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ECONOMIC ADVANTAGES OF EV PARTICIPATION IN GRID SERVICES FOR HOMEOWNERS AND UTILITIES

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Abstract

The global automotive industry is undergoing a profound transformation as the massification of electric vehicles accelerates at an unprecedented pace. According to the targets defined in the European Green Deal, 30 million zero-emission vehicles should be in circulation in Europe by 2030. This surge not only reflects the growing consumer interest in clean and sustainable mobility but also stands as a key aspect towards energy transition. The present study aims to evaluate the economic benefits for EV-using homeowners and utilities via EV supported participation in two types of grid and system services, namely in wind curtailment mitigation and congestion management in distribution grids.

These simulations are based on an algorithm developed under the EV4EU project[1]. The model is based on data and assumptions within the local context of São Miguel Island in the Azores. The primary findings highlight the potential for cost reduction of up to 30% in total household energy expenditures, a figure that could potentially increase to 40% through regular engagement in grid services. This also implies significant benefits for utility companies, potentially leading to an operational cost reduction and deferred investments. Nevertheless, this implementation requires further work on legal frameworks, market dynamics and the development of flexibility aggregators.

Keywords: Vehicle-to-Everything, Distributed Energy Resources, Home Energy Management System, grid services.

1 INTRODUCTION

Advancements in smart grids, network communication, information infrastructure and energy efficiency have considerably enhanced the control capabilities of Home Energy Management Systems (HEMSs), enabling them to significantly improve the energy economy of modern homes (Mahapatra & Nayyar, 2022). In particular, HEMSs may leverage the coupling of smart charging or Vehicle-to-Everything (V2X) techniques with Distributed Energy Resources (DER), such as rooftop installed solar Photovoltaic (PV), to participate in grid services as requested by power system operators. This approach aims to reduce costs for both EV-owning homeowners (via incentives) and utilities (through flexibility services, resulting in the postponement of conventional grid investments).

In this context, numerous distinct household and EV load management techniques have been proposed within the scientific literature. Zafar & Slama (2022) have defined four different rule-based algorithms to schedule household loads and EV charging and discharging actions, considering covered distance, weather conditions, and the influence of electricity pricing on demand, to achieve cost savings for EV using homeowners. On the other hand, the authors Song et al. (2022) propose a genetic algorithm framework to simultaneously optimize cost savings, environment protection, and user comfort, having

[1] More information at ev4eu.eu

achieved significant improvements in all three features. El Makroum et al. (2023) propose a genetic algorithm framework to optimize cost savings whilst maintaining an adequate level of usage comfort, considering real-life energy consumption data.

This study sets itself apart from the state-of-the-art on energy economics and sustainable energy practices by examining grid service participation as a feature of V2X and DER integrated HEMSs. For that effect, the present paper shows the results of a novel decision-making model based on advanced forecast, optimization, and real-time control capabilities, as well as a comprehensive and diverse dataset representative of real-life operating conditions in São Miguel Island, Azores, Portugal.

2 DECISION-MAKING MODEL DESIGN AND DEVELOPMENT

2.1 Data pre-processing

- Solar PV power output: the power output of a 2.2 kWp 6-panel PV system installed on the rooftop of a typical household in São Miguel Island was retrieved from the database of Eletricidade dos Açores (EDA), the Azorean electrical utility (Eletricidade dos Açores, 2023a).

- Household energy consumption: the energy consumption of a typical household without an EV in Madeira Island was retrieved from the Horizon 2020 SMILE project (PRSMA, 2021). To better represent the energy consumption of a typical household in São Miguel Island, each data point was reduced by a factor of 1.5 (adding up to an annual energy consumption of approximately 4 MWh).

- EV usage behaviour: a simplistic yet representative characterization of the mobility behaviour of EV using homeowners in São Miguel Island was conceived based on (Harris & Webber, 2012; Ramos et al., 2020; Tamor et al., 2015; Ul-Haq et al., 2018). In this regard, the EV is considered to: (i) perform around 6 000 km annually (ii) remain mostly at home; (iii) on weekdays, have a 95% probability to carry out a round trip with a uniformly distributed trip duration of 0.5 to 1 hours and a departure time according to hypothesized probabilities (06:00 – 2.5%, 07:00 – 32.5%, 08:00 – 50%, 09:00 – 12.5%, 10:00 – 2.5%); (iv) on weekend days, have an 80% probability to carry out a round trip with a uniformly distributed trip duration of 3 to 8 hours and a uniformly distributed departure time from 08:00 to 15:00.

- Grid service request conditions: the curtailed power output of the total wind installed power of 9 MW and the usage rate of a congested secondary substation (SS) both in São Miguel Island, were retrieved from EDA's database (Eletricidade dos Açores, 2023a).

- Electricity pricing: the Azorean weekly cyclic and tri-hourly grid tariff structure applicable to low voltage clients according to the Energy Services Regulatory Authority (ERSE, Portuguese acronym).

- Weather conditions: São Miguel Island's direct normal irradiance, diffuse horizontal irradiance, global horizontal irradiance, air temperature, solar zenith angle, precipitable water, and relative humidity data were retrieved from the National Solar Radiation Database (NSRD) (NREL, 2023).

2.2 Module description

Structurally, the proposed decision-making model comprises the three following modules: (i) forecast; (ii) daily planning; and (iii) real-time operation. The model's architecture is illustrated in Figure 1.

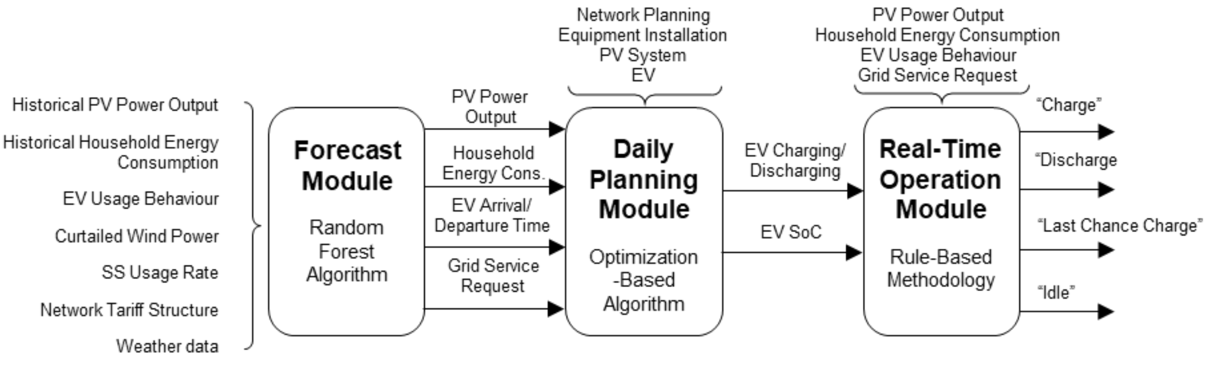

Figure 1. Architecture of the proposed decision-making model

The forecast module is fed the data in Section 2.1 and outputs corresponding day-ahead predictions. In this context, a Random Forest algorithm(Parmar A. et al., 2018) was considering four months of data, one month per season.

The daily planning module then takes the output of the forecast module and additional parameters to produce EV SoC and charging or discharging setpoints. Within the module, distinct control strategies are selectable, namely: (i) V2X (discharging is enabled), (ii) smart charging (discharging is disabled), or (iii) no charging control (discharging is disabled and the EV charges as soon as connected). The created optimization-based algorithm implements a Mixed Integer Linear Programming (MILP) framework resorting to IBM's CPLEX solver to optimally solve the Objective Function (OF) in Equation (1).

$$\mathrm{OF} = \min(\sum_{t=1}^{T}(P_t^i.\Delta_t.p_t^i - P_t^e.\Delta_t.p_t^e + R_t^{WCM}.\Delta_t.c_t^{WCM} + R_t^{CM}.\Delta_t.c_t^{CM})) \qquad (1)$$

where P_t^i and P_t^e indicate, respectively, the power imported/exported from/to the grid at time t, while Δ_t is the simulation's time step, T is the simulation's duration, and p_t^i and p_t^e represent, respectively, the energy import/export price at time t (the electricity export price is considered to be null outside the scope of congestion management grid service participation). For simulation purposes, participation in a requested grid service is deemed mandatory. In this regard, R_t^{WCM} and R_t^{CM} indicate relaxation variables and c_t^{WCM} and c_t^{CM} indicate penalty charges at time t for the respective non-participation in requested wind curtailment mitigation and congestion management grid services.

Finally, the real-time operation module verifies whether the EV is connected and, according to the daily planning module's output, a full year of Section 2.1's data and a simple rule-based methodology, yields one of four distinct EV control methods, namely: (i) "Charge"; (ii) "Discharge"; (iii) "Last Chance Charge"; or (iv) "Idle". "Charge"/"Discharge" instructs when the EV is to be charged/discharged, considering the maximum allowed charge/discharge rate ($\overline{P}_{max}$), EV battery capacity ($\overline{E}_{EV}$), and efficiency of the EV and charging station joint system (η). "Last Chance Charge" instructs the EV to be charged when confronted with the final opportunity before EV departure to fulfil the charging requirements defined by the EV using homeowner, considering contracted power ($\overline{P}_C$) limitations. "Idle" does not stipulate any instruction.

2.3 Scenario definition

Some parameters are pre-defined and thus transversal to every simulation, namely: (i) Δ_t – 15 min; (ii) initial EV SoC – 60%; (iii) $\overline{P}_C$ – 7.2 kVA, (iv) $\overline{E}_{EV}$ – 40 kWh; (v) $\overline{P}_{max}$ – 3.7 kW; and (vi) η – 94.09%.

The probability of an EV being requested to participate in a wind curtailment mitigation service depends on the pool size of already participating EVs (herein, 500 EVs were assumed for the purpose). Considering $\overline{P}_{max}$, requests are only to occur if the curtailed wind power output exceeds 1,850 kW.

São Miguel Island's grid does not currently face any local congestion. However, to properly assess the congestion management performance of the decision-making model, congestion was intentionally assumed using a SS with typical high demand compared to the island's standards. Based on data from Eletricidade dos Açores (2023a), requests are only to occur if the SS's usage rate is over 30%.

Table 1 displays the scenarios for the simulation of the proposed decision-making model.

Table 1. Decision-making model's scenarios

#	1	2	3	4	5
Control Strategy	No charging control	Smart Charging	V2X	V2X	V2X
EV – Grid Service Request Coordination	No	No	No	Wind Curtailment Mitigation	Congestion Management

3 RESULTS

In Figure 2, a cost comparison is presented according to different control strategies.

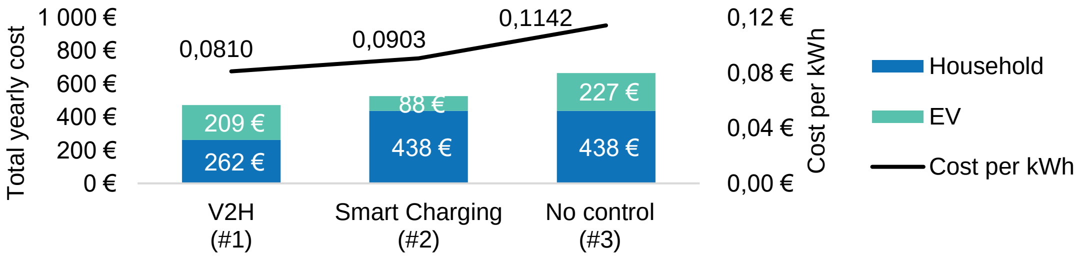

Figure 2. Cost comparison for scenarios #1, #2 and #3

Figure 3 illustrates the wind curtailment mitigation participation rate (*i.e.,* percentage of time the EV is charging during active wind curtailment mitigation service requests) for scenarios #3 and #4, as well as the congestion management grid imports (*i.e.,* percentage of energy which is being imported from the grid during active congestion management grid service requests) for scenarios #3 and #5.

Within scenario #3, the EV sometimes charges coincidently to active wind curtailment mitigation service requests, despite its charging actions being uncoordinated with these requests. Hence, a non-null wind curtailment mitigation participation rate has been obtained. Also, this scenario's congestion management grid import rate is 59% of the total load demand, since local congestion typically occurs when electricity prices are high in this case study and thus the decision-making model opts to feed the household with EV discharged energy.

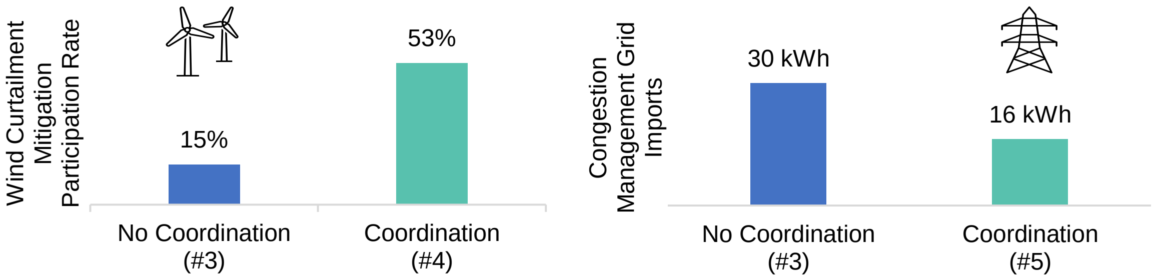

Figure 3. Wind curtailment mitigation participation (left) and congestion management grid import (right) rate

3.1 Cost savings for EV using homeowners

Comparing the non-controlled charging (#1) and smart charging (#2) control strategies in Figure 2, the latter results in a reduction of about 21% for the cost per kWh of consumed energy, since the amount of solar PV energy fed into the EV is much greater (around 10.75 times) than in the former case. On the other hand, comparing the V2X (#3) and smart charging (#2) control strategies within the same figure, the former results in a reduction of about 10% in the cost per kWh of consumed energy, since discharging energy from the EV into the household leverages inexpensive solar PV energy and low electricity prices.

In line with Figure 3 (left), coordinating the EV's charging actions with wind curtailment mitigation grid service requests (#4) results in a wind curtailment mitigation participation rate of around 3.53 times greater than in the uncoordinated case (#3). Considering an electricity import price discount of 100%, the former results in a cost per kWh of consumed energy of around 0.071 €/kWh, that is, a reduction of about 12% when compared to the latter. A more realistic discount of 50% yields a cost per kWh of consumed energy of around 0.076 €/kWh for the former (6% cost reduction to the user).

According to Figure 3 (right), coordinating the EV's charging and discharging actions with congestion management grid service requests (#5) decreases the congestion management grid import rate to about 0.54 times that of the uncoordinated case (#3).

3.2 Cost savings for utilities

The EV defers approximately an additional 158.1 kWh of curtailed wind energy when its charging actions are coordinated with wind curtailment mitigation requests (#4), in comparison to the uncoordinated case (#3).

When the EV's charging and discharging actions are coordinated with congestion management grid service requests (#5), joint household and EV grid imported energy is reduced by almost 2/3 in comparison to the uncoordinated case (#3).

The probability of wind curtailment mitigation or congestion management grid service participation varies non-linearly with the pool size of already participating EVs (in the latter case, due to the SS's usage rate being priorly reduced). Thus, so do the cost savings yearly yielded for the utility. In this regard, the presented cost savings primarily serve an exemplificative purpose.

4 CONCLUSIONS

Significant cost reductions were observed for EV using homeowners through smart charging and V2X control strategies. Moreover, the coordination of EV charging and discharging actions with wind curtailment mitigation and congestion management grid service requests has been proven to substantially amplify these cost savings via electricity price discounts and variable flexibility payments.

Additionally, the coordination of EV charging and discharging actions with wind curtailment mitigation and congestion management grid service requests yielded valuable cost savings for utilities, by reducing curtailed wind energy and grid imported energy related costs.

This study's findings emphasize how leveraging grid service participation within V2X and DER integrated HEMSs supports a more cost-effective energy ecosystem, contributing to the energy field with practical insights regarding a residential energy system representative of real operating conditions.

Future research is proposed on different forms of compensation, particularly those of economic nature, for the participation of EVs in wind curtailment mitigation and congestion management grid services.

However, the implementation of these services requires additional efforts in refining legal frameworks, exploring market dynamics, and developing flexibility aggregators.

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