Optimal Operation of Electric Vehicle Parking Lots with Rooftop Photovoltaics

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***Abstract*— Due to the rapidly increasing share of electric vehicles (EVs) worldwide, the abundance of EV parking lots (with charging capabilities) is becoming necessary to provide for charging needs in addition to attempting to fully utilize EVs for the benefit of future smart grids. Unmanaged charging of EVs can jeopardize stability and reliability of power systems. Hence, well-operated EV parking lots can be a good solution to enhance system stability. Equipping parking lots with rooftop photovoltaics (PVs) has been gaining interest as a good approach for their design and operation. During the day, when EVs are stationed in the parking lot and particularly in more commercial neighborhoods of cities, the EVs can be charged directly through solar generation, so that minimal stress on the distribution system occurs. This work aims to conduct a comparative study investigating the optimal strategies for the operation of PV-equipped EV parking lots. Multiple parameters are taken into consideration including weather conditions, uncertainty of EV owners' schedules, and EV models. This analysis will result in finding the optimal strategy for the operation of the parking lot from the owner/operator point of view in order to minimize costs and maximize services provided to the grid.**

Keywords—Electric vehicles, Energy scheduling, Optimal operation, PV rooftop.

NOMENCLATURE

t	Time
β	Tilt angle
w	Scenario
$P^{En,\ G2PL}$	Injection of the grid to the parking lot
$P^{En,\ PV2PL}$	Injection of the PV rooftop to the parking lot
γ	Rate of charge and discharge of the parking lot
n^{PL}	Number of parked EVs
$P^{En,\ PL2G}$	Injection of the parking lot to the grid
$P^{Res,\ Act}$	Injection on the reserve activated by ISO
SOC	State of Charge
$SOC^{Scenario}$	Energy held in the PL obtained from the input scenarios
Cap^{EV}	Capacity of EV battery
P^{PV}	PV module power
N_s	Number of PV modules connected in series
N_p	Number of PV modules connected in parallel
V^{OC}	PV module open circuit voltage
I^{SC}	PV module short circuit current
FF	Fill Factor
STC	Standard Test Conditions
K_v	Open circuit voltage temperature coefficient
K_I	Short-circuit current temperature coefficient
T^C	Cell temperature
NCOT	Nominal operating cell temperature,
G	Global solar irradiance
T^{amb}	Ambient temperature
η^{PV}	PV module efficiency
λ^{En}	Energy Price
$\lambda^{Cap,\ Res}$	Price for the capacity payment for
$\pi^{unvail.}$	Scenario Probability of being unavailable to
$\lambda^{Tariff,G2V}$	Charging tariff
λ^{R-up}	Regulation up price
λ^{R-down}	Regulation down price
$\lambda^{Tariff,stay}$	Parking usage tariff
Cd^{En}	Battery degradation cost due to energy market
Γ^{Res}	Penalty for not distributing the offered reserve
Cd^{Reg}	Battery degradation cost due to regulation
Γ^{R-up}	Penalty for not distributing the offered
Γ^{R-down}	Penalty for not distributing the offered

I. INTRODUCTION

A. Motivation

With the recognition of climate change as the most serious and threatening global environmental problem, there is an urgent need to find alternatives to enhance society's de-carbonization while decreasing greenhouse gas (GHG) emissions. On one hand, global demand is increasing due to the fast population and economic growth, leading to negative environmental impacts. To fulfill demand requirements, a large-scale penetration of renewable energy sources (RESs) is needed. Among the several RESs, solar photovoltaic (PV) energy is considered as one with the most potential to achieve a low-carbon electricity sector due to two main reasons. First, the sun is the most abundant and inexhaustible source of renewable energy on Earth. Second, the PV market is growing quickly, attracting high levels of investment, which accelerates the decrease of PV cost and payback time [1].

On the other hand, a key element of sustainable development is the electrification of the transport sector, which accounts for around 25% of GHG emissions [2]. To achieve this, EVs need to be widely accepted in the future. Proper application of supportive mechanisms for EVs (e.g., tax cuts to reduce the financial cost for consumers wanting to purchase an EV) can lead towards the electrification of transport sector and consequently sustainable development in future systems.

Electric vehicles are parked for a considerable time during the day being exposed to sunlight. Additionally, 26% of worldwide EVs charging stations are located in parking lots (PL) [3], mostly located near urban populations hubs such as workplaces, shopping centers, hotels, hospitals, and airports. Combining these factors to PV power generation, i.e., covering PLs with rooftop PV systems, presents an opportune and reasonably priced solution for EV charging requirements.

Therefore, the interaction of PV generation and EVs becomes beneficial, since it not only gives the possibility to better cope with power supply and demand but also provides technical and financial utilization of EV parked time. Despite all the evident advantages, some complexities are in the way, such as random arrival/departure times, expected parking duration and the large diversity of EV models. Moreover, from the demand's perspective, the initial state-of-charge (SOC) can also create additional operational problems. In contrast, from the generation's perspective, PV power enlarge problems in terms of grid stability due to its intermittent essence. Accordingly, the aim of this paper is to provide a feasible solution for optimal operation of a PV-equipped EV parking lot, considering several parameters including weather conditions, EV driver's behaviors. On this basis, the proposed model maximizes the parking lot profit that results from market interactions and individual contracts with EV owners.

B. *Literature Review*

A significant number of studies in the literature have evaluated the impacts of PLs on the electrical grids from different perspectives. Among them, in [4] an analysis of the positive impacts of massive plug-in EVs integration is presented on the demand's point of view and PV production on provision perspective. It also investigates the impacts of peak capacity requirements and PV reduction. The area of optimization of the charging/discharging behavior of EVs with different operation objectives is a commonly investigated idea in the literature.

In [5] is presented a model of an EV solar parking lot in order to find the optimal EV's charging scheduling in a PL while maximizing PL's profit. With the development of the technologies, there are more terms related to EVs. The grid-to-vehicle (G2V) and vehicle-to-grid (V2G) allows EVs to cooperate in two different ways with the grid: either through the sell or the purchase of power when needed [6]–[8]. A description of the potential economic returns for using V2G operation mode either as a frequency regulation provider and for peak load reduction is presented in [6]. The economic feasibility of combining these two V2G modes is analyzed in [8]. More recently, the impacts of solar parking's size and its effects on the power grid are discussed in [9] .

C. *Problem Statement*

In order to address the need for integrating more accurate models of PV generation conditions in PL's behavior determination, this study provides a model to optimize the operation of an EV parking lot. Deploying the traffic pattern of EVs from real-case scenarios, a model is proposed in this paper to optimize the parking lot's performance from the operator's point of view. For this reason, the proposed model aims to find the optimal strategy for the operation of the parking lot from the operator's point of view, while maximizing the parking lot's profit from owner/operator perspective, that outcomes from market participations and agreements with EV drivers. The main contributions of this study are listed below:

- The effect of PV generation uncertainty is evaluated considering different season weather conditions such as the inconsistency of the solar irradiance during the day.
- The incorporation of EV's behaviors such as arrival and departure times and arrival SOC.
- The economic impacts of integrating a PV rooftop system on an electric vehicle PL operation.

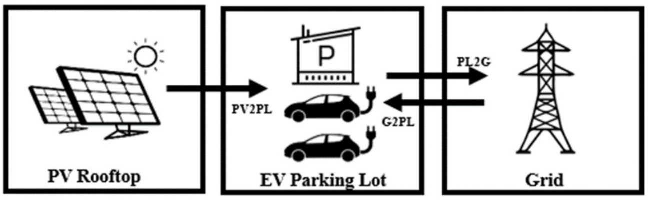

Fig. 1. EV parking lot equuiped with rooftop PV.

II. METHODOLOGY

The proposed electric vehicle PL with a rooftop photovoltaic system scheme which allows bidirectional power is illustrated in Fig. 1. For the purpose of making accurate assumptions and investigating impacts of EVs, two different areas which are residential/student populated and mainly student populated regions are considered. The proposed model has been considered in a 14-bus distribution network.

The PV rooftop is sized according to the Hanwha QCELLS PV panel [10], which is modelled based on parameters provided by the manufacturers datasheet as presented in Table I.

A. *Equations of Parking Lot*

The limits of $\mathrm{P}^{\mathrm{En,\,G2PL}}$ and $\mathrm{P}^{\mathrm{En,PV2PL}}$ are presented in (1) and (2).

$$P_{w,t}^{En,G2PL}+P_{w,t}^{PV2PL}\leq\gamma^{charge}.n_t^{PL} \tag{1}$$

$$P_{w,t}^{En,\,PL2G}+P_{w,t}^{Res\,,\,Act}\leq\gamma^{discharge}.n_t^{PL} \tag{2}$$

The SOC of the parking lot is formulated as shown in (3) [11]:

$$\begin{aligned} soc_{w,\,t}&=soc_{w,\,t\text{-}1}+soc_{w,t}^{arrival}\text{-}soc_{w,t}^{departure}\\ &+(P_{w,t}^{En,\,PL2G}+P_{w,t}^{PV2PL}).\eta^{charge}\text{-}\frac{P_{w,t}^{En,PL2G}+P_{w,t}^{Res,\,Act}}{\eta^{discharge}} \end{aligned} \tag{3}$$

The EVs that arrive/depart to/from the PL present the following SOC upon arrival/departure [11]:

$$soc_{w,t}^{arrival}=\begin{cases} 0,\ SOC_{w,t}^{Scenario}\leq\ SOC_{w,t\text{-}1}^{Scenario}\\ SOC_{w,t}^{Scenario}\text{-}\ SOC_{w,t\text{-}1}^{Scenario},\ SOC_{w,t}^{Scenario}<SOC_{w,t\text{-}1}^{Scenario} \end{cases} \tag{4}$$

$$soc_{w,t}^{departure}=\begin{cases} 0,\ SOC_{w,t\text{-}1}^{Scenario}\ \leq SOC_{w,t}^{Scenario}\\ \dfrac{\left(SOC_{w,t\text{-}1}^{Scenario}\text{-}\ SOC_{w,t}^{Scenario}\right).soc_{w,\,t}}{SOC_{w,t}^{Scenario}},\ SOC_{w,t}^{Scenario}<SOC_{w,t\text{-}1}^{Scenario} \end{cases} \tag{5}$$

where $SOC_{w,t}^{Scenario}$ is represented by (7):

$$SOC_{w,t}^{Scenario}=\sum Cap_{w,t}^{EV}.\,SOC_{w,t}^{EV} \tag{6}$$

The SOC of departure EVS is presented in (7) and (8) [11]:

$$soc_{w,t}^{up}=\begin{cases} 0,\ \ soc_{w,t}^{departure}\leq SOC_{w,t}^{Scenario}\text{-}SOC_{w,t\text{-}1}^{Scenario}\\ soc_{w,t}^{departure}\text{-}\ SOC_{w,t}^{Scenario}\text{-}\ SOC_{w,t\text{-}1}^{Scenario},\ Otherwise \end{cases} \tag{7}$$

$$soc_{w,t}^{down}=\begin{cases} 0,\ \ SOC_{w,t}^{Scenario}\text{-}SOC_{w,t\text{-}1}^{Scenario}\leq soc_{w,t}^{departure}\\ soc_{w,t}^{departure}\text{-}\ SOC_{w,t}^{Scenario}\text{-}SOC_{w,t\text{-}1}^{Scenario},\ \ Otherwise \end{cases} \tag{8}$$

The limits of the total SOC of the parking lot are presented in (9) [11].

$$\sum SOC^{EV\,,min}\leq\ soc_{w,t}\leq\sum SOC^{EV\,,max} \tag{9}$$

TABLE I. PV PANEL DATA

Panel Model	P_{MPP}	η	V_{MPP}	I_{MPP}
Q.PEAK-G4.1	300 W	18.0 %	32.41 V	9.26 A

B. Equations for PV Generation

The maximum output PV power at hour t is determined through the PV module parameters specified by the manufacturer and it can be formulated as (10)-(13) [12]:

$$P^{PV}_{t,\beta} = N_s \times N_p \times V^{OC}_{t,\beta} \times I^{SC}_{t,\beta} \times FF_t \tag{10}$$

$$V^{OC}_{t,\beta} = V^{OC}_{STC} - K_v . T^c_t \tag{11}$$

$$V^{OC}_{t,\beta} = \{I^{SC}_{STC} + K_I . [T^c_t - 25\,°C]\} \frac{G_{t,\beta}}{1000} \tag{12}$$

$$T^c_t = T^{amb} + (T^{NOCT} - 20\,°C) \times \frac{G_{t,\beta}}{800} \tag{13}$$

Therefore, the hourly power injected to the PL is presented in (14):

$$P^{En,PV2PL}_{t,\beta} = \eta^{PV} \times N^S \times N^P \times P^{PV}_{t,\beta} \tag{14}$$

C. Optimization Model

The objective function is illustrated in (15). As it can be observed, the profit results from the difference between nine incomes and nine costs terms:

$$\begin{aligned}
&\underset{P^{En,\,PL\,2G}_{w,t},\, P^{En,\,G\,2PL}_{w,t},\, P^{Res}_{w,t},\, P^{Res,\,Act}_{w,t},\, soc^{up}_{w,t},\, soc^{down}_{w,t}}{Maximize} \{profit^{PL}\} = \\
&Max \sum_w \pi_w \sum_t \{P^{En,\,PL2G}_{w,t} . \lambda^{En}_t + P^{Res}_{w,t} . \lambda^{Cap,Res}_{w,t} + P^{R\text{-}up\,,\,Act}_{w,t} . \lambda^{R\text{-}up}_t \\
&+ P^{R\text{-}down\,,\,Act}_{w,t} . \lambda^{R\text{-}down}_t P^{Res\,,\,Act}_{w,t} . \lambda^{En}_t \\
&+ soc^{up}_{w,t} . \lambda^{Tariff,\ V2G}_t + n^{PL}_t . \lambda^{Tariff,stay}_t - P^{En,\,G2PL}_{w,t} \lambda^{En}_t \\
&- (P^{Res\,,\,Act}_{w,t} . \Gamma^{Res} + P^{R\text{-}up}_{w,t} . \Gamma^{R-up} + P^{R\text{-}down}_{w,t} . \Gamma^{R-down}) \lambda^{En}_t \pi^{unvail.} \\
&- P^{Res\,,\,Act}_{w,t} . \lambda^{Tariff,\ V2G}_t - soc^{down}_{w,t} . \lambda^{Tariff,\ V2G}_t \\
&- (P^{En,\,PL2G}_{w,t} + P^{Reg\,,\,Act}_{w,t}) Cd\}
\end{aligned} \tag{15}$$

The different terms of objective function, i.e., incomes and costs, are elaborated below in (16) to (33)

$$IncomePL1_{t,PVscen} = \sum_t P^{En,\,PL2G}_{w,t} \times \lambda^{En}_t \tag{16}$$

$$IncomePL2_{t,PVscen} = \sum_t P^{Res,\,PL2G}_{w,t} \times \lambda^{Cap,Res}_t \tag{17}$$

$$IncomePL3_{t,w} = \sum_t P^{Res,\,PL2G}_{w,t} \times \pi^{unvail.} \times \lambda^{Cap,Res}_t \tag{18}$$

$$IncomePL4_{t,w} = \sum_t (P^{En,\,PV2PL} + P^{En,\,G2PL}_{w,t}) \times \lambda^{Tariff,G}_t \tag{19}$$

where $\lambda^{Tariff,G2V}_t$ represents the charging tariff from one of the Portuguese networks and it has been extracted from [13].

$$IncomePL5_{t,w} = \sum_t P^{Reg,\,PL2G}_{w,t} \times \lambda^{R-up}_t \tag{20}$$

$$IncomePL6_{t,w} = \sum_t P^{Reg,\,G2PL}_{w,t} \times \lambda^{R-down}_t \tag{21}$$

$$IncomePL7_{t,w} = \sum_t n^{PL}_t \times \lambda^{Tariff,stay} \tag{22}$$

where $\lambda^{Tariff,stay}$ corresponds to an average parking usage tariff in Porto, Portugal and has been extracted from [14].

$$IncomePL8_{t,w} = \sum_t P^{Reg,\,PL2G}_{w,t} \times \pi^{unvail.} \times \lambda^{R-up}_t \tag{23}$$

$$IncomePL9_{t,w} = \sum_t P^{Reg,G2PL}_{w,t} \times \pi^{unvail.} \times \lambda^{R-down}_t \tag{24}$$

$$CostPL1_{t,w} = \sum_t P^{Res,\,PL2G}_{w,t} \times \pi^{unvail.} \times Cd^{En} \tag{25}$$

$$CostPL2_{t,w} = \sum_t P^{En,\,G2PL}_{w,t} \times \lambda^{En}_t \tag{26}$$

$$CostPL3_{t,w} = \sum_t P^{En,\,PL2G}_{w,t} \times \lambda^{Tariff,G2V}_t \tag{27}$$

$$CostPL4_{t,w} = \sum_t P^{Res,\,PL2G}_{w,t} \times \pi^{unvail.} \times \lambda^{Cap,Res}_t \times \Gamma^{Res} \tag{28}$$

$$CostPL5_{t,w} = \sum_t P^{Res,\,PL2G}_{w,t} \times \pi^{unvail.} \times \lambda^{Tariff,G2V}_t \tag{29}$$

$$CostPL6_{t,w} = \sum_t P^{En,\,PL2G}_{w,t} \times Cd^{En} \tag{30}$$

$$CostPL7_{t,w} = \sum_t P^{Reg,\,PL2G}_{w,t} \times Cd^{Reg} \tag{31}$$

$$CostPL8_{t,w} = \sum_t P^{Reg,\,PL2G}_{w,t} \times \pi^{unvail.} \times \lambda^{En}_t \times \Gamma^{R-up} \tag{32}$$

$$CostPL\,9_{t,w} = \sum_t P^{Reg,\,PL2G}_{w,t} \times \pi^{unvail.} \times \lambda^{En}_t \times \Gamma^{R-down} \tag{33}$$

III. CASE STUDIES

For the purpose of analyzing the effect of different power output level, two cases studies have been considered: the PL from a public middle school in Porto, Portugal, and the students' parking lot in the Faculty of Engineering, University of Porto (FEUP). For each case, three different scenarios have been studied considering the variability of the solar irradiance during the day and different seasons.

Scenario I represents the base case where no PV generation is modelled and it is divided in two scenarios according to winter and summer. In scenario II, a 100 kW PV rooftop (with a panel area of nearly 558 m^2) in a typical winter day has been analyzed. Similarly, in scenario III a 100 kW PV rooftop in a typical summer day has been investigated.

In this study, two seasonal power curves, are constructed since PV power generation is mainly conditioned by weather conditions. The power PV output is demonstrated in Fig. 2 which is calculated using the real solar irradiance data of Porto shown in Table II.

All EVs are assumed to be Nissan Leaf [15], so the batteries were expected to be identical for all EVs with the capacity of 30 kWh. The initial SOC of each EV is considered a random variable between 0.2 and 0.8. In order to totally study the market contribution of the parking lot, the data from the Portuguese energy market has been considered. This data corresponds to January 2016 and July 2016 of the Portuguese market [16]. The market prices are presented in Fig. 3.

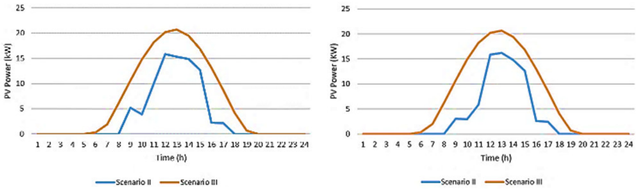

Fig. 2. PV daily power production curve for two seasons.

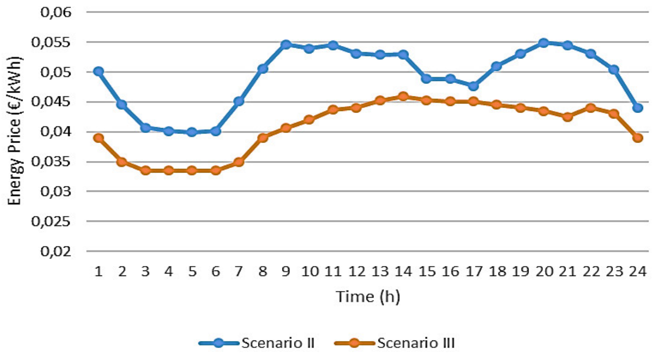

Fig. 3. Considered hourly prices for Scenarioes II and III.

TABLE II. SOLAR IRRADIANCE DATA FOR EACH SEASON

	Solar Irradiance (W/m^2)			
	Middle School		FEUP	
Time	Winter	Summer	Winter	Summer
06:55	0	107.75	0	112.91
07:55	0	335.91	0	341.45
08:55	297.19	570.12	177.23	575.03
09:55	224.54	777.07	173.73	780.69
10:55	554.35	935.85	332.6	937.69
11:55	849.71	1029.19	851.13	1029.07
12:55	821.81	1049.57	864.55	1047.53
13:55	799.31	996.73	797.42	993.03
14:55	689.84	872.20	686.77	867.20
15:55	129.61	689.23	148.80	683.40
16:55	125.88	464.64	139.31	458.49
17:55	0	228.15	0	222.33
18:55	0	37.53	0	37.65

A. *Public School Parking Lot*

For this case study, two different scenarios are conducted according to two seasons (Winter and Summer) considering the PL located in a public middle school. Real data for vehicle's arrival and departures were collected on a weekday (Tuesday 2 April 2019) from 8:00 am until 19:00 pm, at the parking lot of middle school. This parking lot serves school professors, employees and local residents. In this case study, it is assumed that the PL is only monitored during the class period. The arrival/departure schedule of the EVs is shown in Fig. 4.

B. *FEUP Students Parking Lot*

For this case study, two different scenarios are investigated according to two seasons (Winter and Summer) in order to evaluate the proposed model for the students parking lot at FEUP. The arrival and departures times of EVs are arbitrarily distributed according to on a normal distribution based on a study of FEUP student's parking lot. The distribution of arrival times is supposed to be in between 9:00 am and 18:00 pm and 14:00 pm and 21:00 pm. It is assumed that the PL it is not monitored during night time. Therefore, EVs are not accounted. The arrival/departure patterns of the EVs are shown in Fig. 5.

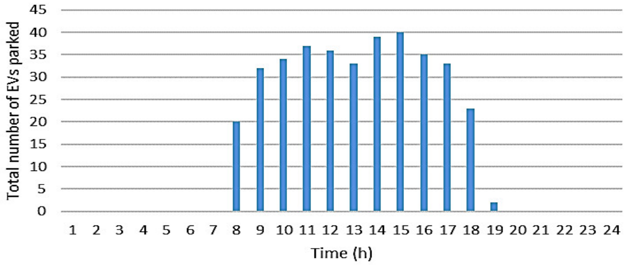

Fig. 4. Total number of EVs in the PL in each hour based on their expected stay duration (Public Middle School Parking Lot).

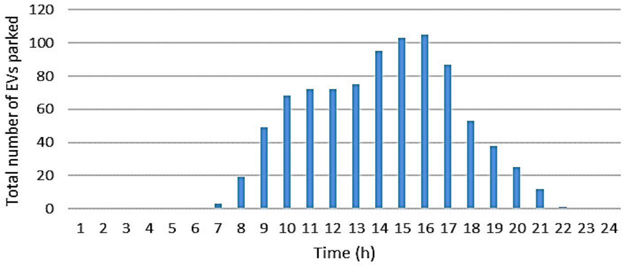

Fig. 5. Total number of EVs in the PL in each hour based on their expected stay duration (FEUP).

IV. RESULTS AND DISCUSSION

A. *Public Middle School Parking Lot*

The total SOC of the parking lot is illustrated in Fig. 7. As it is illustrated, the highest commutative amount of SOC of EVs in the parking lot occurs between hours 9 and 11 and 15 and 17. Additionally, in scenario III the SOC of the parking lot is higher than the other cases in the majority of the hours. Table III presents the different terms of the EV parking lot operator's profit for the considered scenarios. As it can be seen, scenario I is the less profitable scenario, as would be predictable from a base case. A higher PV output mostly seems to result in a higher profit for the EV parking lot.

According to Table III scenario III is the most gainful one for the parking lot. In this case, the parking lot has the highest income from charging the EVS. Moreover, it can be observed that the energy market is preferred to the reserve market. This can be due to low reserve price considered. Regarding EV parking lot's costs, as can be observed, increasing PV power output can increase the cost of the distribution system. This is because in the presence of PV generation, the parking lot discharges some EVs when PV power generation is low and market prices are high. Equally in the evening, the PL discharges the remaining EVs in the parking lot, when the market prices are also high. Both these factors increase the cost paid to EVs for discharge. Moreover, comparing scenario II and scenario II, the numerical results shows that, in the energy market, interaction between the EV parking lot and the PV generation in a winter day is more effective than in a summer day, due to a lower overall expected cost.

B. *FEUP Parking Lot*

The total SOC of the FEUP's parking lot is demonstrated in Fig. 7. As it is illustrated, the highest amount of fluctuating in the SOC happens between hours 15 and 17. These results show that EVs have a higher SOC when they departure and as a result the EV drivers can profit from higher values of energy. Moreover, in scenario II the SOC of the parking lot is higher than the other cases in the majority of the hours. The different terms of EV parking lot's profit are presented in Table IV. It can be observed that scenario I is the one with the lowest profit, followed by scenario II and the most profitable is scenario III. According to Table IV, scenario III is the most rewarding one for the parking lot. In this case, the parking lot has the largest income from charging the EVs. Furthermore, equally to the previous case study, the EV parking lot does not contributes in the reserve market. As it can be denoted, scenario III is the one with the highest cost. In this scenario, the parking lot has the highest cost due to the payment to EVs for discharge. This is due to the presence of a higher PV power generation which results to discharge some EVs in early morning and in the evening, when market prices are superior.

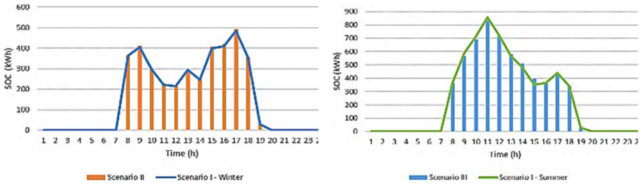

Fig. 6. SOC of the parking lot (Public Middle School).

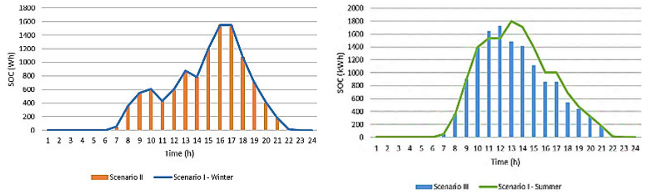

Fig. 7. SOC of the parking lot (FEUP).

TABLE III. COST COMPARISON (PUBLIC MIDDLE SCHOOL)

	Scenario I Winter	Scenario I Summer	Scenario II	Scenario III
Payment cost to EVs for discharge (€)	102.47	119.24	109.61	120.09
Battery degradation costs (€)	21.88	25.46	23.40	25.64
Cost of buying energy (€)	28.45	28.77	26.29	22.31

TABLE IV. COST COMPARISON (FEUP)

	Scenario I Winter	Scenario I Summer	Scenario II	Scenario III
Payment cost to EVs for discharge (€)	102.47	119.24	109.61	120.09
Battery degradation costs (€)	21.88	25.46	23.40	25.64
Cost of buying energy (€)	28.45	28.77	26.29	22.31

V. CONCLUSIONS

In this study, a comprehensive model for the operation of EV parking lots equipped with rooftop PV systems was proposed, considering the intermittent nature of PV generation and different behaviors of EV owners. Different scenarios and cases studies were conducted with the aim of analyzing the impacts of different PV output power on the parking lot's profits, thereby obtaining the optimal strategy for EV parking lot designers and operators. Moreover, the rooftop PV system generation curve was obtained for two seasons to properly examine the impacts of varying generation conditions. As a result, it was observed that the parking lot's profit was higher for the case when a typical summer day was considered; it was followed by the winter day and finally the base case where no PV rooftop was considered. It was also noticed that increasing PV generation output leads to higher costs due to the payment of discharging EVs. The results also indicated that the participation in the reserve market was mainly influenced by the price, which was too low for EVs to participate.

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REFERENCES

[1] J. Jean, P. R. Brown, R. L. Jaffe, T. Buonassisi, and V. Bulović, 'Pathways for solar photovoltaics', *Energy & Environmental Science*, vol. 8, no. 4, pp. 1200–1219, 2015.

[2] eurostat, 'Greenhouse gas emission statistics - emission inventories', Jun. 2018.

[3] 'Charging stations' statistics'. [Online]. Available: https://chargemap.com/about/stats. [Accessed: 04-Apr-2019].

[4] P. Denholm, M. Kuss, and R. M. Margolis, 'Co-benefits of large scale plug-in hybrid electric vehicle and solar PV deployment', *Journal of Power Sources*, vol. 236, pp. 350–356, Aug. 2013.

[5] M. Honarmand, A. Zakariazadeh, and S. Jadid, 'Self-scheduling of electric vehicles in an intelligent parking lot using stochastic optimization', *Journal of the Franklin Institute*, vol. 352, no. 2, pp. 449–467, Feb. 2015.

[6] C. Quinn, D. Zimmerle, and T. H. Bradley, 'The effect of communication architecture on the availability, reliability, and economics of plug-in hybrid electric vehicle-to-grid ancillary services', *Journal of Power Sources*, vol. 195, no. 5, pp. 1500–1509, 2010.

[7] S. B. Peterson, J. F. Whitacre, and J. Apt, 'The economics of using plug-in hybrid electric vehicle battery packs for grid storage', *Journal of Power Sources*, vol. 195, no. 8, pp. 2377–2384, 2010.

[8] C. D. White and K. M. Zhang, 'Using vehicle-to-grid technology for frequency regulation and peak-load reduction', *Journal of Power Sources*, vol. 196, no. 8, pp. 3972–3980, Apr. 2011.

[9] P. Nunes, R. Figueiredo, and M. C. Brito, 'The use of parking lots to solar-charge electric vehicles', *Renewable and Sustainable Energy Reviews*, vol. 66, pp. 679–693, Dec. 2016.

[10] Hanwha Q CELLS, 'Hanwha_Q_CELLS_Data_sheet_QPEAK-G4.1_290-305'. 19-2017.

[11] F. A. S. Gil, M. Shafie-khah, A. W. Bizuayehu, and J. P. S. Catalão, 'Impacts of different renewable energy resources on optimal behavior of Plug-in Electric Vehicle parking lots in energy and ancillary services markets', in *2015 IEEE Eindhoven PowerTech*, 2015, pp. 1–6.

[12] S. R. Tito, T. T. Lie, and T. N. Anderson, 'Optimal sizing of a wind-photovoltaic-battery hybrid renewable energy system considering socio-demographic factors', *Solar Energy*, vol. 136, pp. 525–532, Oct. 2016.

[13] GalpElectric, 'Tarifario GalpElectric'. [Online]. Available: https://galpelectric.pt/assets/tarifario_galpelectric.pdf. [Accessed: 22-Apr-2019].

[14] 'Zonas com estacionamento sujeito a pagamento - Mobilidade - Câmara Municipal do Porto'. [Online]. Available: http://www.cm-porto.pt/mobilidade/zonas-de-estacionamento-tarifado. [Accessed: 24-Apr-2019].

[15] 'Prices & Specifications New Nissan LEAF - Electric car', *Nissan*. [Online]. Available: https://www.nissan.pt/veiculos/novos-veiculos/leaf/preco-e-versoes.html. [Accessed: 22-Apr-2019].

[16] 'SIMEE - Informação Operacional'. [Online]. Available: http://www.mercado.ren.pt/PT/Electr/InfoMercado/InfOp/Paginas/default.aspx. [Accessed: 11-Apr-2019].