Coordinated Operation of Electric Vehicle Parking Lots and Smart Homes as a Virtual Power Plant

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***Abstract*— In recent years, virtual power plants (VPPs) rose as an effective framework to aggregate the collective potential of distributed energy resources (DERs), including distributed generation (DG) and energy storage systems (ESS), through demand response (DR) program implementation. In this work, the operation of two indispensable DER assets, electric vehicles (EVs) and photovoltaic-equipped parking lots (PVPLs), is coordinated in an optimal energy management framework, in order to study their possible aggregation as a VPP. The proposed energy management system (EMS) was developed using the optimization and simulation tools, namely GAMS and MATLAB, and is intended for use by grid operators to coordinate the operation of PVPLs and home energy management systems (HEMSs) in the context of smart cities. The developed model was validated and tested by considering real-life case studies in the city of Porto, Portugal.**

***Keywords* — Electric Vehicles, Smart Grid, Power System Operation, Virtual Power Plant, Optimization Methods.**

I. INTRODUCTION

Electric Vehicle (EV) sales, both purely battery-electric and plug-in hybrids, surpassed 2 million units in 2018 which corresponds to a 58% growth over the previous year [1]. The exponential rise of electric mobility in general and consumer-owned EVs in particular made the latter attractive for use as a semi-dispatchable Distributed Energy Resource (DER) which simultaneously serves as an Energy Storage System (ESS), leveraging the overall sustainability and cost-efficiency of power systems [2].

Owing to the variable output of nowadays highly proliferated renewable energy sources (RESs), grid operators are increasingly looking for providers of balancing services, who can either inject or absorb power from the grid at times when demand is lower or higher than available supply, respectively. The batteries in EVs are ideal to provide such balancing, assuming power can flow in either direction in a controllable manner. Since solar photovoltaic (PV) generation is essentially non-dispatchable and time-varying, as opposed to the controllable nature of EVs, both as an electrical load and ESS, coupling the two is intuitive. On one hand, EVs can help the grid with the supply-demand balance, thereby permitting a larger penetration of RESs. On the other hand, PV production could also enable a larger penetration of EVs, since they do not cause a significant net-load increase if charging directly from local PV sources [3].

However, coupling EVs with PVs this manner has to be done with due care; otherwise it might instead compromise grid reliability. For the grid operator, the main concern over PV generation is its uncertainty. As for the EVs, they may trigger a demand spikes. Both situations could potentially lead to critical power quality degradation and stability issues [4]. As such, small-scale distributed on-grid PV power plants and directly charging the EVs can provide a favorable way of circumventing these issues. This is because the grid would not have to integrate a large PV capacity while not requiring a large reinforcement to satisfy heightened EV demand [5].

Moreover, this solution avoids emissions and the charging infrastructure promotes EV adoption. It could be implemented via solar arrays installed as shade structures over parking lots to charge EVs during the day, i.e., EV solar parking lots (EVSPLs). Worldwide, there is plenty of parking space that can be converted to EVSPLs without requiring the use of new land. They may be installed practically anywhere: workplaces, shopping centers, hotels, hospitals, airports, universities, and so on. To take advantage of EVSPLs, cars need to be parked for long enough during daytime, since to fully charge an EV from empty or to top it up one may need several hours, depending on the connection type [6]. Smart EVSPLs may also act as an aggregator of EVs, easing the interaction between the players, in a virtual power plant (VPP) approach. The concept of VPP is a solution which has been developed to address the need for the effective integration of DERs in the electricity grid regarding both technical and economic aspects [7].

In this sense, the VPP is composed of an EVSPL and several prosumers whose assets include EVs and Smart Homes (SHs) equipped with Home Energy Management Systems (HEMS). This work tries to propose a global energy management framework for smart grid operators, which builds upon the fundamental concept of VPPs. The optimal operation of PVPLs and smart homes is coordinated such that the maximum benefit of EVs can be harnessed for the grid while also maximizing the benefit for the owners. HEMSs are coordinated with EMSs of PVPLs and the resulting effect on grid operation and economic gains (or lack thereof) for all players (PL owners, EV owners, grid operators, among others) is investigated in a full techno-economic analysis of the feasibility of the proposed approach as a VPP model.

In the majority of the existing studies the main objective function has been to decrease the operational cost or maximize the operational profit. In this work, the objective is to improve the power grid performance by coordinating EVSPLs and HEMSs, while simultaneously maximizing the economic benefit of all participants (EVSPL and EV owners).

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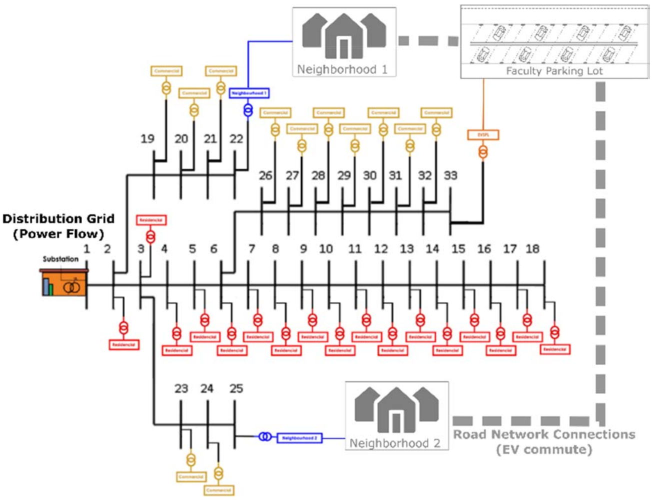

Fig. 1. Conceptual model used for the current study and analysis.

II. METHODOLOGY

A. Conceptual Model

The conceptual model for the proposed VPP model is illustrated in Fig. 1. The following characteristics are present:

- EV owners living in two different smart neighborhoods work and/or attend a faculty which has an EVSPL.
- The faculty EVSPL is operated using the EMS in [6].
- Both neighborhoods have SHs with PV panels and managed using the HEMS proposed in [8]. All the homes participate in a DR program with hourly pricing.
- The power grid is modeled using the IEEE 33-bus standard test system. Neighborhood 1, Neighborhood 2, and the EVSPL are located at buses 22, 25, and 33, respectively.

B. Home Energy Management System Model

The SHs' HEMS in this study is based on [8]. 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:

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

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: 1) Before HEMS implementation, considered as baseline operation intervals based on the end-user preferences; and 2) 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.

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

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).

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

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.

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

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.

$$P_t^D = \sum_{i}^{NA} \sum_{t}^{NT} \left(\frac{S_{i,t} \,.\, P_i}{\Delta t} \right) + \sum_{t}^{NT} \frac{P_f}{\Delta t} \qquad (5)$$

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 that in the previous interval plus the amount of that is transferred (if in charging mode) minus the injected by the battery (if in discharging mode), as 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. Moreover, the energy within the ESS is constrained by upper and lower limits that are defined by Eq. (10).

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

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

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

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

$$E_j^{min} \leq E_{j,t} \leq E_j^{max} \tag{10}$$

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.

$$PV_t = P_t^{PV,used} + P_t^{PV,sold} \tag{11}$$

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:

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

C. *Electric Vehicle Parking Lot Management System Model*

The EVPLMS proposed in [6] 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 EVSPL owners' profit. The inputs to the model can be divided into four parts:

- EV: Arrival/departure times, SOE at arrival, battery specs;
- PV panels: Hourly PV power output at each location;
- Electricity market: Day-ahead, reserve, and regulation up/down prices;
- 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.

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

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

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.

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

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 SOC of 20% and a maximum of 80%, for each EV is been considered.

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

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.

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

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

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

$$SOC_t^{scenario} = \sum Cap_t^{EV} . SOC_t^{EV} \tag{19}$$

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 [6]:

$$\begin{aligned} &\underset{P_{w,t}^{En,\ PL2G},\ P_{w,t}^{En,\ G2PL},\ P_{w,t}^{Res},\ P_{w,t}^{Res,\ Act},\ soc_{w,t}^{up}, soc_{w,t}^{down}}{Maximize} \{profit^{PL}\} = \\ &Max \sum_w \pi_w \sum_t \{P_{w,t}^{En,\ PL2G} . \lambda_t^{En} + P_{w,t}^{Res} . \lambda_{w,t}^{Cap,Res} + P_{w,t}^{R\text{-}up\ ,\ Act} . \lambda_t^{R\text{-}up} \\ &+ P_{w,t}^{R\text{-}down\ ,\ Act} . \lambda_t^{R\text{-}down} P_{w,t}^{Res\ ,\ Act} . \lambda_t^{En} \\ &+ soc_{w,t}^{up} . \lambda_t^{Tariff,\ V2G} + n_t^{PL} . \lambda_t^{Tariff,stay} - P_{w,t}^{En,\ G2PL} \lambda_t^{En} \\ &- \big(P_{w,t}^{Res\ ,\ Act} . \Gamma^{Res} + P_{w,t}^{R\text{-}up} . \Gamma^{R-up} \\ &\qquad + P_{w,t}^{R\text{-}down} . \Gamma^{R-down} \big) \lambda_t^{En} \pi^{unvail.} \\ &- P_{w,t}^{Res\ ,\ Act} . \lambda_t^{Tariff,\ V2G} - soc_{w,t}^{down} . \lambda_t^{Tariff,\ V2G} \\ &- \big(P_{w,t}^{En,\ PL2G} + P_{w,t}^{Reg\ ,\ Act}\big) Cd\} \end{aligned} \tag{20}$$

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, in addition to the AC Optimal Power Flow Studies using the MATPOWER package.

III. CASE STUDY

1) Different Case Studies Considered

For the purpose of evaluating the possible aggregation of the EVSPL and the SHs, as a virtual power plant, four case studies have been considered:

- **Case 1**: No HEMS and No EVPLMS (base case)
- **Case 2**: HEMS and No EVPLMS
- **Case 3**: No HEMS and EVPLMS
- **Case 4**: HEMS and EVPLMS

The first case study was defined as a reference/base case, where neither the HEMS nor the EVPLMS were considered. In the first and third case studies, the EVs and the other loads of the neighborhoods are supplied without adopting any energy management methods while in the second and fourth case studies, the proposed HEMS is adopted for optimally planning of energy consumption/production.

Moreover, in the third and fourth case studies, the existence of an EVSPL, with the respective energy management system, is considered. The number of smart homes matches the capacity of electric vehicles in the parking lot, which are equal to 108, for the proposed study. In other words, each EV is associated to one SH. Moreover, the SHs are grouped in two neighborhoods, located in distinct regions and with different driving distances from the parking lot. The network used for the proposed model, illustrated in Fig. 1, is based on a modified IEEE 33-bus distribution test system and includes renewable and non-renewable generation. As it shown, the parking lot is located on bus 33 and the two neighborhoods on bus 22 and 25, respectively. For the other buses it was considered some Portuguese residential low voltage profiles, BTE and BTN C, respectively, which were constructed based on the information from the Portuguese Energy Regulation Services Entity (ERSE) [9].

The output PV power through an entire specific day was determined considering a house located in Gondomar (41°06'45.8"N 8°32'02.3"W). For the present study, a summer day was chosen, more specifically the first day of July 2019. This house has a photovoltaic production unit of 16 panels with an ESS installed (small batteries). The data was collected from the service Victron Remote Management provided by Victron Energy to their users to remotely monitor their installations all over the world [10]. To obtain the PV Rooftop generation profile, first the normalization of the PV production profile from ERSE [9] is done, so that values fall between 0 and 1. In other words, all the values, during a specific day, from the ERSE profile, are divided by the maximum value registered in p.u., so that the value 1 corresponds now to the maximum value observed. Finally, the normalized data is transformed according to the hourly PV production values coming from the house in order to create a more realistic profile.

The PV power outputs for each house and for the EVSPL are shown in Fig. 2. As shown, the maximum power output occurs at hour 9, which corresponds to the period between 14:00h and 15:00h. In this work, the 24-hour period starts at 06:00h (1 July 2019) and it ends at 06:00h of the next day.

2) *Inputs for HEMS*

The proposed HEMS was implemented in General Algebraic Modeling System (GAMS), applying the Mixed Integer Programming (MIP) solver. The total numbers of houses, analyzed in this work, are distributed by 2 different neighborhoods. The first one is inhabited by students/researchers and the second one by teachers, that share the same parking lot at University. Moreover, the first neighborhood has a total of 72 houses and the second one 36.

Each house has an installed PV system of 3 kW and 48V lithium-ion storage battery, and the same number of home appliances, including one EV. The panel and battery data are shown in Table I and II, respectively. In order to evaluate the proposed model, the self-scheduling of 10 different appliances is analyzed to show the effect of a price-based demand response program on the daily bill before and after implementation of HEMS.

Although the home appliances are common to all the houses, their specifications, like the duration, the baseline time intervals and the allowable operation ranges, can be different according to the end-user's preferences and needs.

The prices, available in Table III, are fixed for a specific period, being higher at peak hours and cheaper in off-peak hours, with the aim to incentivize the end-user to reduce the consumption in peak-hours and increase the consumption in off-peak hours in order to allow a more efficient use of the generation, transmission and distribution resources [11].

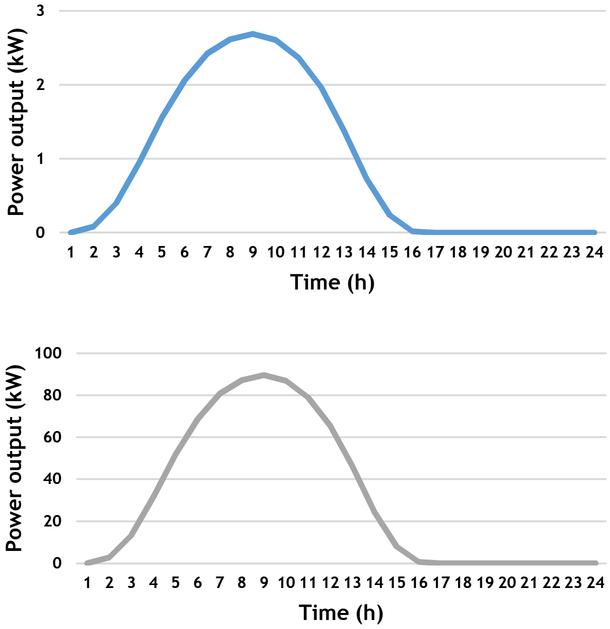

Fig. 2. SH PV system output (top) and EVSPL PV system output (bottom).

TABLE I. HOME PV PANEL DATA [10].

Panel Model	P_{MPP}	V_{MPP}	I_{MPP}	V_{OC}	I_{SC}
SPP042702000	270 W	31.70 V	8.52 A	38.04 V	9.21 A

TABLE II. HOME BATTERY SPECIFICATIONS [12].

Battery Model	Usable Energy	Round-trip η	Max Ch. / Disch. Power
LG RESU 6.5kWh	5.9 kWh	95.0 %	4.2 kW

TABLE III. HOURLY PRICES FOR THE CONSIDERED DAY [87].

Hour	EUR/kWh	Hour	EUR/kWh
00:00-01:00	0.1025	12:00-13:00	0.2287
01:00-02:00	0.1025	13:00-14:00	0.1704
02:00-03:00	0.1025	14:00-15:00	0.1704
03:00-04:00	0.1025	15:00-16:00	0.1704
04:00-05:00	0.1025	16:00-17:00	0.1704
05:00-06:00	0.1025	17:00-18:00	0.1704
06:00-07:00	0.1025	18:00-19:00	0.1704
07:00-08:00	0.1025	19:00-19:30	0.1704
08:00-09:00	0.1704	19:30-20:00	0.2287
09:00-10:00	0.1704	20:00-21:00	0.2287
10:00-10:30	0.1704	21:00-22:00	0.1704
10:30-11:00	0.2287	22:00-23:00	0.1025
11:00-12:00	0.2287	23:00-00:00	0.1025

The specifications of 10 shiftable home appliances regarding one of the 108 smart houses are shown in Table IV, where (Pi) is the rated power of the corresponding appliance and (Ti) the total operation time, in time intervals of 30 minutes. LBb and UBb are the lower and upper bound for the baseline time intervals, respectively. LBs and UBs are the lower and upper bound of the allowable time intervals, respectively.

The total time slots are set as 48, covering 24 hours, and starting at 6:00 am of the first day of July 2019. In other words, the first hour (time slot 1 and 2) comprises the time between 6:00 and 7:00 am. The intervals for some appliances, like the EV, are related with the daily work schedule of its owner, which is elaborated subsequently.

TABLE IV. SPECIFICATIONS OF SHIFTABLE HOME APPLIANCES

Appliance	***Pi***	***Ti***	***LBb***	***UBb***	***LBs***	***UBs***
Dishwasher (1)	1.8	4	5	8	5	10
Washing Machine (2)	0.5	3	6	8	6	10
Clothes Dryer (3)	3.0	2	11	12	11	15
Living Room AC (4)	1.5	2	29	30	28	31
Microwave (5)	1.2	1	29	29	29	30
Laptop (6)	0.1	4	31	34	31	38
Cooker Hob (7)	1.5	1	29	29	29	30
Vacuum Cleaner (8)	1.4	2	9	10	9	12
Room AC (9)	1.0	1	33	33	33	36
Electric Vehicle (10)	3.3	9	28	36	28	47

3) *Inputs for EVPLMS*

The EVPLMS model was implemented in General Algebraic Modeling System (GAMS), applying the MIP solver. In order to evaluate the model, the parking lot from Engineering Faculty of the University of Porto (FEUP), in Porto (41º 10’ 40.8’’ N, 8º 35’ 52.8’’ W), has been considered, as elaborated in [6]. Furthermore, in order to fully analyze the bidirectional energy exchanges between the EVSPL and the grid, a distinct pattern between the prices of energy, reserve and regulation has been considered (different electricity markets). The 100kW rooftop PV output power, presented in Fig. 2, of a typical summer day has been investigated. All the EVs are supposed to be Nissan Leaf with a battery capacity of 30 kWh [2]. With regards to EV charging the following assumptions were made:

- Charging efficiency is 90 % for all EVs;
- Discharging efficiency is 81 % for all EVs;
- Min. and max. SOC is 20% and 80%, respectively;
- Parking lot charge (and discharge) rate is 3.3 kWh;

It is also assumed that the EV owners pay 0.246 EUR/kWh to charge their cars, which represents the charging tariff from one of the Portuguese networks and it has been extracted from [13]. As for the energy prices, the data obtained from the first day of July 2019 of the Portuguese market have been used [14], expressed in the Fig. 3.

The arrival and departure times of EVs are randomly distributed according to on a normal distribution based on a study of the FEUP parking lot [6]. The distribution of arrival times is divided into two groups, depending on the work schedule of the EV owners (morning or afternoon), as shown in Table V. It is assumed that the parking lot is not used during the night-time. Moreover, the SOC lost in the trip home to university and vice-versa, for the 2 neighborhoods are arbitrarily distributed according to on a normal distribution, as shown in Table VI.

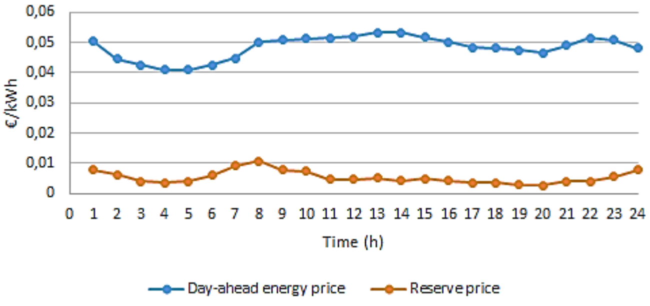

Fig. 3. Considered prices for EVSPL (July 2019).

TABLE V. EVS PROBABILITY DISTRIBUTION PARAMETERS (ARRIVAL/DEPARTURE TIMES).

Work Schedule		**Mean**	**Std. Deviation**	**Max**
Morning	Arrival Time	9:00	50 min	11:30
	Departure Time	18:00		-
Afternoon	Arrival Time	14:00	50 min	16:30
	Departure Time	21:00		-

TABLE VI. EVS PROBABILITY DISTRIBUTION PARAMETERS (TRIP SOC LOST DURING COMMUTE FROM EACH NEIGHBORHOOD).

Commute to EVSPL from		**Mean**	**Std. Deviation**
Neighborhood 1	SOC Lost	20%	2%
Neighborhood 2	SOC Lost	30%	3%

IV. RESULTS AND DISCUSSION

A. *Case 2: HEMS without EVPLMS*

The simulation results for case 2 are shown in Fig 4. The HEMS is used at neighborhoods 1 and 2, at buses 22 and 25, respectively (with uncontrolled charging at the faculty parking lot). There is a 1.749 MW reduction in total active power losses. The voltage profiles clearly show that the upper and lower voltage limits have not been violated.

B. *Case 3: EVPLMS without HEMS*

The simulation results are shown in Fig. 5. There was a mere 0.004 MW reduction in total active power losses, which is insignificant to the previous case. The active power losses and voltage support to the grid are both clearly tied to the level of PV production at the EVSPL.

C. *Case 4: EVPLMS and HEMS*

The results for case 4 clearly show a synergistic effect of employing both the HEMS and EVPLMS. The active power losses compared to the base are shown in Fig. 6.

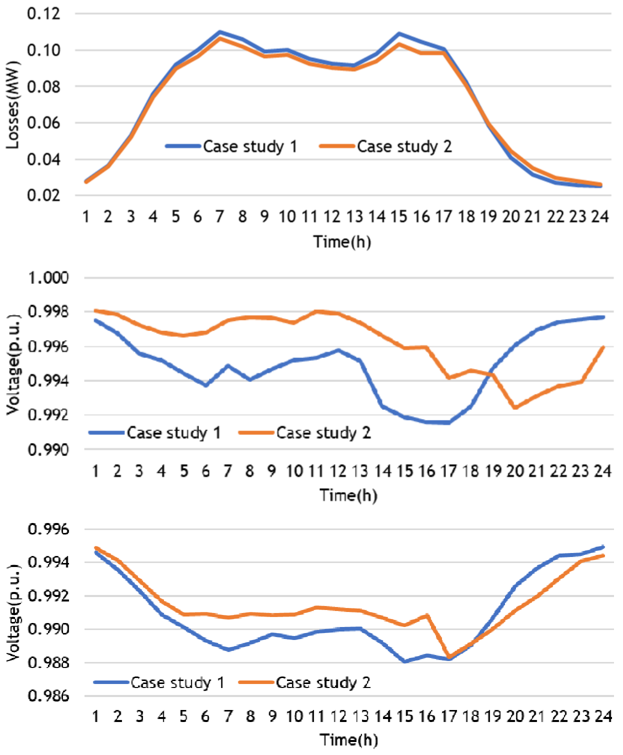

Fig. 4. Comparison between base case and case 2: hourly total active power losses (top), hourly voltage levels at buss 22 (middle) and bus 25 (bottom).

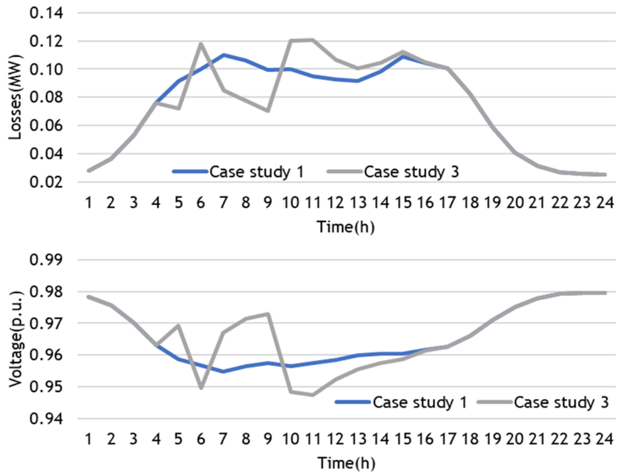

Fig. 5. Comparison between base case and case 3: hourly total active power losses (top), hourly p.u. voltage level at buss 33 (bottom) and bus 25.

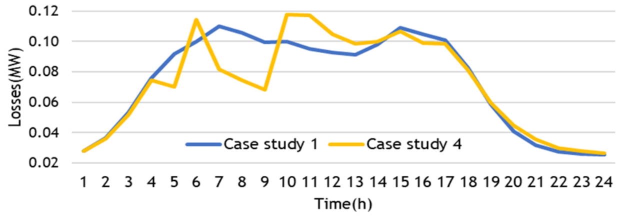

Fig. 6. Comparison between case study 4 and 1 - Total line losses in MW.

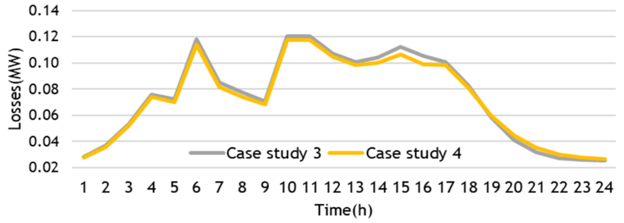

Fig. 7. Comparison between case study 4 and 3 - Total line losses in MW.

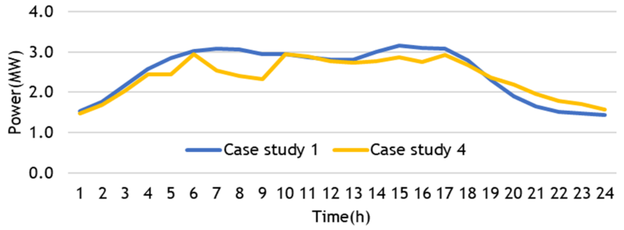

Fig. 8. Comparing case 4 and 1: active power supplied by the grid.

In Fig. 7 it is shown that the simultaneous employment of the EVPLMS and the HEMS at both neighbourhoods leads to a further decrease in total system losses. Fig. 8 shows that the total active power supplied by the grid is decreased compared to the base case. As it can be observed, the power supplied by the grid is lower in the case study 4 almost for all the hours, with exception between 15:00h and 17:00h (hours 10-11), due to an increase of demand verified in the EVSPL, and between 00:00h to 06:00h (hours 19-24) due to an increase of demand verified in the smart houses. Even so, the total reduction achieved, when both the EVPLMS and the HEMSs, is around 2.670 MW.

V. CONCLUSIONS

In this study, a distribution system with residential neighborhoods and a faculty parking lot equipped with PV generation was modeled. The effect of installing HEMSs at the homes and an EVPLMS at the faculty EVSPL was investigated in terms of active power losses and impacts on the voltage profiles. The simulations have shown that the installation of the EMSs led to a significant decrease in active power losses and the total energy supplied by the upstream grid, while maintaining voltage constraints. Given that the EV owners' preferences and work schedules are used as input for both EMSs, the improvement in grid operation is achieved without any sacrifice of user comfort.

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