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Assessing the impact of electric vehicle charging hubs on shared energy in Renewable Energy Communities according to the Italian regulation

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Abstract. Renewable energy communities (RECs) are decentralized energy systems in which local individuals, businesses, and organizations collaborate to generate, consume, store, and share renewable energy. Governments are increasingly recognizing the role of RECs in accelerating the adoption of renewable energy, offering incentives and regulatory support to encourage its development. Conversely, the proliferation of electric vehicles (EVs) is profoundly affecting modern energy systems, engendering both challenges and opportunities for shared energy networks. This paper analyses the impact of different EV hubs on shared energy within RECs. The results show that when considering the installation of columns in a single area, it could be inferred that the residential center has the greatest impact in terms of energy that needs to be imported from REC, while the industrial area improves performance in terms of sharing. However, it is worth noting that as the demand for EV charging increases, scenarios are observed where the export of RECs is effectively reduced, but the total energy imported also increases. This trend is the result of the energy balance between the energy shared by EVs saturating the availability from renewable sources, creating a demand for imports even in time slots where, in the configuration without charging stations, export was present.

1. Introduction

The global energy landscape is undergoing a profound transformation, driven by the urgent need to mitigate climate change, reduce Greenhouse Gas (GHG) emissions, and transition toward sustainable energy systems. Central to this transformation is the rapid adoption of Electric Vehicles (EVs) and the parallel expansion of Renewable Energy Sources (RES), both of which are reshaping the way energy is produced, distributed, and consumed [1,2]. As the transportation sector accounts for a significant share of global emissions, the electrification of mobility - when coupled with clean energy - offers a promising pathway to decarbonize one of the most challenging sectors [3].

In this context, Renewable Energy Communities (RECs) have emerged as innovative models that promote energy self-sufficiency, sustainability, and local economic benefits by leveraging renewable sources such as solar, wind, and biomass. Support from the European Union has led to the creation of these communities, where users of different types can come together and receive incentives for virtually sharing electricity generated by the members' renewable plants within the same time slot. The legal framework introducing and regulating the operation of national energy communities comes from two European Directives: the RED II Directive 2018/2001/EU on the promotion of the use of energy from renewable sources, and the IEMD Directive 2019/944/EU on common rules for the internal market in electricity [4].

As the penetration of EVs continues to grow, their charging patterns exert a considerable influence on the stability of the electricity grid, the efficiency of power distribution, and the integration of renewable energy sources. To achieve optimal decentralized energy generation and consumption within RECs, the integration of EV hubs—comprising charging stations, Vehicle-To-Grid (V2G) technology, and battery storage—assumes a pivotal role in balancing energy supply and demand [5,6]. It is worth noting that the uncontrolled charging of EV can lead to substantial spikes in electricity demand, particularly during evening hours when residential electricity consumption is already high [7]. These spikes can increase dependence on fossil fuel power generation to meet maximum demand.

Some researchers have investigated the benefits of coupling EVs and PV-driven RECs. For example, Ceglia et al. present a configuration involving two office buildings where electric consumption encompasses thermal, cooling, and EV charging demand, with photovoltaics serving as the renewable energy source. Their study provides an energy efficiency analysis and key indicators for REC classification, focusing on private charging infrastructure [8]. Gudmunds et al. [9] demonstrate that a private EV can increase household self-consumption by up to 50% simply by modifying the charging profile, while Liu et al. conduct a similar analysis for a commercial building, optimizing real-time allocation of EV charging to maximize self-consumption [10]. Other studies have highlighted the technical and economic implications of integrating EV charging infrastructure within RECs. Velkovski et al. analyze the necessity of reducing network charges to achieve significant increases in shared energy [11], while Abdullahi et al. emphasize the importance of strategic planning for EV charging station locations to support the growth of electric mobility, noting the increased number of constraints that must be considered [12].

The flexibility of EV loads is another key feature for smart networks. Dong et al. [13], analyzing a taxi fleet, show that an optimized REC management system can ensure a temporally and spatially balanced utilization of charging stations. Casalicchio et al. demonstrate that, within a heterogeneous energy community, introducing 20% flexible load can reduce the requirement for PV production by 13% and the need for storage systems by more than 90% [14]. Furthermore, Ahmed et al. , using a charging monitoring portal, determine the maximum number of EVs that can be charged at any given time according to energy availability, thereby increasing the proportion of shared energy within the community [15].

The work of Blasuttigh et al., which examines a REC in Milan, is notable for being among the earliest to model the integration of EV charging systems more comprehensively than previous literature [16]. Their work demonstrates how the presence of charging hubs can significantly affect PV system design and investment payback periods.

Building on previous work by the authors [17] about the impact of the energy community composition also in terms of position of production plants, this paper seeks to provide best practice recommendations for the introduction of electric vehicle charging infrastructure in a Renewable Energy Community.

The main objective of this research can be summarized as follows:

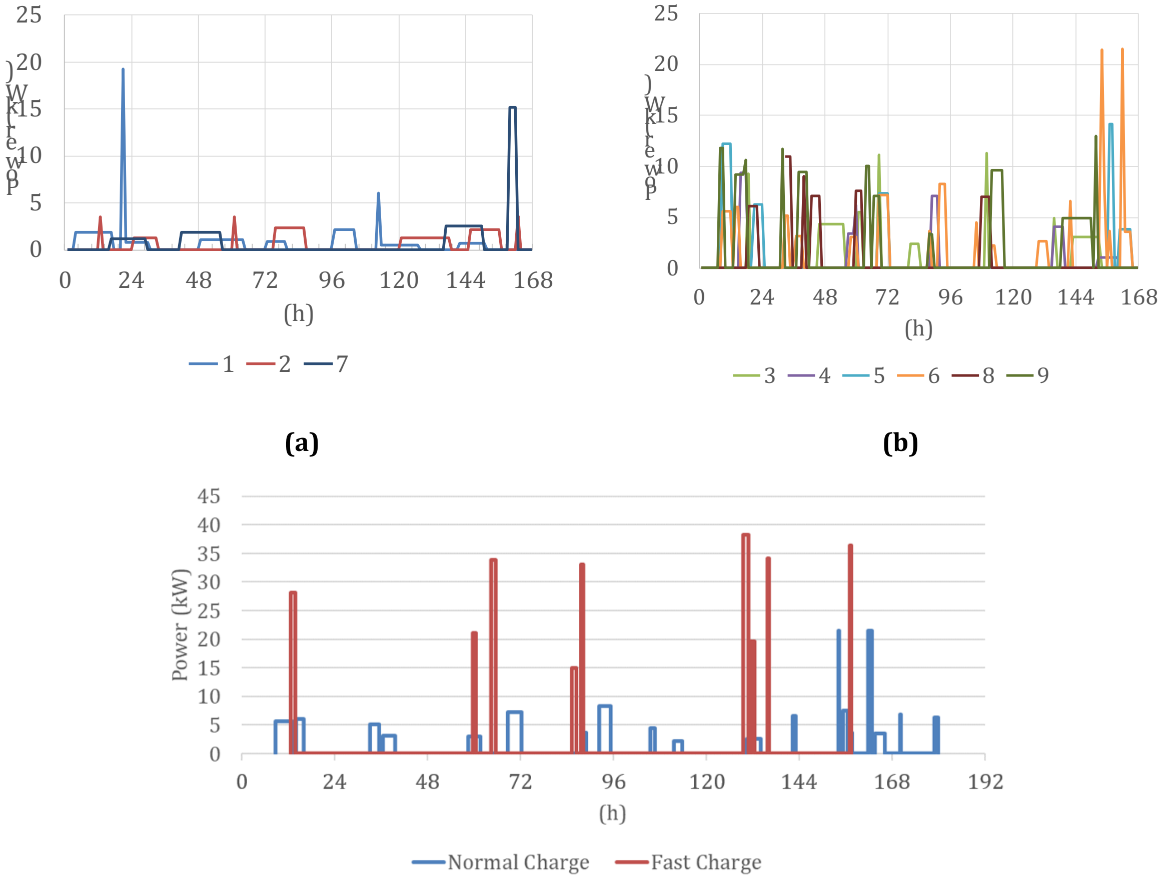
- Evaluates the shared energy and self-sustainability of different configurations of EV charging station within Renewable Energy Communities.
- Exploring the relationship between electric vehicle, charging infrastructure and the operational performance of Renewable Energy Communities.
- Provide evidence how different configurations of EV charging stations affect the Renewable Energy Communities energy balance and sharing.

2. Simulation model

The paper proposes the analysis of a REC configuration that includes an EV charging infrastructure. A MATLAB model has been developed to enable the evaluation of energy flows, self-consumption rates, and grid interaction of each user inside the REC. Details about the algorithm are provided in [17]. Following the details about the simulation of the EV charging system

From a modeling perspective, electric vehicle stations can be conceptualized as a unique category of energy consumers with intermittent and variable load profiles. These profiles are defined by sporadic activation and deactivation of charging sessions and can significantly impact grid stability, especially considering the wide range of power output capabilities of different charging technologies. The charging infrastructure can be further classified based on technological and operational attributes. Specifically, charging stations can operate using Direct Current (DC) or Alternating Current (AC), and their power ratings can vary substantially. Furthermore, a distinction exists between private (e.g., residential wall boxes) and public charging stations, each displaying distinct patterns of use and grid interaction. In the contemporary Italian context, the charging station network has not yet reached saturation; nevertheless, a rapid escalation in EV adoption is anticipated. As of 2024, Italy’s vehicle fleet includes approximately 280,000 Battery Electric Vehicles (BEVs), 288,000 Plug-in Hybrid Electric Vehicles (PHEVs), and 2.7 million Mild-Hybrid Electric Vehicles (MHEVs) [18]. Market analysis indicates that most BEVs sold in Italy support a maximum AC charging power of 11 kW, typically requiring 4 to 6 hours for a full charge [19]. In contrast, ultra-fast charging—primarily DC—can complete a full session in under one hour. PHEVs generally offer a lower maximum AC charging power of 3.7 kW, with full charging times of approximately 3 to 4 hours.

To further analyze consumption patterns; weekly load profiles were collected from nine public charging stations in a province of northern Italy (see Fig. 1). Residential wall boxes were excluded from the analysis due to the difficulty in distinguishing their consumption from overall household electricity demand. The data revealed two primary usage patterns for accelerated charging stations (up to 22 kW): (i) extended charging sessions, resembling private wallbox usage (Fig. 1a), and (ii) shorter sessions, typically lasting 3–4 hours (Fig. 1b). The timing and frequency of charging events varied by location. Fast charging stations (up to 50 kW), as shown in Fig. 1c, generally supported brief, sporadic sessions of about 30 minutes, with between 9 and 19 sessions per week per station. Ultra-fast charging stations (over 50 kW) were not included in this analysis due to insufficient operational data, though it is reasonable to expect their usage patterns to resemble those of fast charging stations.



(a) **(b)**

(c)

Figure 1. One week demand load collected from several charging station in northern Italy.

The principal parameters used to characterize EV charging systems in the model are as follows:

- Type: differentiates wallbox, accelerated, fast, and ultra-fast charging, which determines AC/DC operation and maximum available power.
- Location: the installation site influences the likelihood of station use at different times of day.
- Saturation: probability of station being busy at various times of the day. It is based on the ratio of electric vehicles to available charging stations.

Consequently, charging stations constitute a specialized consumer category, exhibiting variable grid withdrawal patterns contingent on user demand. In light of the impracticality of simulating the behavior of thousands of individual users, the model employs representative consumption profiles. These profiles are designed to capture the influence of identified parameters. Specifically, the probability of charging activity is related to the land use of the location (urban/commercial center, residential or industrial). The probability of utilization for each area is illustrated in the upper graphs as black lines in Figure 2. The scale of 1 to 3 indicates an increasing probability of use. In order to analyze the impact of charging in scenarios involving increasing deployment of electric vehicles, a range of station saturation scenarios have been taken into consideration. In practice, column saturation is estimated by calculating the percentage of hours each time slot is occupied, as shown in Table 1.

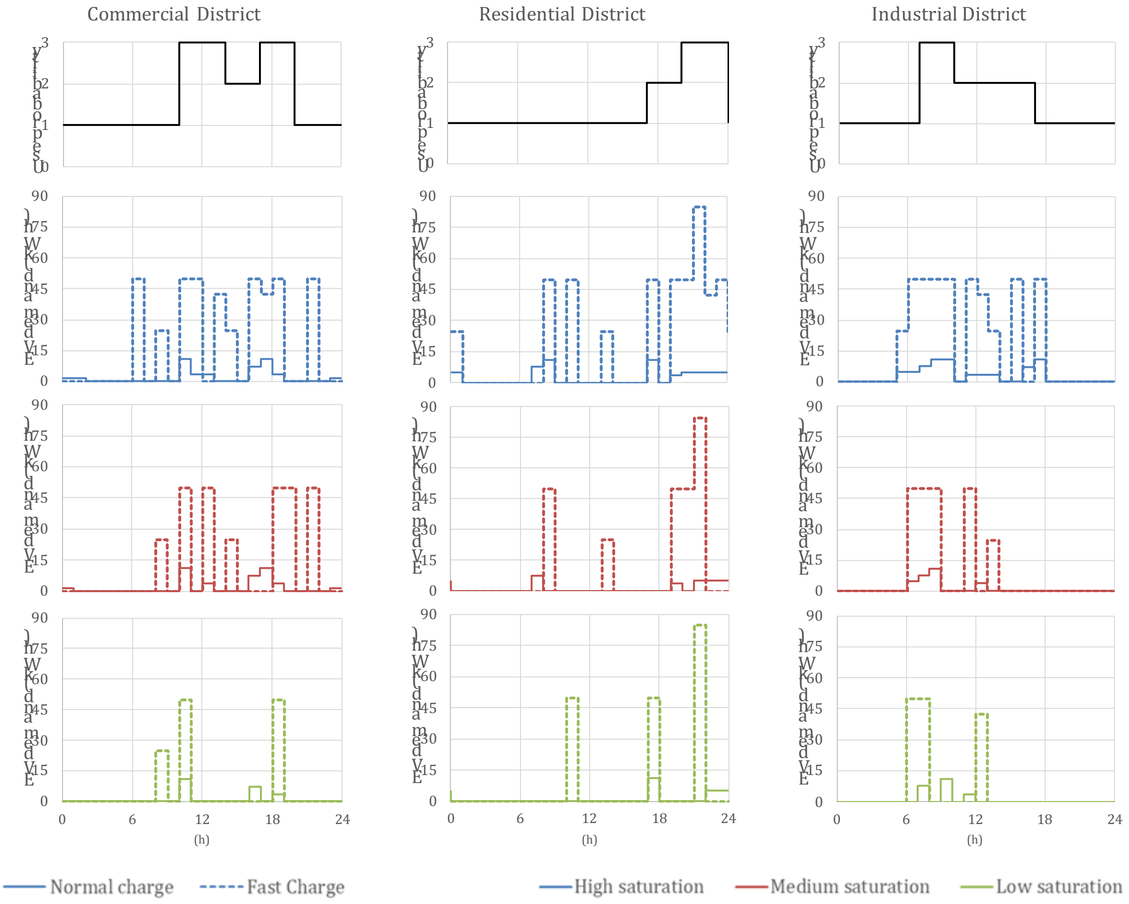


Figure 2. Daily demand profiles generated from the model for charging stations: accelerated (solid lines) and fast (dashed lines) for each district and decreasing level of saturation.

Table 1. Probability of charging device saturation.

Use probability	High saturation	Medium saturation	Low saturation
3 - high	100 %	80 %	60 %
2- medium	50 %	40 %	30 %
1 – low	25 %	20 %	10 %

The adoption of different city districts with different vocations allows for more accurate modeling of the behavior of electric vehicles. The urban commercial district is a space that combines residential and commercial zones. It is designed to facilitate the coexistence of residential dwellings and local commercial establishments. During the day, individuals move between these zones to conduct their errands, with brief periods of stop. At night, these respites are lengthier and more widespread. The residential district is defined as a housing neighborhood where the majority of individuals travel to their workplace during the day, returning in the late afternoon and evening. The charging of electric vehicles is predominantly of a low-level nature, with a consistent occurrence throughout nocturnal hours. The industrial district is distinguished by its daytime operation with high intensity recharge. The model generates the 18 distinct load profiles presented in Figure 2: nine for accelerated charging stations (solid lines) and nine for fast charging stations (dashed lines). Different colors refer to different saturation scenarios. At present, daily and seasonal variations in load are not considered, except in the industrial district, where EV load is set to zero on weekends and holidays.

The calculation of shared energy within the REC, starting from the set of equation provided in [17], is updated to reflect the simultaneity of EV charging demand and PV energy generation. The total community electricity demand is thus adjusted to include charging station consumption, with the updated equations provided in Eqs. 1–3.

$$E_{shared}(i) = \min\left(\sum_{k=1}^{N_{pros}} \min\left(0, PV_{prod_k}(i) - E_{load_k}(i)\right), \sum_{k=1}^{N_{cons}} E_{load\ res_k}(i) + E_{load_{EV}}\right) \qquad \text{(Eq. 1)}$$

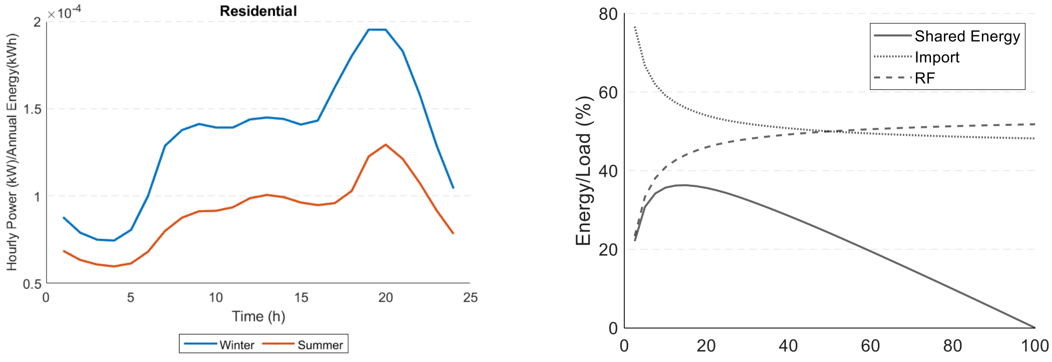
$$Import\ (i) = \min\left(0, \sum_{k=1}^{N_{cons}} E_{load\ res_k}(i) + E_{load_{EV}} - \sum_{k=1}^{N_{pros}} \min\left(0, PV_{prod_k}(i) - E_{load_k}(i)\right)\right) \qquad \text{(Eq. 2)}$$

$$Energy\ sharing = \sum_{i=1}^{8760} \left(\frac{E_{shared}(i)}{\sum_{k=1}^{N_{cons}} E_{load_k}(i) + E_{load_{EV}}}\right) \qquad \text{(Eq. 3)}$$

The shared energy E_{shared} is evaluated (Eq. 1) as the minimum between production from prosumer (N_{pros}) and consumption from consumer (N_{cons}) including the electric load required from the EV charging station ($E_{load_{EV}}$). Import evaluation (Eq.2) includes the amount of energy required from EV charging station and not provided from the prosumer with the installed PV capacity (PV_{prod_k}). Additionally, the $Energy\ sharing$ (Eq. 3) represents the total amount of energy shared within the community, including that from charging stations, compared to the total load from consumers and vehicles. This last parameter, together with the import amount, enables the quantification of the REC's self-sufficiency due to sharing. It also allows for the comparison of different scenarios with varying levels of electric load.

2.1 Case studies

Based on the results of previous research, the impact of different configurations of the EV charging hub has been considered for a REC with a total annual demand of 500 MWh/year. Figure 3 shows the daily demand considered for a typical residential REC (Fig. 3a) and the configuration's performance (Fig. 3b) with different prosumer-to-total user ratios.



(a) **(b)**

Figure 3. Daily demand the REC (a) and REC performance in a configuration without EV (b).

For the reference scenario in particular, self-sustainability (RF), defined as the ratio of renewable energy provided and used by the REC to the REC electric load, is shown by the dashed line. Shared energy and imports are shown by the solid and dotted lines, respectively. Further details about the considered REC configuration and performance are provided in [17]. A single PV size of 20 kW is considered in the analysis and a greater number of prosumer correspond to a greater installed capacity supporting the REC. It is important to point out that the configuration of users, with the exception of EV stations, remains unchanged for all the analysis.

The analysis first compares the location in different districts for an increasing number of stations (1, 5 and 10 stations) and then studies the interference between different sites of installation. Figure 4 illustrates the annual demand for a single charging point, contingent on its geographical location and the saturation level under consideration. It is imperative to acknowledge that each charging point incorporates both an accelerated and an ultra-rapid connection.

Given the high demand (e.g., the "high saturation" in the commercial district shows a demand of about 250 MWh for each charging column), it is reasonable to expect a high impact on community energy performance for some configuration, compared to the demand of other users in the REC of 500 MWh. Finally, the annual energy demand of each case study is reported in Table 2.

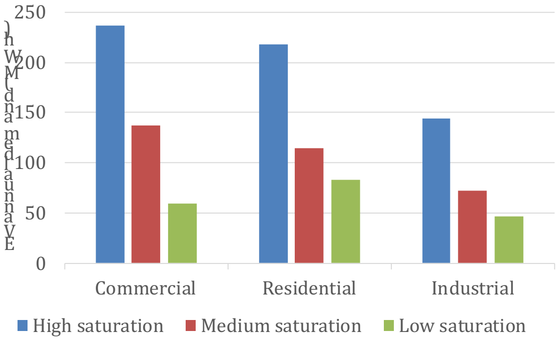


Figure 4. Annual demand of each charging station for different installation sites and different saturation scenarios.

Table 2. Annual demand of each configuration (MWh).

	No EV	Commercial district			Residential district			Industrial district			Mix
N° points	0	1	5	10	1	5	10	1	5	10	10
High sat	500	736	1681	2862	718	1588	2676	644	1218	1936	2471
Medium sat		637	1184	1867	615	1074	1648	572	858	1217	1567
Low sat		559	797	1094	583	914	1327	546	731	962	1122

3. Results and comments

The paper focus on the evaluation of the advantages in terms of shared energy and self-sustainability of different configurations of EV charging station within a REC. The results for the considered case studies are shown with a solid line for shared energy and a dashed line for import. The colors refer to the different EV station saturations, as shown in Fig. 2, and to the reference REC without EVs in gray. It is worth noting that each scenario (no EV and different saturation levels) referee to different levels of demand according to the Eq 1-3 and the value presented in Table 2.

A general trend is observable in the plots of Figure 5. In particular, when considering only one EV charging point, the trend of shared energy is primarily driven by sharing between users without EVs. An increasing ratio of prosumers leads to a reduction in shared energy, as a greater portion of the load is self-consumed. Furthermore, given that import is the negative of the renewable fraction, the asymptotic trend suggests that exceeding the number of prosumers is not conducive to increasing renewable penetration.

The exclusive focus on the commercial district with a single charging station has been demonstrated to enhance energy sharing within the Renewable Energy Community (REC) and to reduce reliance on external energy imports, thereby increasing the community's self-sufficiency. As the number of charging stations increases, a notable benefit of "lower saturation" emerges, particularly when the installed capacity remains below 300 kW or 500 kW. This corresponds to 15% and 25% prosumer participation with five and ten stations, respectively. However, the implementation of a centralized charging hub has been shown to decrease the proportion of shared energy and increase energy imports. This phenomenon is attributable to elevated demand levels that are not matched by available photovoltaic (PV) generation. Furthermore, lower saturation levels indicate a distinct point of maximum operational convenience, while higher saturation becomes more advantageous as the number of prosumers rises. The underlying reason for this phenomenon is that heightened saturation has been demonstrated to augment demand during periods of PV generation, thereby facilitating the optimization of self-consumption.

Conversely, the residential district exhibits a distinctly divergent pattern, with the majority of its energy demand occurring outside of PV production periods. Across all examined configurations, the REC's energy imports have increased, while a higher shared energy ratio has only been achieved with greater PV deployment. A salient feature of the residential sector is its distinctiveness in demonstrating comparatively superior performance at lower saturation levels, although the shared energy ratio persists at a consistently below 30% level.

The industrial district displays a trend analogous to that observed in the commercial sector. An increase in the number of prosumers shifts the point of optimal convenience from scenarios without electric vehicles (EVs) to those with five or ten charging stations. However, the import ratio generally exhibits an upward trend with the introduction of EV infrastructure, with the exception of certain scenarios characterized by high saturation. This outcome is particularly noteworthy for two reasons. First, despite lower annual demand per charging station, the hourly demand profile necessitates a higher proportion of imported energy due to the temporal mismatch with PV generation.

Finally, Figure 6 illustrates the interaction effects when ten charging stations are distributed uniformly across the analyzed district. In comparison with the single-station scenario, the residential load profile exerts a significant influence on the proportion of imported energy. Achieving a reduction in grid imports relative to the no-EV baseline is only possible under certain conditions. Specifically, these conditions include higher prosumer penetration rates combined with lower saturation levels. The proportion of shared energy reaches a level that appears to represent an effective balance across the different districts, with a maximum slightly exceeding 40%. This outcome does not significantly deviate from the optimal sharing scenario without EV integration; rather, it reflects a shift toward greater prosumer participation. A correlation has been observed between limited numbers of prosumers and increased shared energy ratios. However, as the prosumer population increases to intermediate levels, average saturation becomes less effective. In such instances, the shared energy fraction invariably attains its minimum, while grid imports reach their maximum. This phenomenon signifies an unfavorable trade-off between saturation and energy sharing efficiency.

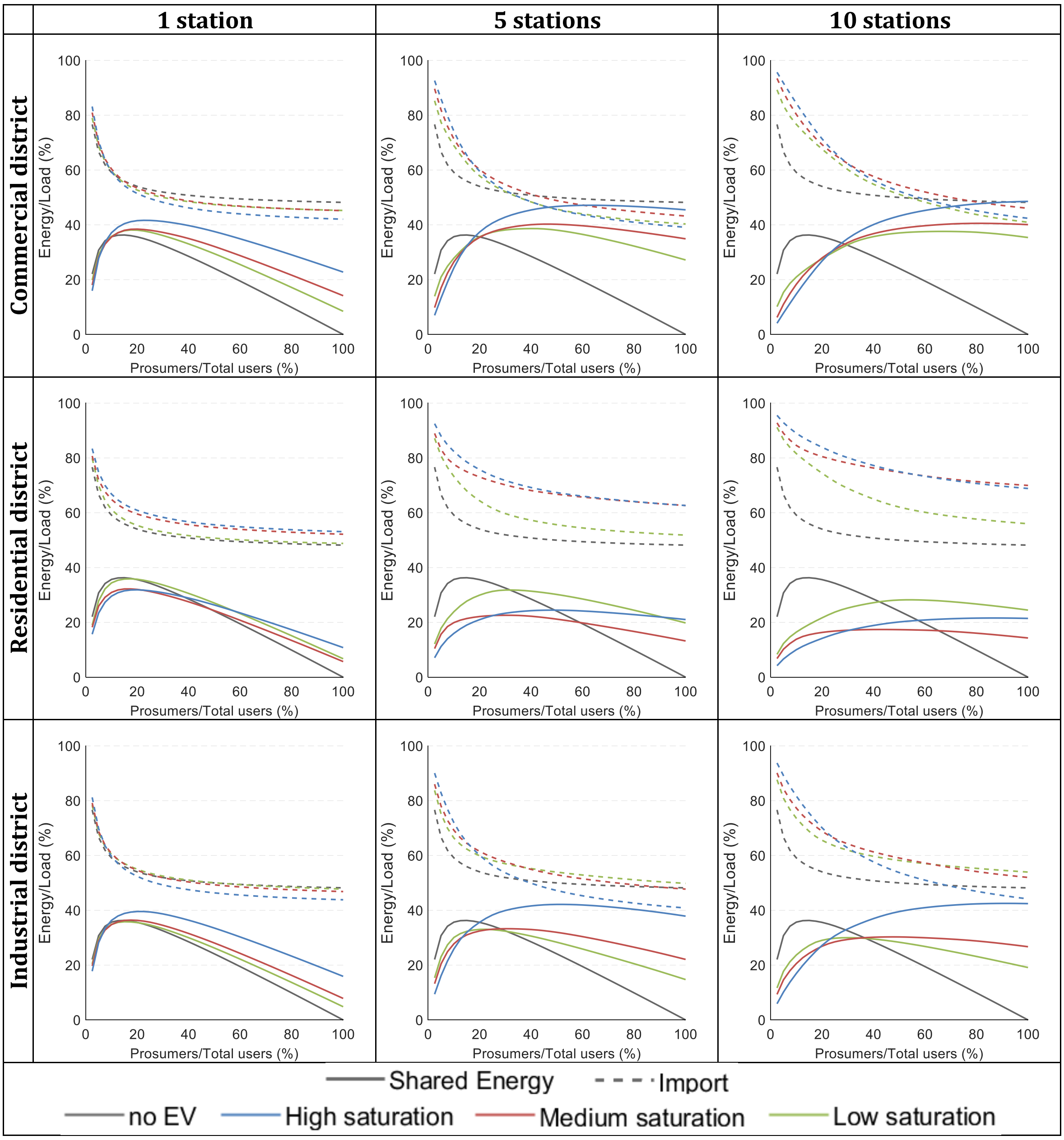


Figure 5. Results in terms of shared energy and import levels for different locations, level of saturations and number of stations.

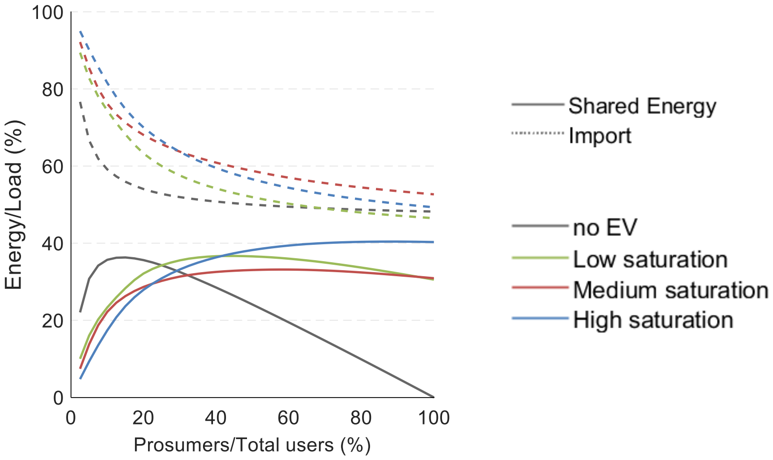


Figure 6. REC performance for a configuration with EV charging hub distributed across different districts.

4. Conclusions

This study has explored the relationship between electric vehicle (EV) charging infrastructure and the operational performance of Renewable Energy Communities (RECs), with a particular focus on energy sharing, self-sufficiency, and grid interaction. The development and implementation of a comprehensive simulation model have yielded novel insights into the impact of varying configurations of EV charging stations on the energy dynamics within RECs. These configurations encompass a range of parameters, including the number, location, and saturation of the stations.

The findings underscore that the incorporation of electric vehicle (EV) charging stations engenders considerable variability in community energy flows, with outcomes exhibiting a high degree of dependence on the spatial distribution of chargers and the temporal synchronization of charging sessions with renewable energy generation. In commercial and industrial districts, the strategic placement and moderate saturation of charging infrastructure can enhance shared energy and reduce grid imports, especially when charging demand coincides with periods of photovoltaic (PV) generation. Conversely, in residential districts, where load profiles are less synchronized with PV output, higher imports and lower shared energy ratios are observed. This emphasizes the importance of tailored infrastructure planning for different land-use contexts.

The study's results indicate that while the integration of EV charging infrastructure entails challenges, such as elevated demand peaks and the possibility of increased grid reliance, it offers significant prospects for enhancing community-level sustainability and energy autonomy through optimized planning.

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