

Partitioning Algorithm for Integrating Electric Vehicles into Residential Renewable Energy Communities

Manuela Minetti¹, Andrea Bonfiglio¹, Maria Martino¹, Renato Procopio¹

¹ *University of Genoa, Genova*

Abstract – The rapid growth of Electric Vehicles (EVs) and Renewable Energy Communities (RECs) introduces new challenges in energy management and requires innovative solutions for enhancing local self-consumption. This paper introduces a Virtual Partitioning Algorithm (VPA) for the energy storage systems of EVs, aiming to improve EVs integration within RECs. The VPA improves the use of the available EV storage capacity to increase the economic benefits, and the shared energy of a REC equipped with residential photovoltaic systems or other renewable energy sources. The proposed approach is tested on a realistic case study involving a multi-family housing with a shared photovoltaic installation. Results demonstrate the effectiveness of the VPA in increasing overall gains and increasing both self-consumption and environmental sustainability.

Keywords-*Electric Vehicles, Renewable Energy Communities, Vehicle-to-Home.*

I. INTRODUCTION

The spread of electric vehicles (EVs) emerged as a promising solution to reduce pollutant emissions and to ensure a better coupling between energy generation and consumption, mitigating Renewable Energy Sources (RESs) fluctuations [1-3] as well as providing economic advantages. EV can play an important role in ensuring grid stability, in reducing power outage episodes, in increasing global energy efficiency and providing additional grid services [4, 5]. EVs' batteries can be seen as a rolling accumulation system that allows peak reduction, absorbing or providing energy to the grid, as required in each moment. This service is called Vehicle to Grid (V2G) and its variants are Vehicle to Home (V2H) and Vehicle to Building (V2B), all of them being a two-way system that allows energy to be injected from the car into the grid and vice versa [6, 7]. In this context, EVs are identified as active contributors to the energy transition, not only associating EV with mere transportation, but by making them active players in the flexibilization of the electricity system to facilitate RES integration in the grid while still involving the final user.

Focusing on V2H application, the stored energy is at disposal of residential user to be used for final user power plant and building [8]. This is particularly convenient for prosumers with PV installations that can use the EV battery to store excess PV production during peak hours that will later feed domestic electricity demand [9-11]. As reported in [12], this strategy is beneficial both for the prosumer's self-consumption and for the resilience of electric distribution grid with high penetration of RES. In this context, a great portion of the research body on V2H has focused on developing optimization strategies to integrate EV into the building's energy system to reduce the electricity supply cost [13, 14].

Notably, recent studies have investigated the inclusion of EVs in Renewable Energy Communities (REC)[15, 16], as in [17] that proposes an optimization model with benefits descending from integrating external EV owners into an energy community. An optimal energy management strategy for a local energy community composed of DC microgrids with electric vehicle charging stations is presented [18]. The impact of EV charging stations on the electrical load of smart buildings, with a particular focus on energy communities is analysed in [19].

To the best of the authors' knowledge, the research body on V2H technology has primarily focused on the combination between EV ST and traditional renewable energy production systems, investigating energy-related aspects and developing management algorithms and optimized charging strategies for multi-energy systems in buildings, addressing primarily cost optimization for different daily scenarios. These studies present the EV battery as a single unit, without involving the end user in its management. Therefore, the following literature gaps have been highlighted:

- Lack of applicability of the algorithms for both single-family homes and residential REC.
- The insufficient attention to the users' willingness to participate in the services
- No possibility to dedicate an a priori portion of EV energy for V2H service.

Building on this, the aim of the article is to define an algorithm based on the creation of virtual partitions of an electric vehicle (EV) battery, allowing a user-defined

allocation of available energy for V2H services and support to the Renewable Energy Community (REC), while the remaining energy is fully reserved for user mobility. Specifically, the article applies the Virtual Partitioning Algorithm (VPA) strategy for EV battery management within a realistic residential energy community. In this context, it is highlighted that the effective implementation of virtual partitioning of EV batteries for V2H services within a REC depends on accurate measurements and reliable digital infrastructure, as detailed in [20, 21].

The paper is structured as follows: in Section II, the proposed VPA is generalized for a REC. Section III describes the study case and Section IV provides the simulation results of VPA application in a residential, multi-family housing with shared PV. Finally, some conclusive remarks are included in Section V.

II. VIRTUAL PARTITIONING ALGORITHM

The idea behind the VPA is to create a virtual partition of the physical storage capacity so that each portion can be dedicated to different purposes, specifically for mobility and to provide V2H service and support to the REC.

The EV State of Charge SOC_{EVT} at time t can be expressed as the ratio of the actual energy E_{EVT} to the total EV battery $E_{EVT,max}$, in percentage. SOC_{EVT} evolves according to the following equation:

$$SOC_{EVT}(t) = SOC_{EVT,0} + \int_0^t \tilde{P}_{EV}(\tau) d\tau \quad (1)$$

Where P_{EV} is the power of the EV charging station in kW and $SOC_{EVT,0}$ the initial SOC of the EV. From (1) on, power is expressed in the passive sign convention (positive power for charging and vice versa).

Within the VPA the percentage of the EV battery energy to dedicate to V2H services can be defined by the user and is indicated with the coefficient $\varepsilon_{V2H} \in [0,1]$. Therefore, the partial virtual capacities of the EV battery for V2H service $\tilde{E}_{V2H,max}$ and actual mobility $\tilde{E}_{EV1,max}$ can be expressed as:

$$\begin{cases} \tilde{E}_{V2H,max} = \varepsilon_{V2H} E_{EVT,max} \\ \tilde{E}_{EV1,max} = (1 - \varepsilon_{V2H}) E_{EVT,max} \end{cases} \quad (2)$$

Hereafter, quantities marked with a tilde will represent virtual values, to differentiate them from physical counterparts. The two virtual SOC can, thus, be defined considering $\tilde{E}_{V2H}$ and $\tilde{E}_{EV1}$, referring to the virtual energy allocated to the two respective partitions expressed in kWh, and the maximum values $\tilde{E}_{V2H,max}$ and $\tilde{E}_{EV,max}$. The virtual power signals associated with the EV mobility $\tilde{P}_{EV1}$ and to the V2H service $\tilde{P}_{V2H}$ that charge or discharge each virtual partition must comply with the actual power of the physical charging station P_{EV} all expressed in kW:

$$P_{EV}(t) = \tilde{P}_{EV1}(t) + \tilde{P}_{V2H}(t) \quad (3)$$

The maximum power assigned to charge the mobility virtual partition ($\tilde{P}_{EV1,max}$) can be configured by the owner based on their charging needs, following the standard procedure used in state-of-the-art EV, where this is typically managed through the vehicle-to-human interface. The value must remain below the maximum power capacity of the charging infrastructure $P_{EV,max}$ to ensure sufficient margin for V2H services. The user's choice directly affects the power reserved to the V2H service. The virtual powers of the VPA are linked to their corresponding virtual SOC dynamics as follows:

$$\begin{cases} SOC_{EV1}(t) = SOC_{EV1,0} + \int_0^t \tilde{P}_{EV1}(\tau) d\tau \\ SOC_{V2H}(t) = SOC_{V2H,0} + \int_0^t \tilde{P}_{V2H}(\tau) d\tau \end{cases} \quad (4)$$

with $SOC_{EV1,0}$ and $SOC_{V2H,0}$ indicating the initial SOC of the virtual partitions which are proportional to EV initial SOC $SOC_{EVT,0}$.

Typically, $\tilde{P}_{EV1}$ is assigned the maximum value defined by the user, as long as it aligns with the current SOC of the respective virtual partition, regarding this virtual partition, it only can charge (i.e. the power can only be positive or null), therefore:

$$\tilde{P}_{EV1}(t) = \begin{cases} 0 & \text{if } SOC_{EV1}(t) = 100\% \\ \tilde{P}_{EV1,max} & \text{elsewhere} \end{cases} \quad (5)$$

the value of $\tilde{P}_{V2H}$ is subject to V2H needs. Let $\tilde{P}_{V2H}^*$ be the V2H partition power request, the actual power is linked to the relative SOC from the relations:

$$\tilde{P}_{V2H}(t) = \begin{cases} 0 & \text{if } (\tilde{P}_{V2H}^*(t) > 0 \text{ and } SOC_{V2H}(t) = 100\%) \\ 0 & \text{if } (\tilde{P}_{V2H}^*(t) < 0 \text{ and } SOC_{V2H}(t) = 0\%) \\ \tilde{P}_{V2H}^*(t) & \text{elsewhere} \end{cases} \quad (6)$$

Finally, the physical power of the EV, to which the two partitions are related must satisfy the CI bound:

$$|P_{EV}(t)| \leq P_{EV,max} \quad (7)$$

When violating (7) the V2H power request is curtailed so not to interfere with the EV charging need, which has priority between the two virtual partitions. Therefore, if the battery power limit is exceeded, the $\tilde{P}_{V2H}$ contribution is curtailed according to:

$$\begin{cases} \tilde{P}_{V2H}(t) = P_{EV,max} - \tilde{P}_{EV1}(t) & \text{if } \tilde{P}_{V2H}^*(t) > 0 \\ \tilde{P}_{V2H}(t) = -P_{EV,max} - \tilde{P}_{EV1}(t) & \text{if } \tilde{P}_{V2H}^*(t) < 0 \end{cases} \quad (8)$$

A. Virtual partitioning for a residential REC

This paper proposes the implementation of the VPA in the context of a REC consisting of a multi-user residential building with N apartments and a common PV system, as illustrated in the schematic of Fig. 1.

For this scenario it is considered that every residential unit has a EV, to which VPA is applied individually. The methodology remains applicable even when only a portion of the residents have EVs, with no impact on its general validity. In this case the VPA is used to maximize the REC revenue, generated by Shared Energy (SE), defined as the minimum between total energy production and total energy consumption, on an hourly basis [22].

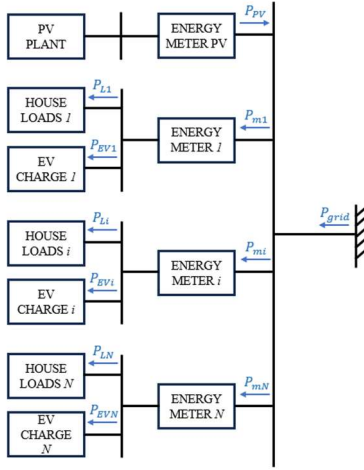


Fig. 1. Layout and power convention of the considered multi-family residential building.

The SE in the generic time interval Δt can therefore be calculated for the test case as:

$$SE(t) = \min \left(P_{PV}(t), \sum_{i=1}^N P_{mi}(t) \right) \cdot \Delta t \quad (9)$$

When deploying VPA for a REC, a centralized management system that collects N units' measurements performs the definition of the V2H set points. Therefore, relations (1)-(8) take subscript i (from 1 to N) for the i -th user.

For the i -th residential unit, the overall consumption profile is expressed by:

$$P_{Ltoti}(t) = P_{Li}(t) + \tilde{P}_{EV1i}(t) \quad (10)$$

With P_{Li} and $\tilde{P}_{EV1i}$ representing the load profile and the EV charging profile of the i -th residential unit, respectively. This represents the user power demand without the V2H partition, which is accounted for in the total measured power P_{mi} :

$$P_{mi}(t) = P_{Li}(t) + \tilde{P}_{EV1i}(t) + \tilde{P}_{V2Hi}(t) \quad (11)$$

The deviation from perfect SE is represented by ΔP_{SE} :

$$\Delta P_{SE}(t) = P_{PV}(t) - \sum_{i=1}^N P_{Ltoti}(t) \geq 0 \quad (12)$$

The following operating conditions (mutually exclusive) dictate the functionality of the V2H:

- (i) When there is null PV production, SE is null, the set point $\tilde{P}_{V2Hi}^*$ can be calculated independently from

SE maximization as:

$$\tilde{P}_{V2Hi}^*(t) = -P_{Li}(t) - \tilde{P}_{EV1i}(t) \quad (13)$$

- (ii) With non null P_{PV} and positive (12) there is an amount of PV production that exceeds the load demand, which leads to SE not being maximized. Accordingly, to increase SE, the V2H should ensure that each EV absorbs power proportionally to its maximum available power allocated for the V2H service.

$$\tilde{P}_{V2Hi}^*(t) = \frac{P_{EV,maxi} - \tilde{P}_{EV1i}(t)}{\sum_{i=1}^N (P_{EV,maxi} - \tilde{P}_{EV1i}(t))} \Delta P_{share}(t) \quad (14)$$

The power requested in (14) for V2H is positive, coherently with the sign convention adopted for the EV charging station, there is a need for power absorption.

- (iii) With non null P_{PV} and negative (12), SE is maximized, but there is an excess of load demand. In this case, V2H service implies that all users should limit their power absorption, with the sum of all contributions not exceeding ΔP_{SE} to stick to maximum SE. Accordingly, the V2H contribution of the i -th unit is calculated as follows:

$$\tilde{P}_{V2Hi}^*(t) = \max \left(\frac{-P_{EV,max} - \tilde{P}_{EV1}(t)}{\sum_{i=1}^N (-P_{EV,max} - \tilde{P}_{EV1}(t))} \Delta P_{share}, -P_{Li}(t) - \tilde{P}_{EV1i}(t) \right) \quad (15)$$

The power requested in (15) for V2H is negative, coherently with the sign convention adopted for the EV CI, there is a need of power production.

- (iv) With non null P_{PV} and null (12) SE is maximized and V2H is not requested, setting:

$$\tilde{P}_{V2Hi}^*(t) = 0 \quad (16)$$

In all the four cases described, the V2H power request must be limited to (8) whenever (7) is not satisfied.

III. CASE STUDY

The VPA performance is tested in the context of V2H service provision within a multi-family residence organized as a REC. Specifically, the setup involves a three-unit apartment operating as a REC, powered by a 13.8 kW peak photovoltaic installation on the rooftop. Each apartment includes a 6 kW bi-directional charging station and an EV featuring a 45 kWh battery.

Fig. 1 reports loads and PV production for the analysed week. Both the load and PV production profiles are based on real-world data collected from three separate households located in northern Italy.

The connection of the three EV to the charging system varies depending on the daily routines of their respective users. Table 1 outlines the usage patterns, specifying for each vehicle and day the time intervals during which it is

unplugged and reconnected, along with the energy consumed for each trip. Note that energy consumed while the EVs are not connected to charging infrastructures is obtained from the virtual storage portion reserved for mobility purposes.

The analysis proposes a comparison with a reference scenario in which V2H functionality is not implemented, and the EVs are charged at the same power levels as those assumed in the V2H configuration.

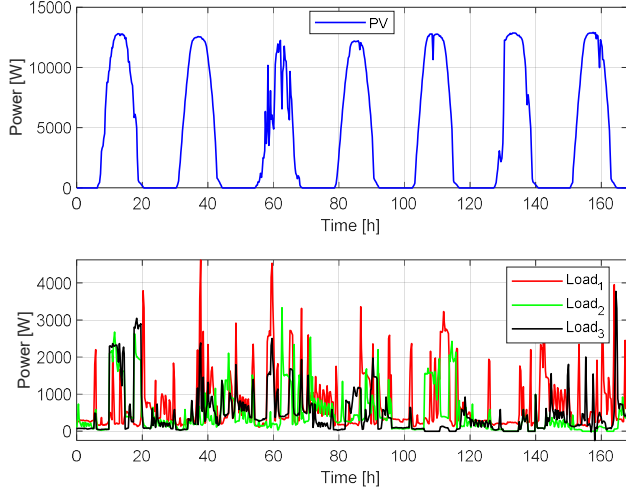


Fig. 1. Load and PV profiles.

TABLE I
EV TRANSIT SCHEDULING AND ENERGY CONSUMPTION

	EV ₁	EV ₂	EV ₃
Day 1	07:45-13:30 13 kWh 18:00-19:15 3 kWh	12:15-13:15 3 kWh 17:15-18:15 3 kWh	07:45-14:45 13 kWh
Day 2	07:45-13:30 13 kWh 18:00-19:15 3 kWh	07:15-17:15 13 kWh	07:45-14:45 13 kWh
Day 3	07:45-13:30 13 kWh 18:00-19:15 3 kWh	07:15-17:15 13 kWh	12:15-13:15 2 kWh 17:15-18:15 2 kWh 20:15-22:15 10 kWh
Day 4	07:45-13:30 13 kWh 18:00-19:15 3 kWh	12:15-13:15 3 kWh 17:15-18:15 3 kWh	08:15-15:15 13 kWh
Day 5	07:45-13:30 13 kWh 18:00-19:15 3 kWh	07:15-17:15 13 kWh	08:15-15:15 13 kWh
Day 6	11:45-13:15 2 kWh 19:00-22:15 10 kWh	08:15-12:15 10 kWh 14:15-17:15 10 kWh	08:15-23:15 13 kWh
Day 7	-	13:15-20:15 13 kWh	14:15-23:15 13 kWh

IV. SIMULATION RESULTS

Fig. 2 displays the physical and virtual SOC of the three EVs, considering the EV disconnection from the charging infrastructure. As one can observe, the V2H virtual partition significantly supports the exploitation of PV generation in the REC and is used to cover loads demand. Notably, the mobility virtual SOC (black lines) is not

affected by VPA, and the user can increase the V2H service share if needed. Fig. 3 also shows the PV system power profile and the overall power profile P_m , which is the sum of the measured active powers P_{mi} .

The VPA enhances the exploitation of PV generation, especially when production exceeds the total REC load, as shown by the frequent overlap between the red and blue curves in the upper panel of Fig. 3. Additionally, it allows to provide service to user in the evening hours. This dual action boosts self-consumption within the REC and supports the REC objective of maximizing the self-consumption. Fig. 4 illustrates the power demand at the three EV charging stations. It can be observed that the VPA enables greater utilization of the charging infrastructure, which, at certain times during the week, operates at full capacity. In this configuration, the VPA serves both shared REC objectives and individual user needs.

In order to estimate the financial advantage introduced by the VPA in the REC context, the analysis assumes a compensation rate of 0.25 € per kWh for the energy shared within the community and a market price of 0.10 € per kWh for the sold energy. The REC self-consumption reaches 520.1 kWh, compared to 228.0 kWh without VPA. This results in a remuneration of 130.03€ with VPA, while it is only 57.00 € without it. Conversely, the energy sold by the REC is equal to 204.2 kWh with VPA and to 496.3 kWh without VPA, leading to earnings from energy sales of €20.42 and €49.63, respectively. Overall, the total gain amounts to €150.45 with VPA and €106.63 without it. Therefore, the implementation of the VPA, which increases self-consumed energy within the REC by reducing the amount fed into the distribution grid, results in higher economic returns for REC members.

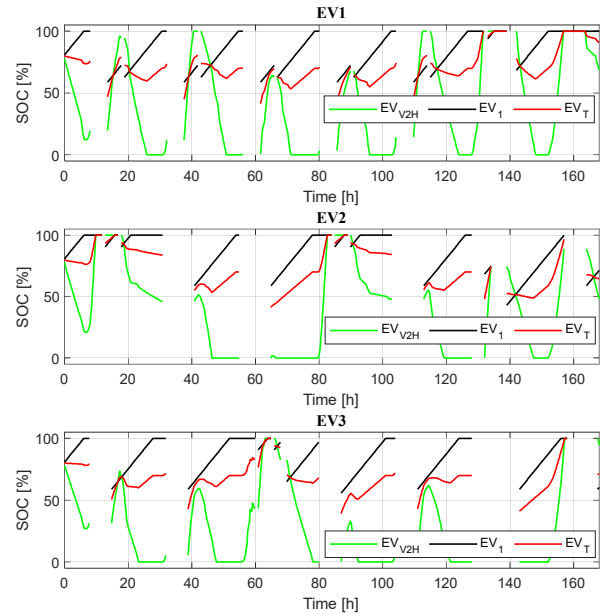


Fig. 2. SOC profiles of the mobility and virtual partitions.

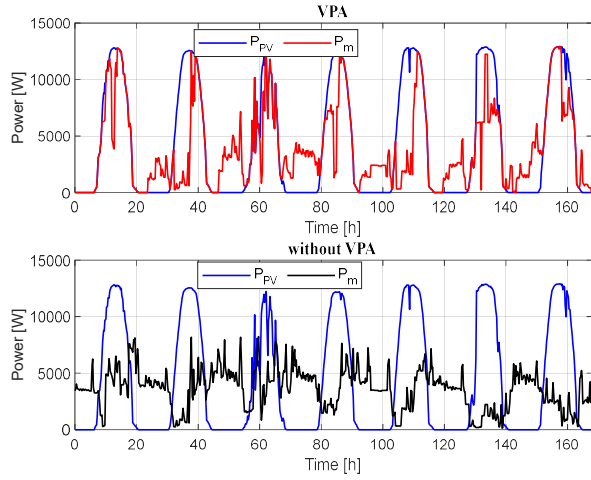


Fig. 3. P_m and P_{pv} power profiles.

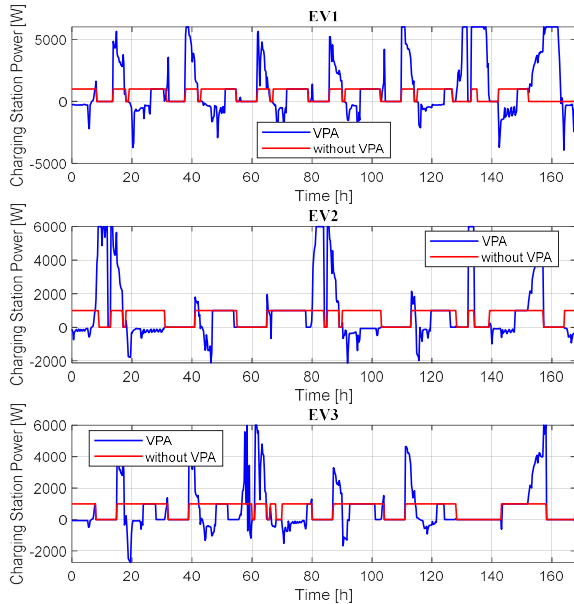


Fig. 4 Charging stations power profiles.

V. CONCLUSION

This paper introduces an innovative approach for the virtual partitioning of EV batteries, aimed at efficiently providing V2H services. The concept of virtual partitioning is first presented and then applied to a specific scenario involving multi-family housing with a shared PV system, forming a REC. The feasibility of the method was assessed through simulations using realistic REC, with actual data for residential load and PV production in a multi-family housing setup. The simulation results demonstrate the VPA effectiveness in providing both economic advantages and technical benefits to REC participants, such as enhanced exploitation of RESs and reduced power fluctuations at the grid connection point.

Future work will focus on developing optimization approach to determine the most efficient energy allocation for V2H services, considering the EV usage patterns.

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