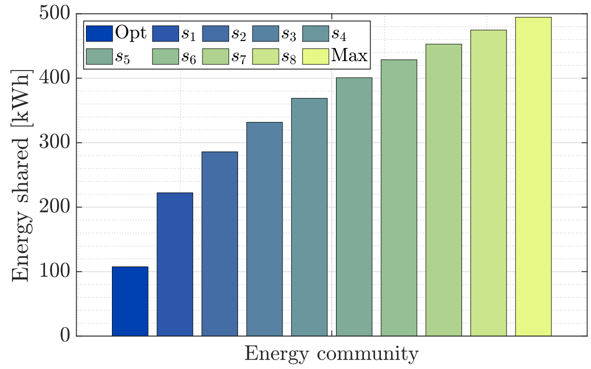

Fig. 6. Yearly shared energy at renewable energy community level, for the considered scenarios.

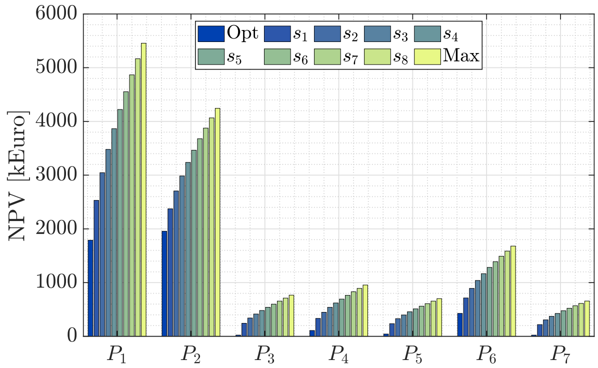

Fig. 7. 20 years NPV of parking lots P1-P7, for all the considered scenarios.

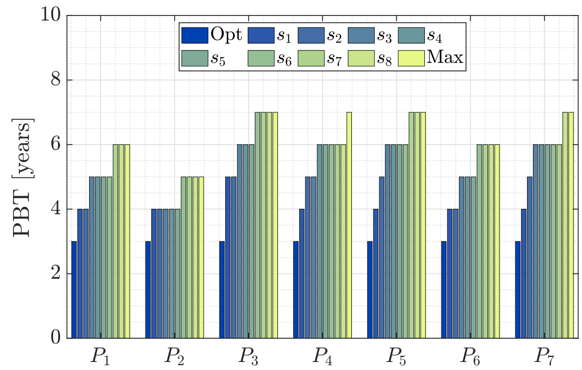

Fig. 8. PBT values of parking lots P1-P7, for all the considered scenarios.

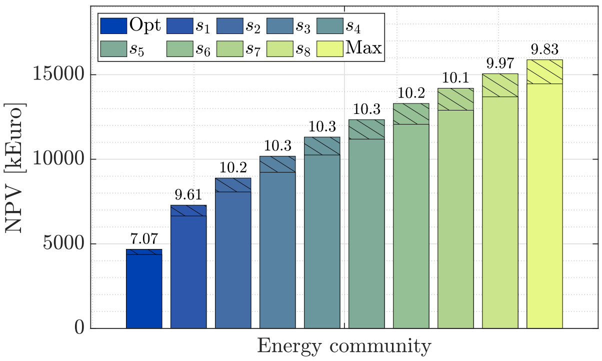

Fig. 9. Aggregated NPV values at REC level in the different scenarios without incentives (uniform colour of bars), and their change due to REC incentives (texture fill area).

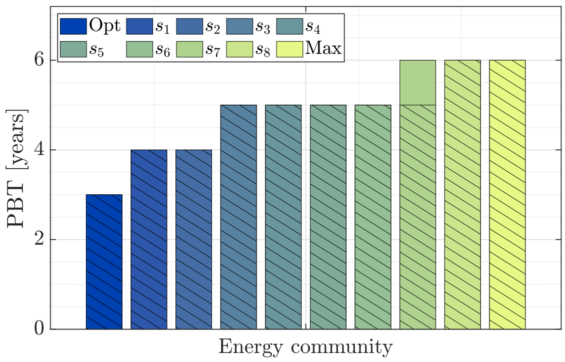

Fig. 10. PBT values at REC level in the different scenarios without incentives (uniform colour of bars), and their change due to REC incentives (texture fill area).

It can be observed that, in each scenario, the aggregated increase in NPV shown in Fig.9 is naturally positive due to the incentives of the REC. However, starting from a gain of 7%, there is an increase up to 10.3% for the s_3, s_4 and s_5 scenarios, before decreasing again to 9.83%. From this analysis it is therefore possible to appreciate how at the aggregate REC level, the optimal sizing falls for these three scenarios where the increase in aggregate NPV is maximum.

From the point of view of the community-level PBT shown in Fig.10, calculated using the aggregate NPV in the two cases seen above, the results appear to be nearly unchanged, except for the s_7 scenario where in the REC case it decreases from 6 to 5 years. While this is apparently counter-intuitive, it can be ascribed to the discrete PBT scale, which is commonly expressed in integer years, so that variations in the days or months range cannot be appreciated.

V. Conclusions

In this paper, the techno-economic evaluation of a charging hub in a renewable energy community (REC) context was analysed, considering different scenarios with several PV canopy sizing in the individual parking lots. A case study was considered that includes eleven parking lots in total located in the city of Milan, Italy, seven of which are suitable for the installation of PV systems, while the remaining four are only considered as electrical loads as their underground structure is not compatible with PV systems. Starting from a reference initial scenario, where the PV systems were designed with the aim of achieving roughly 80% self-consumption for all parking lots, and an upper-limit scenario in which all parking lots install the maximum available PV capacity, determined on the basis of availble areas, eight intermediate sizing solutions were evaluated from a technical and economic point of view, both for individual parking lots and the aggregate REC.

The presented results highlight the economical sustainability of the considered charging hub REC, which exhibits very reasonable PBT. Additionally, they empirically prove the existence of an optimal between PBT and NPV obtained by slightly over-sizing the overall PV capacity with respect to the standard sizing used in the *Opt* scenario, which will be object of further investigation.

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