Smart Parking Optimal Design for Renewable Energy Communities Integration in Power System

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Abstract

The increasing penetration of renewable energy generation, further accelerated by the introduction of Renewable Energy Communities (RECs), and the widespread adoption of Electric Vehicles (EV) represent a transformative shift toward more sustainable and decentralized energy systems. These developments offer significant opportunities, particularly through Vehicle-to-Grid (V2G) technology, which enables EVs to operate as mobile energy storage units, supporting grid stability and improving local self-consumption. However, they also introduce substantial challenges, such as the complexity of managing bidirectional power flows, the need for advanced control and optimization strategies, and the absence of clear regulatory frameworks to support large-scale V2G deployment. Addressing these issues is essential to unlock the full potential of integrated smart energy ecosystems. This paper investigates the optimal design of smart parking infrastructures within RECs, focusing on the interaction between photovoltaic generation, energy storage systems, and V2G charging stations. A case study, the University of Palermo campus (connected

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to the main grid), is analyzed to assess the technical and economic benefits of V2G-enabled smart parking in different grid contexts. The results demonstrate the potential of such systems to improve grid flexibility, reduce carbon emissions, and maximize local energy value.

Renewable Energy Communities, Vehicle-to-Grid, Energy Storage System, Smart Parking, Photovoltaic Generation.

1 Introduction

The advent of car electrification is a key step in the strategy to reduce greenhouse-gas due to global warming. The automotive market has evolved significantly in recent years; in fact, out of a total of about 1,47 billion cars on the road in the world today, about 40 million are electric, accounting for 2.7 percent of the global car fleet [1]. The growing development of the electric car market in Europe is a key element in making European states climate neutral by 2050. To achieve this goal, the European Commission adopted the "Fit for 55" package to reduce car emissions by 55 percent by 2030 and bring new car emissions to zero by 2035 [2]. Electric vehicles are an important tool for achieving the goals set by Europe, but their impact on the electric grid should not be neglected [3], [4]. In fact, it has been observed that charging electric vehicles can cause power quality problems, such as voltage dips, current and voltage harmonics, and power imbalances [5].

In addition, charging EVs during peak loads can cause increased energy demand and increased generation capacity [6]. These problems can be overcome or at least reduced by using smart charging that is able to charge vehicles so as not to negatively impact the grid [7]. Smart charging prevents exceeding the maximum energy capacity of smart parking by taking advantage of dynamic management of EVs connected simultaneously. At the same time, it enables the integration of renewable energy sources by promoting local self-consumption [8]. It is, therefore, an energy sharing, allowing charging operators to distribute the smart parking's energy capacity proportionally among all active charging stations in the parking lot. In this way, smart charging allows energy to be distributed in an optimal way that also benefits the power grid and the environment. If the one-way smart charging, identified as V1G, is added to the ability to give energy back to the grid, then it is called bidirectional charging identified as V2G [9]. To date, in fact, V2G allows electric vehicles to recharge during off-peak hours and return to the grid during peak hours when there is a demand for additional energy. The application of this charging is ideal in smart parking garages: cars stay in parking lots 95% of the day, so with careful planning and the right infrastructure, parked and connected electric vehicles could become massive power banks, stabilizing the electric grids of the future. The standard can be used for both wired (AC and DC) and wireless charging of electric vehicles.

A further step toward sustainable and distributed energy management is the Renewable Energy Communities (RECs), recently regulated in Italy through the CACER decree [10], which implements the requirements of the European RED II Directive and promotes the diffusion of collective self-consumption and the emergence of RECs on a local scale. RECs, defined as local groups of consumers and producers connected to the same HV/MV station that share the energy produced by one or more renewable source plants, are born with the aim of optimizing collective self-consumption, reducing dependence on fossil sources, lowering energy costs and increasing the resilience of local grids. But if not properly designed, they risk failing to achieve the intended objectives [11]. Within this context, the integration of smart parking equipped with smart charging stations for electric vehicles represents a strategic opportunity. In fact, current regulations explicitly allow the inclusion of storage systems and electric vehicles among the infrastructures that can participate in self-consumption and energy sharing within RECs, as long as they are located within the perimeter of the primary reference substation. The bidirectional exchange of energy between vehicles or Energy Storage Systems (ESSs) and the local grid can thus transform the parking lot into an active community player, capable of absorbing excess energy produced by renewable facilities during daylight hours and returning it to the grid or other community members at times of highest demand.

With the aim of achieving more efficient use of the infrastructure and energy resources included in RECs, this paper presents a method for sizing the PV system and ESS to be installed within V2G smart parking serving RECs.

Section II presents the methodology. Section III describes the case study analyzed and the results obtained. Finally, conclusions are presented in Section IV.

2 Methodology

Studying the impact of RECs on the distribution system is crucial to understanding the changes they introduce into the technical management of the power grid [12]. RECs promote local production and consumption of renewable energy, mainly PV, by inserting themselves into the low- and medium-voltage level of the grid. From a technical point of view, the introduction of uncontrolled distributed generation can lead to significant variations in power flows, which can become bidirectional, causing local surges, line congestion, frequency fluctuations and difficulties in coordinating protections.

Referring to the simplified REC model shown in Fig. 1, the purpose of the proposed method is to choose the size of the PV system and ESS to be included within a smart parking serving a REC to maximize local self-consumption and thus reduce the impact on the grid.

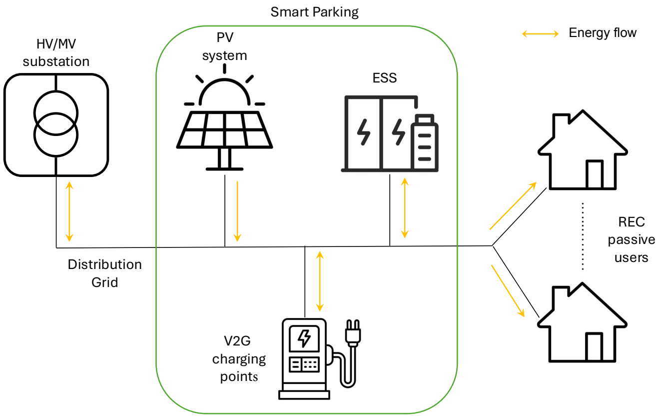

Figure 1: REC architecture under study.

Maximizing local self-consumption in a REC means using internally generated renewable energy as much as possible, in real time. This allows for reduced costs associated with grid use, higher incentives associated with energy sharing, and, through the presence of an ESS, to avoid the low-priced sale of unused energy. Consequently, economic optimization within a REC directly results in maximizing local self-consumption and thus reducing the impact on the distribution grid.

Considering the Italian regulatory framework, for the REC model shown in Fig. 1, the total annual cost can be defined as:

$$\begin{aligned} C_0 = c^{ess} \cdot Q + c^{pv} \cdot P + \sum_{h=1}^{3600} \Big(& P_h^{buy} \cdot q_h^{g2l} \\ & - P_h^{sell} \cdot q_t^{l2g} - P_h^{inc} \cdot q_h^{sh} \Big) \end{aligned} \tag{1}$$

Where:

- c^{ess} and c^{pv} indicate the annualized investment costs of the battery [€/kWh] and PV [€/kW], respectively, evaluated by multiplying the average specific cost by the sum of the amortization, maintenance, and inflation coefficients;

- Q indicates the capacity of the ESS [kWh];

- P denotes the PV power [kW];

- P_h^{buy}, P_h^{sell}, and P_h^{inc} [€/kWh] indicate the purchase price, sale price, and price associated with the energy sharing incentive at h-hour, respectively;

- q_h^{g2l} indicates the energy consumed from the grid by the REC at hour h [kWh], which is represented by the difference between the REC's demand, production and energy provided by the ESS;

- q_t^{l2g} indicates the energy fed into the grid by the REC at hour h [kWh], which is represented by the difference between production, energy stored in the ESS, and the REC's demand.

- q_h^{sh} indicates the flow of shared energy [kWh], defined as the minimum at reference hour h between total REC consumption and total production.

The following constraint on the installation power of the PV system is defined:

$$P_{\text{pv, max}} = \frac{E_{rec}}{h_{eq} \cdot K} \tag{2}$$

Where:

- $P_{textpv,max}$ is the maximum installable PV power (kW);
- E_{rec} is the total average daily consumption of the REC (kWh),
- h_{eq} represents the equivalent hours of daily PV production in the considered month,
- K is the overall efficiency of the PV system, conventionally assumed equal to 0.75.

In order to limit the wearing of the ESS, the state of charge (SOC) is considered to be between 20% and 90% at all times and it can only execute one charge/discharge cycle per day, thus:

$$SOC_d \geq SOC_{d'} \tag{3}$$

- SOC_d is the capacity of the ESS at the beginning of the day;

- $SOC_{d'}$ is the capacity of the ESS at the end of the day;

Finally, the sizing of the PV system and ESS to be installed in a smart parking serving the REC is conducted by searching for the optimal combination of PV and ESS sizes that minimize the costs of the REC, namely:

$$OF = min\ C_0 \tag{4}$$

In this way, it is therefore possible:

- maximize the sharing of energy produced within the REC, so as to supply the users in the smart parking and the buildings that are part of the REC;
- minimize the electricity consumption from the grid;
- optimize ESS management to be able to ensure coverage of the REC's loads during nighttime hours when PV is not producing;
- to reduce CO_2 emissions, which is the main goal of RECs.

Given the REC's consumption, the ESS capacity that can be charged up to SOC_{max} is calculated for each value of the installable PV power. The procedure can result in the identification of several capacity values that satisfy the desired condition; from these, the maximum value is chosen, i.e., the one that allows the largest amount of energy to be stored. This choice even if it involves a higher initial investment allows maximizing the energy sharing and thus consuming less energy from the grid. With a consequent increase in the incentive and a reduction of the total annual cost.

Finally, to assess the economic feasibility of the installation, the difference between the annual costs of the REC in the absence (C') and in the presence of PV and ESS (C_0) is calculated:

$$\Delta C = C' - C_0 \tag{5}$$

A negative value of ΔC or otherwise a very low value is identifying the affordability of the investment.

Next, the payback time, the Net Present Value and Profitability Index (PI) are calculated. The latter is calculated as the ratio of the Net Present Value to the total costs incurred in installing the PV system and the SSE. Accordingly, only solutions for which revenues are greater than expenditures are considered, i.e. PI >0.

3 Case Study and Result

The main objective is to reduce the overall costs for the REC. According to the proposed method, this means maximizing the shared energy by minimizing the energy taken from the grid to cover the REC's energy needs by optimally choosing the PV system size and ESS capacity. To evaluate its effectiveness, the method presented in Section II was implemented in the Matlab environment and applied to size the PV and ESS system to be installed in the smart parking to be integrated into a REC within the University of Palermo (UNIPA) campus.

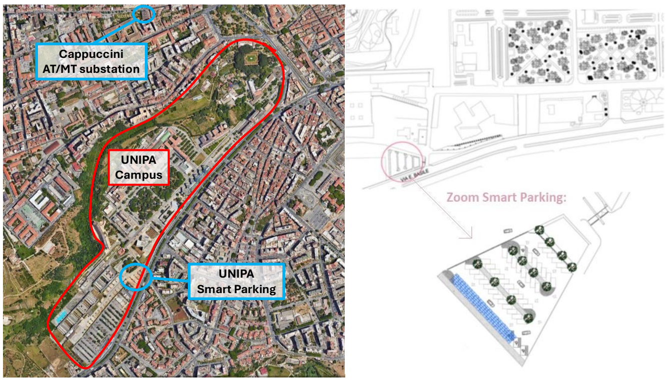

Figure 2: Unipa Smart Parking.

The university campus power grid consists of 20 kV cable line. The line starts from the HV/MV station named "Cappuccini" and feeds 11 secondary substations located within the campus (Fig. 2). The MV/LV substation named "Carrubba University" is assigned to supply electricity to Building 9 and the area close to it including the Faculty of Architecture. This area is the focus of the study aimed at the realization of a REC consisting of:

- a smart parking, part of which is dedicated to charging electric vehicles;
- from the complex of buildings adjacent to the parking;
- a PV system;
- an ESS.

To test the effectiveness of the proposed method, two scenarios are analyzed:

- Scenario 1: electric vehicles are considered loads, V1G configuration;

- Scenario 2: vehicle batteries can be operated to provide auxiliary services to the grid and to partially power evening loads, V2G configuration.

3.1 Scenario 1: V1G

The starting data to execute optimal sizing of the PV system and ESS to be installed in the smart parking are the consumption of the loads that are part of the REC, including vehicles owned by the parked staff and students, and the specific producibility of the PV system.

The total load diagram of the buildings adjacent to the smart parking and vehicles shows a difference between weekdays and weekends. From Monday to Friday, the power demand is initially stable between 25 and 30 kW until 7:00 a.m., and then increases to a peak of about 70 kW between 10:00 a.m. and 12:00 noon. After that it gradually decreases, dropping below 40 kW around 7 p.m., coinciding with the closing of the campus. On weekends, however, the trend is stable between 25 and 30 kW, with lower values due to the reduced presence of people in the REC buildings. While, the specific producibility of the PV system to be installed can be estimated for different months of the year through the use of the online tool PVGis [13].

These data were introduced into the model and the results obtained are shown in Fig. 3.

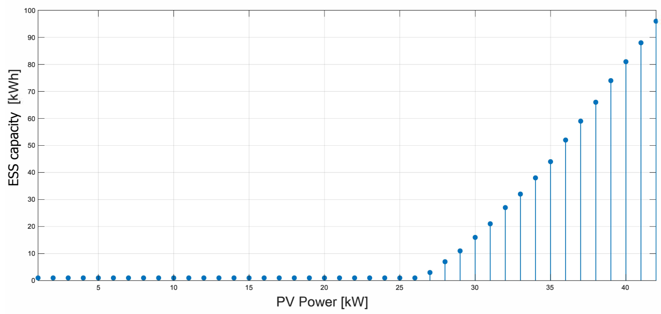

Figure 3: ESS optimal capacity at varying PV installed power.

Specifically, from Fig. 3 it can be seen that as the installed PV power varies, the algorithm chooses the ESS capacity with power equal to the power of the PV system to minimize both the injection of renewable energy into the grid and the consumption of the grid by REC users. The value of the ESS capacity is equal to 1 kWh up to an installed PV power of 27 kW, and then starts to increase as the PV size increases. The maximum value reached at 42 kW is 97 kWh. Higher values would result in too high costs.

The following figures show the energy flows during a typical weekday Fig. 4 and weekend Fig. 5 of June 2024 of the REC analyzed after the installation of the PV and ESS system calculated condidering the charging of vehicles during the production hours so as to maximize the energy sharing.

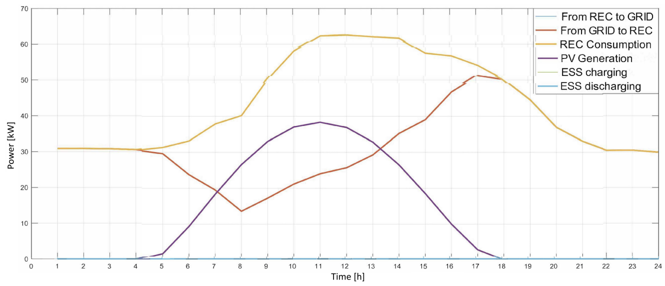

Figure 4: REC energy flows weekday in June 2024.

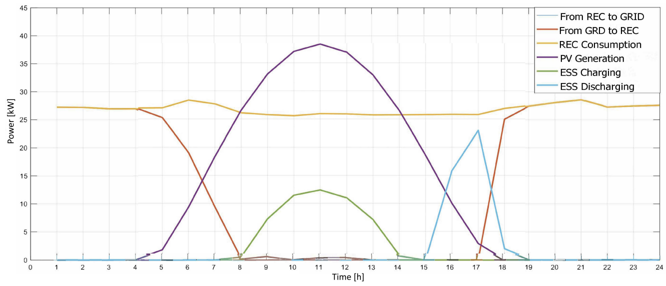

Figure 5: REC energy flows weekend in June 2024.

Fig. 4 shows how during the week, as the load is always greater than the production, all the energy produced is consumed by the REC while minimizing the consumption from the grid, and the ESS is never charged. Whereas, the Fig. 5 shows that, during weekends, due to the reduced load, some of the energy produced is used to charge the ESS and, to reduce the consumption from the grid, the stored energy is then used to power the REC.

The following table shows all the energy and economic quantities evaluated by the algorithm.

The results obtained show how optimal sizing of the PV system and ESS starting from the analysis of REC users' consumption and commanding vehicle charging during production hours allow reducing the overall costs. Specifically, for the case under study, an investment of nearly 85 thousand euros yields an annual energy purchase resouce of about 25 thousand euros, a payback time of 5 years and 1 month, and a CO2 reduction of about 480 thousand tons per year.

Table 1: REC UNIPA – Summary of Energy and Economic Quantities

Category	Description	Value
PV and ESS Size		
	PV Power [kW]	42.00
	ESS Capacity [kWh]	97.00
Energy Quantities		
	PV Generation [kWh/year]	86,715.00
	PV Energy Consumption [kWh/year]	86,715.00
	Energy Sold [kWh/year]	0
	Energy Sharing [kWh/year]	89,992.00
	Energy Consumed from Grid [kWh/year]	302,930.00
Economic Quantities		
	Self-consumption Savings [€/year]	24,117.00
	REC Incentive [€/year]	9,899.10
	ARERA Incentive [€/year]	7,199.30
	Energy Sales [€/year]	0
	Energy Purchases [€/year]	59,159.00
	Benefits [€/year]	41,216.00
	System Investment Cost [€/year]	85,207.00
Other Quantities		
	Payback Time [years]	5 years and 1 months
	PI (Profitability Index)	15.32
	CO_2 Avoided in 20 Years [Tons]	479.19

3.2 Scenario 2:

At this point it is examined what happens if the presence of electric vehicles connected to the charging stations with the possibility of exchanging energy with the grid bidirectionally is included. Considering the presence of 5 vehicles with a battery capacity of 30kWh, and assuming that each one makes 30% of the capacity available, 45 kWh of energy would be available that could be used both during the day to cope with fluctuations in producibility and in the late afternoon/evening to partially power the REC loads.

The integration of V2G technology would result in a significant reduction in the capacity of the ESS needed, as some of the energy would be dynamically provided by connected EVs. Specifically, the availability of an additional 45 kWh provided by EVs would allow the stationary battery to be downsized from 97 kWh to about 52 kWh, while maintaining the flexibility needed for supply and demand management within the REC. This reduction results in a significant decrease in investment costs, estimated at about €60,000 compared to the initial €85,000. In addition to the direct economic benefit, there is also an improvement in the profitability ratio and a decrease in the payback time of the investment, which would be reduced to about 3 years and 5 months.

From an operational perspective, using vehicles as a flexible energy resource also improves system resilience and can help optimize self-consumption and active user participation in community management. However, this solution introduces new organizational and technical complexities, such as variability in vehicle availability, the need to define economic compensation mechanisms for owners, and the implementation of advanced control systems to coordinate energy input and output.

To mitigate these critical issues, a viable strategy could be to employ University service vehicles, dedicated in part or in full to community needs. Such vehicles, having more predictable and controllable usage profiles, could provide a stable resource for load shifting operations, contributing structurally to the community's energy balance.

4 Conclusions

This study highlighted the strategic potential of integrating smart parking systems equipped with PV, ESS within Renewable Energy Communities. Through an optimized approach, it has been demonstrated how it is possible to increase local self-consumption, reduce energy consumption from the grid, and maximize economic and environmental benefits for the community. The case study related to the University of Palermo campus confirmed the effectiveness of the proposed methodology in identifying the optimal sizing of PV and ESS systems. The results obtained in the V1G scenario show a significant reduction in power costs and CO_2 emissions, with a profitability index above 15 and a payback time of about five years. The introduction of V2G technology has further improved economic sustainability, allowing a significant reduction in the capacity required for stationary storage and lowering the payback time to less than four years.

Besides technical and economic achievements, V2G integration introduces new perspectives in terms of flexibility and resilience of energy management, turning electric vehicles into active resources for the grid. However, it also brings operational and organizational challenges, including variability in vehicle availability, the need to define economic compensation mechanisms for users, and the implementation of advanced control systems. In this regard, future work will focus on several areas of development: adopting intelligent algorithms for real-time management of energy flows, testing participation models based on service vehicles with predictable usage profiles, and extending the analysis to multi-community scenarios. In addition, regulatory developments and the definition of appropriate incentive tools will be key elements in fostering large-scale deployment of these solutions.

References

[1] International Energy Agency (IEA), "Global ev outlook 2024," tech. rep., International Energy Agency, Parigi, 2024. Accessed: 2025-05-21.

[2] European Commission, "Fit for 55: delivering the eu's 2030 climate target on the way to climate neutrality." `https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal/delivering-europes-digitaleconomy-and-green-transition\_en\#fit-for-55`, 2021. Accessed: 2025-05-21.

[3] M. L. Di Silvestre, R. Musca, E. R. Sanseverino, G. Sciumè, A. Vasile, and G. Zizzo, "A feasibility study for the transition to electric mobility in the island of favignana," in *2021 IEEE International Conference on Environment and Electrical Engineering and 2021 IEEE Industrial and Commercial Power Systems Europe (EEEIC / I&CPS Europe)*, 2021.

[4] G. Sciumè, C. Iurlaro, S. Bruno, R. Musca, P. Gallo, G. Zizzo, E. R. Sanseverino, and M. L. Scala, "A blockchain-based architecture for tracking and remunerating fast frequency response," *Sustainable Energy, Grids and Networks*, vol. 40, p. 101530, 2024.

[5] B. Harish and U. Surendra, "A review on power quality issues in electric vehicle interfaced distribution system and mitigation techniques," *Indonesian Journal of Electrical Engineering and Computer Science*, vol. 25, p. 656, 02 2022.

[6] B. Kamana-Williams, D. Bishop, G. Hooper, and J. Chase, "Driving change: Electric vehicle charging behavior and peak loading," *Renewable and Sustainable Energy Reviews*, vol. 189, p. 113953, 2024.

[7] O. Sadeghian, A. Oshnoei, B. Mohammadi-ivatloo, V. Vahidinasab, and A. Anvari-Moghaddam, "A comprehensive review on electric vehicles smart charging: Solutions, strategies, technologies, and challenges," *Journal of Energy Storage*, vol. 54, p. 105241, 2022.

[8] P. Barman, L. Dutta, S. Bordoloi, A. Kalita, P. Buragohain, S. Bharali, and B. Azzopardi, "Renewable energy integration with electric vehicle

technology: A review of the existing smart charging approaches," *Renewable and Sustainable Energy Reviews*, vol. 183, p. 113518, 2023.

[9] M. O. Dioha, T. H. Ruggles, S. Ashfaq, and K. Caldeira, "Idealized analysis of relative values of bidirectional versus unidirectional electric vehicle charging in deeply decarbonized electricity systems," *iScience*, vol. 25, no. 9, p. 104906, 2022.

[10] Ministero dell'Ambiente e della Sicurezza Energetica (MASE), "Decreto Ministeriale del 07/12/2023, n. 414 sulle Comunità Energetiche Rinnovabili (*in Italian*)," 2023.

[11] M. L. D. Silvestre, F. Montana, E. R. Sanseverino, G. Sciumè, and G. Zizzo, "An algorithm for renewable energy communities designing by maximizing shared energy," in *2023 AEIT International Annual Conference (AEIT)*, 2023.

[12] A. Dimovski, M. Moncecchi, and M. Merlo, "Impact of energy communities on the distribution network: An italian case study," *Sustainable Energy, Grids and Networks*, vol. 35, p. 101148, 2023.

[13] European Commission, Joint Research Centre, "Photovoltaic Geographical Information System (PVGIS)," 2025. Accessed: 2025-04-07.