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Smart Energy community for electric vehicles recharge in a building environment

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ABSTRACT

Electric mobility can reduce energy consumption and polluting emissions and is one of the key elements of the current energy transition. Electric vehicles take over is hampered by different problems, above all the scarce diffusion of adequate recharging infrastructures. The objective of this paper is to design a smart system for the shared charging of electric vehicles. Such system minimizes the necessity of additional infrastructure by valorizing the electricity not used by a residential building. The effectiveness of such a system has been demonstrated in two realistic scenarios with a building consisting of 3 apartments and an elevator, a photovoltaic system, and up to 4 electric vehicles.

Keywords: intelligent energy systems, electric vehicles, optimized recharge system, energy community, building energy consumption

1. INTRODUCTION

The global energy consumption increases over 2% per year [1] impacting on the environmental integrity [2]. Therefore, numerous nations are trying to promote energy saving through different actions as a part of important structural changes in the global energy sector [3], better known as energy transition. This process aims to mitigate energy consumption and reduce the emission of greenhouse gases and pollutants through several technological alternatives, such as: i) incrementing the renewable energy penetration (photovoltaic systems, wind turbine etc.) [4, 5, 6]; ii) improving the buildings efficiency [7]; iii) developing and diffusing electric mobility [8]; iv) growing of smart grids [8].

Electric mobility has crossed a critical threshold and leverages on several increasingly important issues: carbon constraints, high oil prices, rise of organized car-sharing, and intermodality [9]. However, there are still several shortcomings that slow down Electric Vehicles (EVs) diffusion: high purchase and battery cost [10], uncertain battery life, limited battery range, “range anxiety” also due to limited capillarity of recharging infrastructures [9, 11], and long charging times.

The limited diffusion of recharging infrastructures is one of the major problems that hinders the growth of electric mobility [9]. Moreover, a wider penetration of EVs could generate problems on the grid such as phase imbalances, energy quality reductions, and overloading of transformers and lines [12, 13]. This study fits into this complicated context. We develop a condominium system for shared recharging of EVs implementing a charging logic and a pricing policy aimed at the intelligent use of the available energy and existing infrastructure.

2. METHODOLOGY

Figure 1 represents the scheme of the proposed system highlighting all energy and data flows. The main components are: i) The PhotoVoltaic system (PV), ii) the Residential Building (RB), iii) the Recharge-Dedicated

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Electric Line (RDEL), iv) the Recharging System (RS), and v) the EVs.

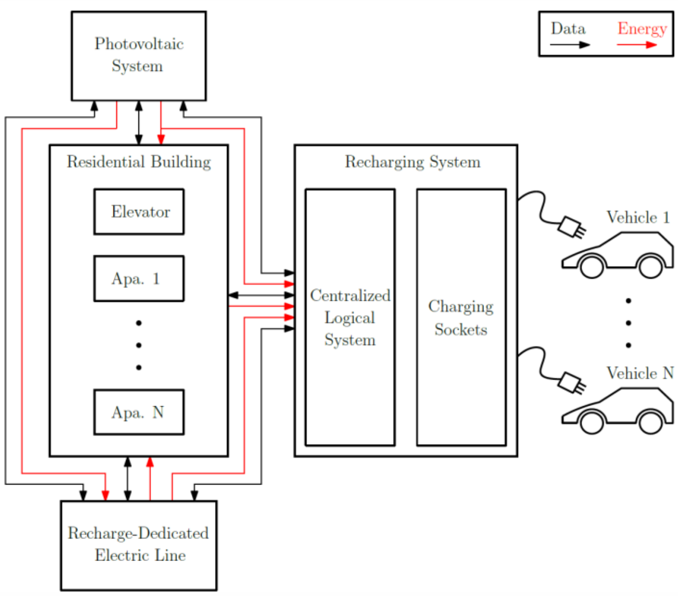

Figure 1: Scheme of the main elements of the plant.

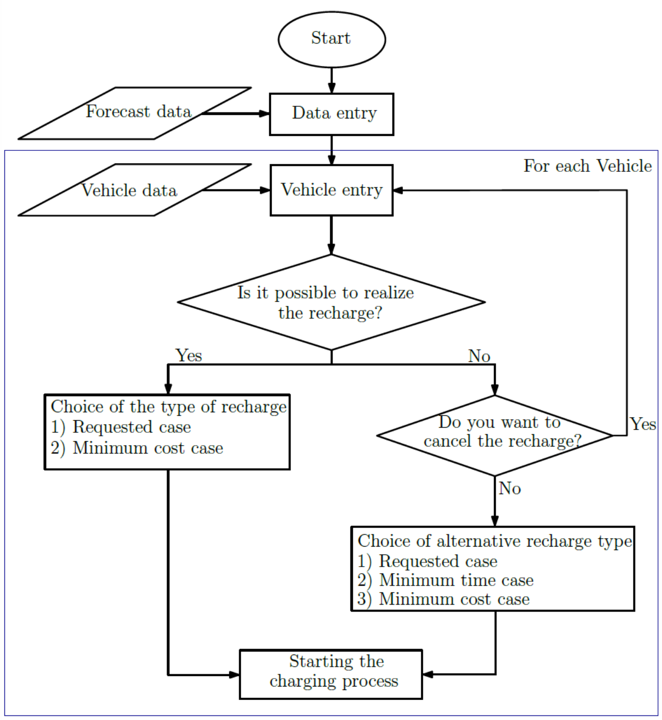

Figure 2: Logical structure of the RS for the recharge schedule choice.

The RS optimally manages three different energy sources following this priority order for the recharge: i) the PV, ii) the RB, and iii) the RDEL. The PV energy is primarily used to satisfy the demand of the apartments. The energy surplus can be used to recharge EVs. Each of the apartments composing the RB has an installed 3 kW electric line. Similarly, the elevator has 6 kW of installed power. However, the energy load of the apartments and of the elevator is variable and often lower than the installed power. Therefore, the unused power is a source of energy for EVs recharge that does not require an additional investment in infrastructure. Finally, the RDEL takes over when the energy that can be withdrawn from the PV and from RB is not sufficient to meet the defined charging process. The centralized recharging system manages the continuous exchange of data and energy between the components of the plant.

Once an EV is connected, the RS estimates the recharge dynamics following the logic shown in Figure 2 and considering the eventual presence of other EVs already in charge. To this aim, the RS uses forecasted energy loads of the building, and PV production profiles on a 15-minutes base. The user provides several data of the EV: i) the model, ii) the initial and required final State Of Charge (SOC), and iii) the time by which the recharge process has to finish. Based on these data, the RS informs the user if it is possible or not to complete the required charging process. In case of feasible recharge schedule, the RS provides the possibility to choose an alternative process that minimizes the cost by extending the recharge time. For both the alternatives the recharge system forecasts the recharge cost. If instead the required recharge schedule is infeasible, the user can choose whether to cancel the operation or adopt one of the following: i) ending the recharge process at the established time without reaching the required SOC, ii) meeting the required SOC in the minimum possible time, and iii) meeting the required SOC with the minimum possible cost. The forecast of the recharge cost depends on the power required and assumes that the energy has a different cost based on the source from which it is taken, as can be seen in Table 1. Such pricing policy aims to administrate the energy demand responsibly, by discouraging the RDEL use.

Table 1: Cost of energy based on the source.

Source	$€/kWh$
Photovoltaic system	0.06
Residential Building	0.18
Recharge-Dedicated Electric Line	0.25

Specifically, the forecast cost of the EV recharge for a quarter of an hour C_Q is defined as follows:

$$C_Q = X(C_{PV} + C_{RB} + C_{RDEL}), \qquad 1$$

where X is a multiplicative factor that ranges between 1 and 2, C_{PV} is the cost of the energy taken from the PV, C_{RB} is the cost of energy taken from RB, and C_{RDEL} is the cost of energy taken from the RDEL. Considering E_w as the total energy that can be withdrawn from the charging system, E_d as the energy drawn, and α a parameter dependent on the number of EVs, the definition of X is:

$$\begin{cases} X = 1 \text{ if } E_d \leq \dfrac{E_w}{\alpha} \\ 1 < X < 2 \text{ if } E_d > \dfrac{E_w}{\alpha}. \\ X = 2 \text{ if } E_d = E_w \end{cases} \qquad 2$$

The factor X is directly proportional to the energy drawn and aims at discouraging excessively fast recharges for which it is necessary to use a large part of the available energy. In fact, if all the energy available in a given period of time is used to recharge a single EV then it will not be possible, in the same period of time, to recharge other EVs. Such behavior is inappropriate for a condominium recharge system such as the one considered. Finally, the expected total cost associated with the recharge of a vehicle C_{tot} can be defined as the sum of the forecast costs C_{Qi} relating to all the Q quarters of an hour composing the charging process:

$$C_{tot} = \sum_{i=1}^{Q} C_{Qi}. \qquad 3$$

Once the user chooses the recharge schedule for the EV, the RS starts the charging process and monitors the energy and data flows from the various elements of the system. In this phase, the user can control the progress of the recharge procedure through the SOC and the actual cost of recharging. At the same time, the owner of each apartment can limit in real time the energy flow that goes from his home to the RS. In this case, the energy required for the process is taken from another source, if possible. In the same way, if for any reason the energy supply of one of the sources changes instantly, the system takes the energy required, according to the logic already specified, from the other sources. At the end of every quarter of hour, the RS verifies if the recharge proceeds as expected. If not, the lacking energy is equally distributed and added to the energy required in the remaining quarters of hours. At the end of the process, the system outputs the energy stored in the battery, the SOC, and the actual recharge cost.

3. RESULTS

3.1 System design

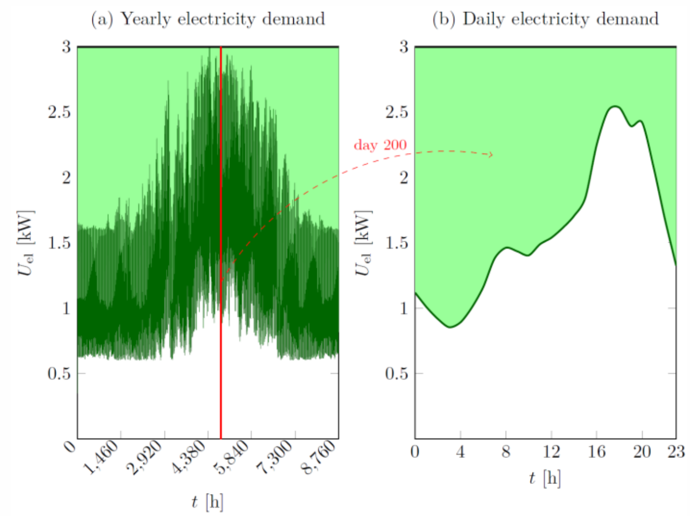

Figure 3: Electric energy load of an average apartment: a) yearly demand, b) demand of day 200. Data from [14].

For the system design we consider the yearly electric energy load of an average apartment with 3 kW of installed power, as reported by the office of Energy Efficiency and Renewable Energy (EERE) in [14]. Figure 3 (a) represents such data, and Figure 3 (b) shows the hourly load on the 200th day of the year. In both plots, the green area represents the energy that, exceeding the apartment load, is available to recharge the vehicles. In detail, the annual energy not used by the apartment and therefore usable for vehicle recharging is 15204 kWh, that is 57.9% of the total. More precisely, the daily available energy for recharge ranges from 23 kWh to 50 kWh. Moreover, in most of the multi-floor buildings there is an elevator. Such system is a discontinuous 6 kW load that activates 5-10 times per hour. Therefore, the elevator can supply to the recharging system approximately 120 kWh per day of unused energy.

Four EV models have shared more than 70% of the European market in 2018 [15]: Nissan Leaf, Renault Zoe, BMW i3, and Volkswagen e-Golf. The battery capacity for these vehicles ranges from 36 kWh to 42 kWh. We select the Nissan Leaf as the reference vehicle for our case studies because it is the most sold. Moreover, terms of battery capacity it is the median of all the bestselling

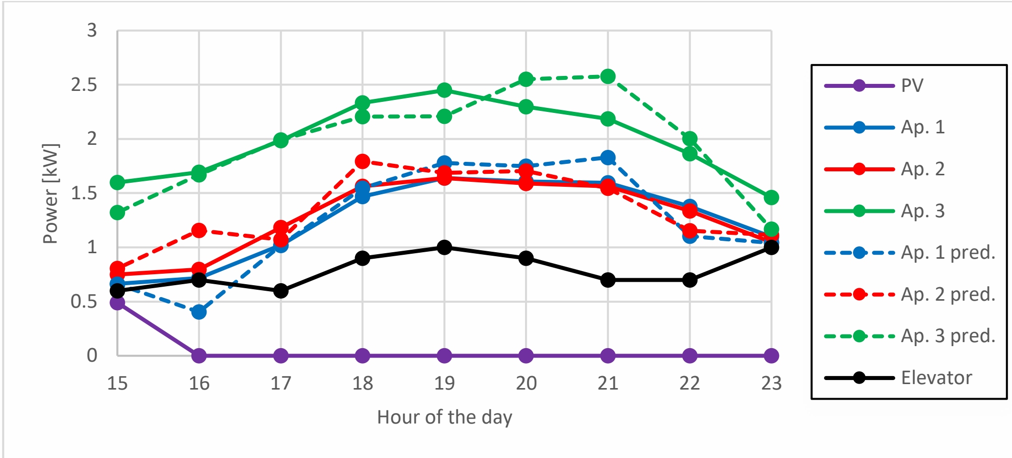

Figure 4: Input data to the recharge system for the realistic scenarios

group (40 kWh). According to the Worldwide Harmonized Light Vehicles Test (WLTP), the Nissan Leaf consumes 20.6 kWh/100 km [16]. Then, considering that the average daily distance travelled in Europe by car is 33 km [17], we find that the average daily energy demand of a Nissan Leaf is 7 kWh. Since the daily available energy for an average apartment is at least 23 kWh from the energy standpoint it is possible to recharge at least one average electric vehicle exploiting the unused installed electrical power. Similar conclusions can be drawn considering the unused power of the elevator (120 kWh).

Therefore, the energy system for our case studies consists of: i) a RB composed of 3 apartments and 1 elevator, ii) up to 4 EVs, iii) the RS, iv) a 10 kW RDEL, and v) a 10 kWp PV. We select such photovoltaic size because it can be easily installed on the roof of an average apartment. In fact, in Europe the average size for a two-person apartment is 85 m^2 [18], while the average photovoltaic power density is higher than 120 $\mathrm{W/m}^2$ [19, 20]. Here, we set the parameter $\alpha = 4$ in equation 2 because we consider 4 EVs.

In the following case studies, we consider the energy loads reported in Figure 4 for three average apartments (one of which is the same reported in Figure 3) from the dataset in [14]. Such data represent the energy consumption for the first day of the year. To generate the forecasted energy loads (also shown in Figure 4) we randomly apply white noise to the real energy loads. In this way, we simulate the inaccuracy of the forecast to prove the recharge system response. Moreover, we generate the photovoltaic production curve in Figure 4 from the PVGIS tool [21], considering the city of Viterbo. Figure 4 also represents the elevator electric load.

3.2 Realistic scenarios

In the first realistic scenario we use the recharge system for 3 EVs with the following schedule: i) enters at 3 PM with 0% initial SOC and requires 80% final SOC by 6 PM, ii) enters at 5 PM with 0% initial SOC and requires 60% final SOC by 8 PM, and iii) enters at 6 PM with 0% initial SOC and requires 60% final SOC with the minimum possible cost. The system completes the recharge for all the three EVs with the required scheduling, completing the request of the third vehicle at 11 PM. The final recharge costs are 7.2€, 5.8€, and 4.6€ respectively. The first EV has the highest recharge cost because it requires more energy than the other vehicles and within 3 hours. The second EV has the same recharge time of the first EV but needs less energy, therefore pays less for recharge. Finally, the third EV has the lowest recharge cost because it requires the same energy of the second EV selecting the most economic recharge profile without time constraints.

In the second realistic scenario we use the recharge system for 4 EVs that all arrive with 0% initial SOC and require 80% final SOC with the following schedule: i) enters at 4:30 PM and exits at 6:30 PM, ii) enters at 5 PM and exits at 8 PM, iii) enters at 5:30 PM and exits at 9 PM, and iv) enters at 6 PM and exits at 10 PM. The system accomplishes all the requests with the following recharge costs in order: i) 9.9€, ii) 11.5€, iii) 12.4€, and iv) 13.2€. The recharge cost monotonically increases with the hour of the day because the apartment energy loads increase (Figure 4), reducing the available energy. Moreover, the logic implemented in the system tends to use as much as possible of the available energy from the PV and from the RB prioritizing the first comers. Therefore, the EV connected later will rely more on energy from the recharge-dedicated electric line, that has higher cost.

4. CONCLUSIONS

The exploitation of unused electric energy in existing buildings can help to mitigate one of the greatest obstacles to electric mobility diffusion, that is the lack of recharging infrastructure. The rationale is that in most buildings the instant required power is often lower than the installed power (usually 3 kW). More unused energy can also come from on-site photovoltaic system. Therefore, in this work we present a building control system for the recharge of electric vehicles. Such a system promotes an energy-responsible recharge through a pricing policy that discourages the use of electric energy not already available in the building (i.e. from a recharge-dedicated electric line).

Results show that a building composed of 3 apartments, a photovoltaic system, and one elevator can manage to recharge at least 4 vehicles (more than one per apartment) daily minimizing the usage of the recharge-dedicated electric line. Moreover, the cost of recharge can be reduced up to 21% for the same energy request just with flexibility on the recharge schedule.

The system could be used to find the optimal size of the recharge-dedicated electric line. Further developments of the study regard the implementation in a real existing building environment, and the extension to other renewable sources and to storage solutions.

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