Economic Analysis of Coordinating Electric Vehicle Parking Lots and Home Energy Management Systems

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Abstract—**Two increasingly popular distributed energy resources (DERs), especially within the European context, are photovoltaic (PV) installations and electric vehicles (EVs). Numerous models have been proposed for optimal management thereof, such as Home Energy Management Systems (HEMSs) and EV parking lot management systems (EVPLMS). However, these approaches are often designed to benefit only one party without taking into account the effect of any other management systems. I.e., HEMSs are designed to only maximize the economic benefit of home owners, while EVPLMSs are designed to only maximize the profit of parking lot owners. In this study, the coordinated use of these systems is modeled and simulated to investigate whether a synergistic relationship exists in which consumers (EV owners) have an added economic benefit by the simultaneous operation of HEMSs and EVPLMSs. As such, a cost-benefit analysis is conducted from the point of view of the EV owners, utilizing a HEMS at home and an EVPLMS at work. The analysis was performed on case studies that are based on real facilities, locations, meteorological data, and electricity market prices in Porto, Portugal.**

Keywords—**Smart Grid, Energy Management Systems, Power System Operation, Electric Vehicles, Optimization.**

I. INTRODUCTION

A. Background and Motivation

People's well-being, industrial competitiveness and even the overall functioning of human society all greatly depend on safe, reliable, sustainable, and affordable energy systems [1]. Due to the limitations and environmental drawbacks of conventionally used fossil fuels for electricity generation, the ever-growing demand in energy markets, and concerns on security of supply, it became mandatory to consider other forms of sustainable and environmentally friendly energy sources during the past few decades [1], [2]. Renewable energy sources (RES), such as photovoltaic (PV) solar power generation, are environmentally friendly and can help meet the fast-growing load demand. However, given their unpredictable and intermittent nature, certain challenges still need to be addressed. Since PV installations are to a great extent non-dispatchable and time-varying, it is necessary to couple them with other geographically distributed energy resources (DERs) to mitigate these effects [3].

Typically, Energy Storage Systems (ESS) have been used alongside RES to compensate for their non-dispatchable nature and provide more control for the grid operators. One example is the use of hydroelectric ESS with wind farms to store unforeseen surplus generation and feed it back into the grid when unforeseen shortage of generation is encountered. For PV systems, batteries are commonly used as the coupled ESS [4], [5].

In recent years, the exponential rise of electric mobility in general and consumer-owned electric vehicles (EVs) in particular made the latter attractive candidates as a DER which could be used as a semi-dispatchable DER which simultaneously serves as an ESS, leveraging the overall sustainability and cost-efficiency of power systems [6]. A significant number of recent studies have addressed the concept of coupling EVs with PV technology. An effective way is the use of PVs where the EVs are parked for long periods of time: at homes and parking lots. The first involves the incorporation of EVs into Home Energy Management Systems (HEMSs) while the latter gave rise to PV-equipped EV parking lots (EVPL) [4], [7].

B. State-of-the-Art Review

1) Electric Vehicle Parking Lot Management Systems

In [8], the authors proposed a dynamic programming algorithm for optimal management of EV parking lots. The study focused on parking lots situated in commercial areas, where EVs are parked during the day (peak hours for the power grid), and indicated this in contract to typical night-time charging at home. Uncertainties in arrival and departure times, dynamic electricity prices, in addition to the EV parking lot's commitment to fully charge the EVs by their time of departure were all considered in the proposed EVPLMS. By solving for the optimal hourly charging/discharging schedule for each EV, the results showed that the EVPLMS was successful in significantly decreasing the parking lot owner's costs.

Another EVPLMS algorithm was proposed by the authors in [9], based on fuzzy logic inference. In this study, the capacity of the parking lot was introduced as a variable parameter, and a comparative study was performed versus conventional uncontrolled charging. Rather than focus on the owner's profitability, the objective in this case was to utilize the parking lot to mitigate grid overloading, without sacrificing the EV owners' charging requirements. The proposed algorithm was shown to be effective at achieving this objective. The authors is [10] were one of the first to conduct a study involving the mutual interaction of EV parking lots (with distribution grid interaction) and RES-based DERs. A two-level optimization model was proposed which aimed at maximizing the parking lot owner's profit while minimizing the distribution system operator's (DSO's) costs. The problem was formulated as a stochastic mixed-integer linear programming (MILP) one to account for different RES generation scenarios and uncertainties associated with the EV schedules. The simulations performed

that the coordination between the parking lot and DERs effectively reduced the DSO costs and maximized the parking lot owner's profits.

In [11], a EVPLMS was proposed for a parking lot having a PV-equipped rooftop. The grid interaction was modeled by considering the distribution system constraints and the dynamic electricity pricing. The proposed optimization model was designed for real-time operation, in which near-optimal charging or discharging of the parked EVs is determined to maximize the parking lot owner's profit without sacrificing the EV owner charging requirements.

As an extension to the work performed in [10], the authors in [7] modelled a PV-equipped EV parking lot, also taking into consideration grid interaction, EV schedule uncertainty, PV generation uncertainty, fixed and running costs of installations, and dynamic electricity tariffs. The proposed MILP model for day-ahead operational planning showed that EVPLMSs are capable of significantly increasing the parking lot owner's profits, without any sacrifice neither to the EV owners' charging requirements, nor that of the DSO (on the contrary, a significant portion of the additional profit came from providing ancillary services to the grid).

2) Home Energy Management Systems

In [12], the primary objective of smart homes was identified as minimizing the total electricity bill of the owners while improving the grid independence. The latter was shown to be achieved through accurate modelling of the system, leading to optimized utilization of local DERs such as PV generation and EVs which maximizes self-consumption leading to leveraged grid-independence.

The authors in [13] proposed a MILP model for a HEMS that incorporated local RES generation, an ESS, and an EV. The home owner provided their preferred times of consumption and a forecasted load demand was made based on that, meteorological forecasts, and historical consumption data of the residents. The objective function of the model minimized both electricity consumption cost and user discomfort associated with consumption rescheduling, which was verified by the performed case study.

Online management of a smart home was investigated in [14], accounting for random occupancy and thermal loads. By The proposed model managed to effectively control thermal loads to guarantee thermal comfort of the occupants while minimizing energy usage. The authors recommended the incorporation of a model for Demand Response (DR) program participation in future work, as it was not considered by this study.

A multi-objective MILP-based model was proposed in [15] for a HEMS, minimizing the electricity bill of the owners and their discomfort levels. The HEMS takes into consideration the owner preferences for the ideal operating hours of shiftable appliances (which includes the EV charging hours) and the required consumption duration of each of them. To obtain the optimal day-ahead consumption schedule which offers a trade-off between the electricity bill savings and user discomfort, the study utilized fuzzy decision making and the epsilon-constraint method. Participation in a DR program was modelled through Time-of-Use (ToU) tariffs.

One of the very few studies found coordinating the operation of a HEMS (having PV generation and an EV) with another EMS was in [16]. The authors performed a case study on the Japanese distribution system model, and found that by coordinating between the HEMS and the DSO EMS, a further reduction in operating costs (of both parties) is obtained, in addition to increased PV curtailment.

C. Novel Contributions

From the conducted literature survey, one take note of two important points:

- Many recent studies have addressed the implementation of EVPLMSs, mainly aiming at either maximizing the parking lot owner's profit or that of the DSO.

- Numerous studies have also addressed HEMSs, showing their effectiveness in minimizing the home owners' electricity bills with little sacrifice of comfort.

Accordingly, we identified a gap in presently available scientific literature:

- No research works were found to study the simultaneous impact of having both systems (EVPLMSs and HEMSs), especially on the EV owners whose cars are parked for the most part of the day, and thereby being economically influenced by those two systems in particular.

In the context of smart cities and modern smart grids, this appears to be a critical gap in current research on the topic. Therefore, the novel contributions of this study is to interlink a HEMS and an EVPLMS, coordinating their operation by providing the same EV owners' schedules (considering different types of schedules), RES uncertainty (for rooftop PVs, and electricity market data.

According to the authors' knowledge, this is the first study of its kind to address this issue.

D. Paper Organization

This manuscript is organized as follows: Section I (current section) provides the background and motivation of this work, a survey of relevant scientific literature identifying the research gap addressed by this study, and an indication of the novel contributions of this work. Section II presents the employed methodology, introducing the conceptual model for this study in addition to the mathematical formulation of the EVPLMS and HEMS used. In Section IV, the case study used for simulation is defined, with the different scenarios presented. In Section V, the results of the simulations are presented and discussed. Finally, the main conclusions and suggestions for future work are given in Section VI.

II. METHODOLOGY

A. Conceptual Model

In Fig. 1, the conceptual model used in this study and analysis is illustrated:

- EV owners working at a given faulty (with a EVPL), live in different neighborhoods. This reflects the variation and uncertainty of their transit times.

- The faculty EVPL is equipped with a rooftop PV panels, is grid-interactive, and is operatured using the EVPLMS proposed in [7]. The EVPL therefore participates in providing ancillary services to the grid, with a DR program participation.

- All the homes are smart homes equipped with PV panels and managed using the HEMS proposed in [15]. All the homes participate in a DR program with dynamic hourly pricing.
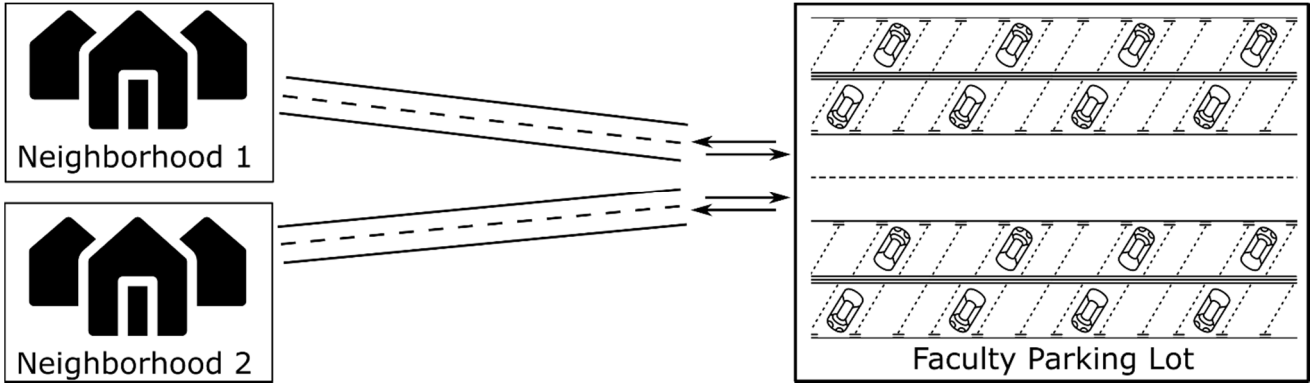
Fig. 1. Illustration of the conceptual model used for the current study and analysis.

- The hourly pricing corresponding the electricity market and DR programs, as well as the PV generation scenarios are synchronized between the smart homes and the EVPL at the faculty.

B. Home Energy Management System

The HEMS proposed in [15] was used in the smart homes in this study. The objective of the proposed self-scheduling model for HEMS is to minimize the total daily cost of electricity bill. The cost is the difference between the energy bought from the grid and the energy sold back to the grid by the house-owned assets that are able to provide energy (PV and ESS). In the presented EMS, the energy provided by the ESS is used directly to cover a portion of the house needs and is never injected into the grid. The main function (Z) can be stated as below:

$$Minimize\ Z = \sum_t \left(\frac{P_t^{G2H}}{\Delta t} \lambda_t^{buy} - \frac{P_t^{H2G}}{\Delta t} \lambda_t^{sell} \right) \quad (1)$$

In this equation P_t^{G2H} is the variable that represents the total power bought from the grid at time t, and the P_t^{H2G} represents the total power sold to the grid, which is due to the excess energy produced by the PV system. Two main cases are defined:

- Before HEMS implementation, considered as baseline operation intervals based on the end-user preferences.
- After HEMS implementation, where the flexible loads are optimally schedule based on the predefined tariffs.

The baseline operation intervals are subjected to the binary parameters, $B_{i,t}$, and the bounds for each appliance are available based on the end-user preferences. Equation (2) sets that the operation status of the corresponding appliance would be '1' during the baseline intervals and '0' before and after the considered operation bounds.

$$B_{i,t} = \begin{cases} 0 & t < LB_{i,b} \\ 1 & LB_{i,b} \le t \le UB_{i,b} \\ 0 & t > UB_{i,b} \end{cases} \quad B_{i,t} \in \{0,1\} \quad (2)$$

The lower and upper bounds are $LB_{i,b}$ and $UB_{i,b}$, respectively. With the HEMS implementation, the flexible loads can be shifted before or after the baseline operation intervals in order to reduce the costs. Since hourly tariffs affect the total operation cost, the end-users can benefit from optimal self-scheduling based on predefined tariffs. In this regard, the user can set the allowable time intervals for plunging in the appliances, as shown by Equation (3).

$$S_{i,t} \le \begin{cases} 0 & t < LB_{i,s} \\ 1 & LB_{i,s} \le t \le UB_{i,s} \\ 0 & t > UB_{i,s} \end{cases} \quad S_{i,t} \in \{0,1\} \quad (3)$$

Self-scheduling of the appliances within the HEMS allows the owners to view the impact of each appliance to the total electricity bill and thus can help to modify their behavior to optimize the bill within their own preference ranges. It is evident that, for each home appliance, the operation duration should be the same for both cases, as shown by Equation (4). I.e., it means that the end-user just changing the operation time intervals doesn't change the daily energy consumption that should remain the same after HEMS implementation.

$$\sum_{t=1}^{N_T} S_{i,t} = \sum_{t=1}^{N_T} B_{i,t} = T_i \qquad \forall_i = 1,2,\dots,N_A \quad (4)$$

The total demand of the house is presented in Equation (5). The first part of the equation is related with the energy consumption of 10 shiftable appliances whereas the second part is related with the non-shiftable loads. The appliance details will be defined in the case study section.

$$P_t^D = \sum_i^{NA} \sum_t^{NT} \left(\frac{S_{i,t} \cdot P_i}{\Delta t} \right) + \sum_t^{NT} \frac{P_f}{\Delta t} \quad (5)$$

The usage status of appliance i at time t is a binary variable, represented by ($S_{i,t}$), and the rated power of the corresponding appliance is (P_i). On the other hand, (P_f) represents the fixed demand in the house at each time slot. Moreover, in this study, the time slots are considered to be in 30 minutes. So, for a 30-min interval the (Δt) coefficient, number of intervals in 1 hour, must be 2 and the total time slots are set as 48 for daily operation.

The constraints in Eq. (6)-(10) are used for ESS modeling (EV when parked). Eq. (6) shows binary variables which aim to restrict the ESS to be in either a charging or discharging mode at any given time as it is impossible for the ESS to operate in both modes simultaneously. Eq. (7) and (8) impose a limit on the charging ($P_{j,t}^{Ch.}$) and discharging ($P_{j,t}^{Disch.}$) power of the ESS. The energy stored at a specific interval is a function of the energy stored in the previous interval plus the amount of energy that is transferred (if in charging mode) minus the energy that is injected by the battery (if in discharging mode). This is shown in Eq. (9) which also includes an efficiency factor for charging and discharging. It is considered that the SoC at the end of the operation horizon

should be equal to the initial SoC at the start of the operation horizon. Moreover, the energy within the ESS is constrained by upper and lower limits that are defined by Eq. (10).

$$0 \leq I_{j,t}^{Ch.} + I_{j,t}^{Disch.} \leq 1 \qquad (6)$$

$$P_{j,t}^{Ch.} \leq I_{j,t}^{Ch.}.P_j^{Ch.max} \qquad (7)$$

$$P_{j,t}^{Disch.} \leq I_{j,t}^{Disch.}.P_j^{Disch.max} \qquad (8)$$

$$E_{j,t} = E_{j,t-1} + \eta_j^{Ch.}.P_{j,t}^{Ch.} - \frac{1}{\eta_j^{Disch.}}.P_{j,t}^{Disch.} \qquad (9)$$

$$E_j^{min} \leq E_{j,t} \leq E_j^{max} \qquad (10)$$

Equation (11) enforces the fact that the actual power provided by the house-owned PV system (PV_t), in each time slot, can be used to cover a portion of the house needs and in case of an excess of generation, injected to the grid.

$$PV_t = P_t^{PV,used} + P_t^{PV,sold} \qquad (11)$$

Equation (12) states that the total residential load plus the charging of the ESS must either satisfied by the grid (P_t^{G2H}) or by the combined energy supply of the PV and the ESS. Adding to this equation, there is the energy sold back to the grid (P_t^{H2G}). Mathematically, the power balance for each time slot is as follows:

$$PV_t + P_t^{G2H} = P_t^D + P_{j,t}^{Ch.} - P_{j,t}^{Disch.} + P_t^{H2G} \qquad (12)$$

C. Electric Vehicle Parking Lot Management System

The EVPLMS proposed in [7] is used in this study. In this model, the charging and discharging of EVs in a parking lot with rooftop PV installations is controlled, aiming at maximizing the EVPL owners' profit. The inputs to the model can be divided into four parts:

- EV – Arrival time, departure time, SOE at the arrival time, battery capacity;
- PV panels – Hourly PV power output consider the season and location;
- Electricity market – Day-ahead energy price, reserve price and regulation up/down price;
- Finance – Energy tariff, parking usage tariff.

On one hand, the limit of power injection from the grid to parking lot is limited by Eq. (13) in accordance with the rate of charge of EVs. On the other hand, Eq. (14) presents the limit of power injection from the parking lot to the grid, based on the rate of discharge of the EVs.

$$P_{w,t}^{En,G2PL} + P_{w,t}^{PV2PL} \leq \gamma^{charge}.n_t^{PL} \qquad (13)$$

$$P_{w,t}^{En,PL2G} + P_{w,t}^{Res,Act} \leq \gamma^{discharge}.n_t^{PL} \qquad (14)$$

One additional constraint is presented in (15), in order to limit the injection of power from the PV rooftop to the parking lot (PV2PL), has been added. The maximum power that can be injected to the parking lot depends on the SOC from the previous hour and the state-of-energy from arrived/departed EVs.

$$P_t^{En,PV2PL} \leq SOC^{max} \times PLCapcom_t \\ - (SOC_{t-1} + PLSOEnet_t) \qquad (15)$$

where $PLCapcom_t$ is the sum of EVs capacity in the parking lot and $PLSOEnet_t$ consist on the difference between $PLSOEin_t$ and $PLSOEout_t$.

The SOC of the parking lot at each hour t, presented in (16), is based on the SOC from the previous hour, the energy exchanges with the grid in both directions and the SOC from both arrived and departure EVs. A minimum state of charge of 20% and a maximum of 80%, for each EV has been considered.

$$SOC_t \\ = SOC_{t-1} + SOC_t^{arrival} - SOC_t^{departure} \\ + (P_t^{En,G2PL} + P_t^{PV2PL} + P_t^{R.down}).\eta^{charge} \qquad (16) \\ - \frac{P_t^{En,PL2G} + P_t^{Res.Act} + P_t^{R.up}}{\eta^{discharge}}$$

The SOC of departure EVs is presented in (17) and (18). On the one hand, in (17) is represented the SOC that is added to the EV during its stay in the parking lot, i.e., denotes the amount of energy that is injected into an EV. On the other hand, in (18) is represented the amount of energy that is absorbed from an EV.

$$SOC_t^{up} = \\ \begin{cases} 0, & SOC_t^{departure} \leq SOC_t^{scenario} - SOC_{t-1}^{scenario} \\ SOC_t^{departure} - SOC_t^{scenario} - SOC_t^{scenario}, & Otherwise \end{cases} \qquad (17)$$

$$SOC_t^{down} = \\ \begin{cases} 0, & SOC_t^{scenario} - SOC_{t-1}^{scenario} \leq SOC_t^{departure} \\ SOC_t^{departure} - SOC_t^{scenario} - SOC_{t-1}^{scenario}, & Otherwise \end{cases} \qquad (18)$$

where ($SOC_t^{scenario}$) is represented by:

$$SOC_t^{scenario} = \sum Cap_t^{EV}.SOC_t^{EV} \qquad (19)$$

The objective function aims to maximize the profit from the parking lot's operator point of view. The profit results from the difference of several incomes and costs terms, which are detailed in [7]:

$$\underset{P_{w,t}^{En,PL2G},\, P_{w,t}^{En,G2PL},\, P_{w,t}^{Res},\, P_{w,t}^{Res,Act},\, soc_{w,t}^{up},\, soc_{w,t}^{down}}{Maximize} \{profit^{PL}\} =$$

$$Max \sum_w \pi_w \sum_t \{ P_{w,t}^{En,PL2G}.\lambda_t^{En} + P_{w,t}^{Res}.\lambda_{w,t}^{Cap,Res} + P_{w,t}^{R-up,Act}.\lambda_t^{R-up}$$

$$+ P_{w,t}^{R-down,Act}.\lambda_t^{R-down} P_{w,t}^{Res,Act}.\lambda_t^{En}$$

$$+ soc_{w,t}^{up}.\lambda_t^{Tariff,V2G} + n_t^{PL}.\lambda_t^{Tariff,stay} - P_{w,t}^{En,G2PL}\lambda_t^{En} \qquad (20)$$

$$- (P_{w,t}^{Res,Act}.\Gamma^{Res} + P_{w,t}^{R-up}.\Gamma^{R-up} \\ + P_{w,t}^{R-down}.\Gamma^{R-down}) \lambda_t^{En}\pi^{unvail.}$$

$$- P_{w,t}^{Res,Act}.\lambda_t^{Tariff,V2G} - soc_{w,t}^{down}.\lambda_t^{Tariff,V2G}$$

$$- (P_{w,t}^{En,PL2G} + P_{w,t}^{Reg,Act})Cd \}$$

D. Computational Implementation

The individual HEMS and EVPLMS were implemented using the General Algebraic Modelling System (GAMS), applying the Mixed Integer Programming (MIP) solver. Coordination between the different EMSs was performed using MATLAB 2019b.

III. CASE STUDY

The main aspects of assumed case study can be listed as follows:

- 108 smart homes (SH), distributed into two different neighbourhoods. Each house has an installed 3 kW PV system with a 48V lithium-ion storage battery. All houses have the same number of appliances, including one EV and are all equipped with the same HEMS, albeit with different preferences reflected through discomfort indices in the HEMS model.
- An EVPL with a 100 kW PV rooftop. The EVPL represents that of a faculty, where is assumed that all residents from both neighbourhoods work or study.
- Both the houses and the faculty are located in Porto, Portugal. As such, data from the Portuguese daily market is used for the hourly energy prices and historical PV generation data from the same region is used.
- Since a faculty parking lot is considered, a typical working week in the winter (from 21 to 25 January 2019) was used for this analysis.

Multiple parameters are taken into consideration including uncertainty of EV owners' schedules and trips i.e., arrival and departure times, State-of-Charge (SoC) drop during trips, etc.

Four cases have been considered to evaluate the impacts of coordinating the EVPL and HEMSs.

The first (S1) was defined as the base case, excluding both HEMSs and the EVPLMS. In the second (S2), only HEMSs were considered. In the third (S3), only EVPLMSs were considered. Finally, in the fourth (S4), both HEMSs and EVPLMSs were incorporated.

All EVs are assumed to be Nissan Leaf with battery capacity of 30kWh. The EVs are charged in a regular wall plug with a charge power of 2.3kW (AC / 230V / 1x10A). It takes about 14.5 hours to charge from 0 to 100% SOC.
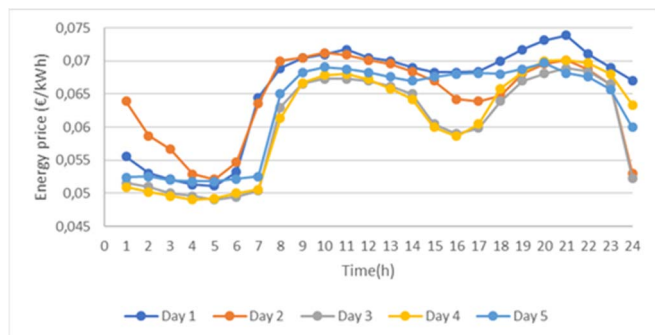

Fig. 2. Hourly energy prices from the Portuguese market corresponding to the considered working week.

TABLE I.   EV PREFERENCES (MORNING WORK SCHEDULE).

	P_i	T_i	LB_b	UB_b	LB_s	UB_s
Day 1	2.3	8.5	19h30	04h00	19h30	07h30
Day 2	2.3	7	20h30	03h30	20h30	08h30
Day 3	2.3	7.5	18H30	02H00	18h30	07h30
Day 4	2.3	8	19h30	03h30	19h30	06h30
Day 5	2.3	8	19h30	03h30	19h30	08h30

TABLE II.   EV PREFERENCES (AFTERNOON WORK SCHEDULE).

	P_i	T_i	LB_b	UB_b	LB_s	UB_s
Day1	3.3	6	19h30	01h30	19h30	07h30
Day2	3.3	5	20h30	01h30	20h30	08h30
Day3	3.3	5.5	18h30	00h00	18h30	07h30
Day4	3.3	5.5	19h30	01h00	19h30	06h30
Day5	3.3	5.5	19h30	01h00	19h30	08h30

Regarding the energy prices, the data corresponds to a week from 21 to 25 January 2019 of the Portuguese daily market. The market prices are presented in Fig. 2. The electric vehicles come from different areas in the city of Porto, so that the SOC lost in the trip from home to university and counter wise has different values according to the driving distance and time. The SOC lost percentages, during the trips, are arbitrarily distributed according to on a normal distribution for each considered area. It's assumed that each EV can be charged either at the parking lot or at home.

The EV owner's houses have a HEMS that aims to optimize the scheduling of several electrical appliances by shifting them across time in order to reduce the electricity bill for the homeowner. 10 appliances can be controlled and allowed the customer to decide on the operational time frames and the power limits. The details thereof can be found in [15]. One of those appliances is the EV, which is the focus of this study. An important factor to be considered is the work schedule of the EV owners.

While each of the 108 EVs were considered to have randomized schedules to account for this uncertainty, there were two main groups: morning and afternoon schedules. The ideal user preferences for the EV charging of each one of them are detailed in Tables I and II.

IV. RESULTS

The results for the total weekly electricity bill (in Euros) in the case of the morning and afternoon schedules is shown in Figures 3 and 4, respectively. The results clearly show that the HEMSs have introduce a significant reduction in the electricity bill of the EV owner. The EVPLMS is shown to in fact have an adverse effect, slightly increasing the total cost incurred by the EV owner.

Furthermore, the afternoon schedules are associated with lower overall electricity bills as they are capable of utilizing locally generated electricity through PV systems (at home or at the EVPL) for a longer period compared to the morning work schedule case. With that being said, the percentage reduction in costs due to HEMS implementation (and increase due to EVPLMS) is insignificant compared to the morning work schedule case.
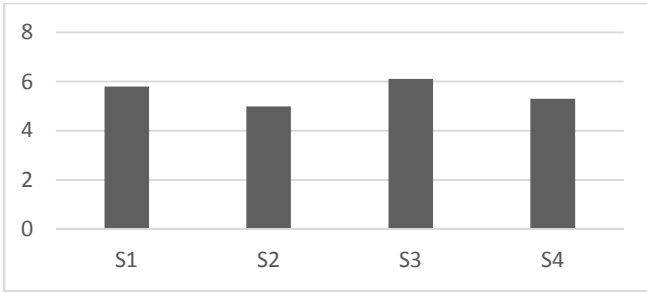
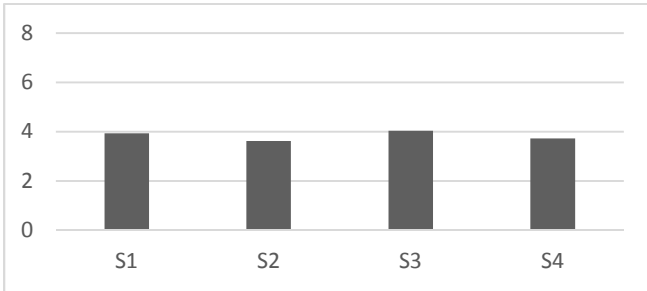Fig. 3. Weekly electricity bill for each of the four scenarios corresponding to a morning work schedule.

Fig. 4. Weekly electricity bill (in EUR) for each of the four scenarios corresponding to an afternoon work schedule.

Overall, the considered HEMS have a positive economic benefit for EV owners. Moreover, EVPLMSs have an adverse economic effect on EV owners, particularly those with HEMSs installed. This is expected since the EVPLMSs are designed to maximize profits for their owners. However, multi-objective optimization can be introduced to guarantee mutual benefit, as well as increasing participation.

V. CONCLUSIONS

EMSs are often designed to benefit only one party without taking into account the effect of any other systems. I.e., HEMSs are designed to only maximize the economic benefit of home owners, while EVPLMSs are designed to only maximize the profit of parking lot owners. In this study, the coordinated use of these systems was modeled and simulated to investigate whether a synergistic relationship exists in which consumers (EV owners) have an added economic benefit by the simultaneous operation of HEMSs and EVPLMSs. As such, a cost-benefit analysis is conducted from the point of view of the EV owners, utilizing a HEMS at home and an EVPLMS at work. The analysis was performed on case studies that are based on real neighborhoods and a faculty located in Porto, Portugal. The results showed that HEMSs always have a positive economic effect on EV owners while EVPLMSs have an adverse effect, particularly for those with morning work schedules.

For future work, the following is recommended: First, multi-objective optimization can be introduced to EVPLMSs in order to guarantee mutual benefit and increasing participation. This can be done by tuning the incentives provided to EV owners; Moreover, the effect of the distribution grid should be included, both as an economic analysis and from the perspective of power flow.

REFERENCES

[1]	J. A. P. Lopes et al., "The future of power systems: Challenges, trends, and upcoming paradigms," WIREs Energy Environ., Dec. 2019.

[2]	M. Lotfi, C. Monteiro, M. Shafie-Khah, and J. P. S. Catalao, "Evolution of Demand Response: A Historical Analysis of Legislation and Research Trends," in 2018 20th International Middle East Power Systems Conference, MEPCON 2018 - Proceedings, 2018, pp. 968–973.

[3]	G. J. Osório, M. Shafie-khah, M. Lotfi, B. J. M. Ferreira-Silva, and J. P. S. Catalão, "Demand-Side Management of Smart Distribution Grids Incorporating Renewable Energy Sources," Energies, vol. 12, no. 1, p. 143, Jan. 2019.

[4]	M. Alramlawi and P. Li, "Design Optimization of a Residential PV-Battery Microgrid with a Detailed Battery Lifetime Estimation Model," IEEE Trans. Ind. Appl., pp. 1–1, 2020.

[5]	N. B. G. Brinkel et al., "Impact of rapid PV fluctuations on power quality in the low-voltage grid and mitigation strategies using electric vehicles," Int. J. Electr. Power Energy Syst., vol. 118, Jun. 2020.

[6]	G. Osório, M. Shafie-khah, P. Coimbra, M. Lotfi, and J. Catalão, "Distribution System Operation with Electric Vehicle Charging Schedules and Renewable Energy Resources," Energies, vol. 11, no. 11, p. 3117, Nov. 2018.

[7]	H. M. D. Espassandim, M. Lotfi, G. J. Osorio, M. Shafie-Khah, O. M. Shehata, and J. P. S. Catalao, "Optimal operation of electric vehicle parking lots with rooftop photovoltaics," in 2019 IEEE International Conference on Vehicular Electronics and Safety, ICVES 2019, 2019.

[8]	L. Zhang and Y. Li, "Optimal Management for Parking-Lot Electric Vehicle Charging by Two-Stage Approximate Dynamic Programming," IEEE Trans. Smart Grid, vol. 8, no. 4, pp. 1722–1730, Jul. 2017.

[9]	S. Hussain, M. A. Ahmed, and Y. C. Kim, "Efficient Power Management Algorithm Based on Fuzzy Logic Inference for Electric Vehicles Parking Lot," IEEE Access, vol. 7, pp. 65467–65485, 2019.

[10]	M. Shafie-Khah, P. Siano, D. Z. Fitiwi, N. Mahmoudi, and J. P. S. Catalão, "An innovative two-level model for electric vehicle parking lots in distribution systems with renewable energy," IEEE Trans. Smart Grid, vol. 9, no. 2, pp. 1506–1520, 2018.

[11]	Y. Zhang and L. Cai, "Dynamic Charging Scheduling for EV Parking Lots with Photovoltaic Power System," IEEE Access, vol. 6, pp. 56995–57005, 2018.

[12]	M. Yousefi, A. Hajizadeh, and M. N. Soltani, "A Comparison Study on Stochastic Modeling Methods for Home Energy Management Systems," IEEE Trans. Ind. Informatics, vol. 15, no. 8, pp. 4799–4808, Apr. 2019.

[13]	X. Hou, J. Wang, T. Huang, T. Wang, and P. Wang, "Smart Home Energy Management Optimization Method Considering Energy Storage and Electric Vehicle," IEEE Access, vol. 7, pp. 144010–144020, 2019.

[14]	L. Yu, T. Jiang, and Y. Zou, "Online energy management for a sustainable smart home with an HVAC load and random occupancy," IEEE Trans. Smart Grid, vol. 10, no. 2, pp. 1646–1659, 2019.

[15]	M. Sadegh Javadi, M. Lotfi, A. Ashraf, A. E. Nezhad, M. Gough, and J. P. S. Catalao, "A Multi-Objective Model for Home Energy Management System Self-Scheduling using the Epsilon-Constraint Method," in 2020 IEEE 14th International Conference on Compatibility, Power Electronics and Power Engineering (CPE-POWERENG), 2020.

[16]	H. Kikusato et al., "Electric Vehicle Charge-Discharge Management for Utilization of Photovoltaic by Coordination between Home and Grid Energy Management Systems," IEEE Trans. Smart Grid, vol. 10, no. 3, pp. 3186–3197, May 2019.