Modeling an Electric Vehicle Parking Lot with Solar Rooftop Participating in the Reserve Market and in Ancillary Services Provision

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Abstract

Electric vehicles (EVs) are seen as a crucial tool to reduce the polluting emissions caused by the transport and power systems (PS) sector and the associated shift to a cleaner and more sustainable energy sector. The combination of EVs and solar photovoltaics (PV) in PS, specifically through the aggregation of EVs in parking lots (PLs), may improve the reliability and flexibility of the PS, assisting the power network in critical moments. This work proposes a novel aggregator agent in the energy system which is an EV charging station with an installed PV system. In this work, an optimal operation strategy for the solar-powered EV PL (EVSPL) operation is presented. The model optimizes the EVSPL's participation in various energy and ancillary services markets, including the effects of capacity payments. The results show that the EVSPL leads to higher profits. The EVSPL's participation in ancillary services is highly influenced by the prices. The results of this work show that this novel agent can actively participate in the energy system in an economically viable manner while respecting the technical constraints of the network and providing important ancillary services to the system operator.

Keywords: Ancillary service; Electric vehicles, Efficiency operation; photovoltaic panels; Reserve market; Solar parking lot.

Nomenclature

Abbreviations

EU	European Union
EV	Electric Vehicle.
EVSPL	Electric Vehicle Solar Parking Lot.
FEUP	Faculty of Engineering of University of Porto.
G2PL	Grid to Parking Lot.
G2V	Grid to Vehicle.
GHG	Green House Gases.
GSO	Grid System Operator.
GAMS	General Algebraic Modeling System Software
HEV	Hybrid Electric Vehicle.
ICE	Internal Combustion Engine.
MPPT	Maximum Power Point Tracking.
MILP	Mixed Integer Linear Program.

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PL	Parking Lot.
PL2G	Parking Lot to Grid.
PV2PL	Solar Photovoltaic Energy to Parking Lot.
PV	Solar Photovoltaic Energy.
PS	Power System.
RES	Renewable Energy Sources.
ISO	Independent System Operator.
STC	Standard Test Conditions.
SoC	Battery State-of-Charge.
SOE	State of Energy.
V2G	Vehicle to Grid.
VAT	Value Added Tax.

Symbols

ΔS	Discretization upper limits of apparent power [kW].
Act	Active reserve by the ISO [kW].
$call$	Reserve called by ISO in the reserve market [kW].
Cap	Capacity of EV battery [kW].
Cap, Res	Capacity payment to participate in the reserve market [€/kWh].
Cd	Degradation cost [€].
$down$	EV SoC departure lower than arrival index.
En	Energy [kWh].
EV	Electric vehicle index.
F	Maximum number of blocks to linearize.
f	Partition segment of the blocks.
FF	Fill factor.
FOR	Forced outage rate.
G	Global solar irradiance [W/m^2].
$G2PL$	Energy injection of the grid to the parking lot [kWh].
$G2V$	Grid to vehicle index.
I	Current flow [A].
i, j	Buses index.
$I2$	Square of the current flow.
K_I	Short-circuit current temperature coefficient [A/ºC].
K_v	Open-circuit voltage temperature coefficient [V/ºC].
N	Number of buses.
η	Battery charge/discharge efficiency.
n	Amount of parked EVs.
$NCOT$	Nominal operating cell temperature [ºC].
NOM	Nominated amount.
P	Active power [kW].
$PL2G$	Energy injection from the PL to the grid [kWh].
$PV2PL$	Energy injection from PV rooftop to the PL [kWh].
R	Resistance [Ω].
Res	Reserve index.
RN	Renewable generation index.
S	Sub-transmission.
STC	Standard test conditions.

t	Time [h].
T^{env}	Environment temperature [ºC].
T^{c}	PV cell temperature [ºC].
$unavail$	Unavailable index to inject energy in the grid.
up	EV SoC departure higher than arrival index.
V	Voltage flow [V].
$V2$	Square of voltage.
$V2G$	Vehicle-to-grid index.
w	Scenario's index.
X	Reactance [Ω].
Z	Impedance [Ω].
β	Tilt angle [deg].
γ	Charge/discharge parking lot rate.
η^{PV}	PV module efficiency.
λ	Electricity price [€/kWh].
π	Probability scenario.
Γ	Penalty ratio to not deliver the offered energy [€/kWh].

1. Introduction

1.1. Background

Globally, power systems are facing a paradigm shift caused by factors related to energy supply, global warming, and economic efficiency/independence. This paradigm shift is characterized by the movement away from relying on fossil fuels to derive useful energy towards using renewable energy resources (such as wind and solar energy) to meet the energy needs of our society.

There needs to be further research into the integration of renewable energy sources (RES), energy efficiency measures, and new transport technologies to reach GHG emissions related and climate-friendly power systems (PSs) targets which are of utmost importance (Lin, et al., 2020).

New opportunities and efforts are under development, or already available, for the integration of more sustainable electric vehicles (EVs), reducing the investments or development incentives given to internal combustion vehicles. EVs not only offer the possibility of no GHG emissions during operation, increasing air quality, but can also mitigate noise pollution. A sustainable, cleaner, and efficient transport sector can be obtained by taking advantage of the vast range of EVs benefits (Das, et al., 2020).

RESs have numerous advantages for the PS but the large-scale integration may be challenging, especially with the inclusion of EVs. This may cause PS instability (voltage and frequency) and PS inflexibility (from conventional generation, energy flow, and grid limits), threatening the PS's reliability. The main disadvantages of PV are the variability and uncertainty and EVs can potentially degrade power quality thus destabilizing the conventional PS by overloading the PS (Shepero, et al., 2018).

The integration of PVs with the EVs' charging infrastructure, or an EVs' Parking Lot (PL) with RES infrastructure, can be a successful combination to mitigate a PS's problems (Sedding, et al., 2019). If EVs replace internal combustion engines (ICE) vehicles without a power system paradigm shift it is expected that GHG and pollutant emissions will increase.

In this context, charging EVs through PV is a promising solution that can provide several practical and economic opportunities and does not represent a source of concern to PSs. The PVs parking lots for EVs (hereinafter referred to as an EVSPL) do not involve significant environmental damages (Kobashi, et al., 2020). Optimally planned and managed, PV and EVSPL systems can contribute to environmental goals by using endogenous PV capacity. This accelerates the transition towards clean transport thus overcoming possible ecological and technical problems (Turan et al., 2019). The economic incentives in both systems to reach the global GHG and pollutant emission targets is an important topic that should be carefully considered (Münzel, et al., 2019).

1.2. Related Works

There have been notable efforts in the scientific community and governments in recent years to provide studies, solutions, and incentivize the integration of RES and EVs in conventional PSs in the way to accelerate the energy transition. A major review of the most recent advances, Fachrizal, et al., (2020) shows that the interaction between PV, EVs, and conventional PSs can increase the PV's and EV's integration, minimizing the electricity consumption impact in conventional PSs.

The work calls for an assessment of the impacts of schemes for charging EVs in various locations as solar irradiance can vary significantly between locations. Thus, this current research directly answers this aspect as it provides an analysis of a smart charging program for an EV parking lot located in Porto, Portugal. The research also calls for a deeper analysis regarding the role of forecasting and uncertainty within the optimal operation of EV parking lots. The current research assesses the impacts of various types of uncertainty and the results show the impacts of these scenarios.

In Ghazvini and Olamaei, (2019), an optimal heuristic algorithm was proposed which analyses the optimal sizing of PV, batteries, and conventional generation system, to implement in a PL with vehicle-to-grid (V2G) features as controllable loads, according to the electricity prices. The authors did not consider interactions between the EV parking lot and the electricity markets. This interaction is thought to be very important as the parking lot may provide valuable energy and ancillary services to the market and be compensated accordingly which may incentivize the owners of the EVs to enroll in such a program.

There are other examples of recent publications that do not only focus on PV or PLs. For instance, in Zhuang, et al., (2020) an exhaustive state-of-the-art review is presented. It covers the various configurations of hybrid EVs and their possibilities to enhance fuel economy, driving, autonomy, and connectivity with PSs. It has developed a multilayer control framework for a fleet of hybrid electric vehicles.

The authors have focused on an energy management system based on dynamic programming based on the technical specification of the vehicles without considering the economic aspects or potential of controlling the charging of EVs through economic signals which also respect the technical characteristics of the distribution network. The combination of technical and economic modelling (as is carried out in this current work) may present improved results when compared to just technical optimization.

An optimization strategy to implement V2G features in a microgrid was presented by Mortaz, et al., (2019). This model aimed to improve the EV's benefits acting in the electricity market, taking advantage of EV’s capabilities to exchange energy with the grid, when arbitrarily requested by the electricity market, improving the operation as well, the financial payback period for the EVs, and the long-term microgrid economy.

The model used to size and place VG2 facilities shows that installing V2G facilities can be economically beneficial however the authors focused solely on energy transactions between the V2G facilities and the grid while including the potential for the V2G facilities to participate in the ancillary services markets may increase the economic benefits further.

In Li, et al., (2020) a spatiotemporal interaction of EVs with a complete Australian power system with RES was presented. The model considered global irradiance system data and a competitive electricity supply-demand model on an hourly basis. The goal of the proposed work was the low-cost grid reconfiguration to include RES and EVs in different levels, until the full integration, where EVs charging, RES spillage, levelized operation cost, and other constraints were considered. The authors have considered various technologies to meet the peak demand of the fleet charging but do not consider energy storage technologies, to harness the full potential of renewable energy sources, energy storage is required. The absence of storage technologies means that the results should be interpreted carefully.

An extensive structure and operating mechanism for EV parking lots, located in urban areas, with fast-charging stations were developed by Khalkhali and Hosseinian, (2020). The authors considered a three-stage scheduling framework, with stochastic programming and predictive control through several time frameworks, including real-time planning.

The authors have found that energy transferred through a Vehicle-2-Vehicle scheme helped to alleviate the impacts of the fast-charging infrastructure. The authors only considered the price of energy for the economic inputs and did not consider participating in ancillary services markets.

In Runqi, et al., (2020) an EV aggregator flexible evaluation approach to reduce the power imbalance from exchanged the clustered EVs to act as the power reserve, considering the EV's flexibility was proposed. The proposed approach also considered several constraints such as balancing the load demand, the EVs SoC, EVs trip behavior, and other factors to determine the EV's role in the flexible response.

The authors showed that the fleet of EVs had the technical potential to deliver flexibility services to the grid however, a discussion of how EV owners would be incentivized to participate in such a program was not addressed. The authors of the proposed current EV parking lot model address this issue by modelling payments received by the EV aggregators for energy and flexibility services delivered to the market.

Calise, et al., (2020) presented detailed research concerning sustainable mobility, based on EVs, PVs, and energy storage systems, considering the advantages and disadvantages of V2G features and applied considering two real and independent EV's fleets case studies located in Italy. In both case studies, the EVs' behavior was analyzed on an hourly basis, considering different suggested EVs charge station locations coupled with PV generation and different battery energy storage systems.

The findings highlighted the impact of the season of the year, the best solution to reduce the impact on PSs, and the investment payback period. The authors did not include the effects of uncertainty on the mode such as the variation in solar irradiance. The authors did not consider other forms of revenue generation for the system, such as providing energy and ancillary services to the energy market. This market participation can lead to increased revenues thus shorting the payback period for this sustainable mobility scheme.

In Barhagh, et al., (2020) a robust optimization approach with uncertainty measure features to EVs aggregators participate in the electricity markets minimizing the risks and market cost was proposed. To this end, a microgrid considering different RES, conventional generation, EVs integration, and different energy storage systems were considered, achieving the goals designed for EVs aggregators from the optimization approach. The authors only consider the energy market while considering the ancillary services markets (as is done in the current paper) offers more opportunities to increase the revenues for the aggregator.

The existing state of the art research considered in this paper is summarized in Table 1 below. It shows that there are numerous differences in each of the models reviewed and none of them addresses all the aspects considered in this model. This shows how the proposed model extends the current state of the art. The literature reviewed above shows that the concept of aggregating EVs into parking lots and then optimizing their charging against time-of-use tariffs is an interesting and relevant research area with several high-quality papers emerging recently. The current manuscript extends the state of the art, mainly through allowing the EV parking lot to participate in the ancillary services market which opens new revenue streams for the aggregator and the consumers to benefit from.

Table 1.
Comparison between existing literature and the proposed model.

	Type of optimization	**Uncertainty considered**	**EVs used**	**Parking lot used**	**Grid constraints**	**Market participation**	**Ancillary services**	**Environmental aspects**
Ghazvini and Olamaei (2019)	Robust optimisation	Market price	✓	✕	✕	✓	✕	✕
Zhuang, et al., (2020)	Iterative Dynamic Programming	--	✓	✕	✕	✕	✕	✕
Mortaz, et al., (2020)	Two-stage stochastic model	Demand, RES output	✓	✓	✓	✓	✕	✕
Li, et al., (2020)	Linear programming	--	✓	✕	✕	✕	✕	✕
Khalkhali, Hosseinian, (2020)	Stochastic programming	Market price, demand, EV arrivals	✓	✓	✕	✓	✕	✕
Runqi, et al., (2020)	Dynamic trip chain model	RES output	✓	✕	✕	✓	✓	✕
Calise, et al., (2020)	Dynamic simulation	--	✓	✓	✕	✕	✕	✓
Barhagh, et al., (2020)	Heuristic optimisation	RES output	✕	✓	✕	✕	✕	✕
Proposed Model	**MILP**	**RES Output, EV arrival,**	✓	✓	✓	✓	✓	✓

1.2. Contributions and Paper Structure

In line with the latest advances concerning EVs and PV features and challenges and EVSPL implementation to increase PSs' flexibility while reducing the impact of the massive integration of RES and EVs in conventional PSs and coping with the environmental impacts mitigation goals required, the presented work provides an innovative strategy for the optimal operation of a PV-equipped EV parking lot (EVSPL). In the proposed model and design multiple parameters are taken into consideration, including weather conditions and EVs owner’s uncertainty schedules.

The proposed analysis also shows the optimal strategy for the EVSPL operation, considering both the EVs owners' and EVSPL operator's points of view to maximize profits by providing services to the grid while also respecting the EVs owner's comfort. The profits were calculated considering the interaction of EVSPL in different electricity markets, including the effect of a capacity payment, which is discussed and addressed together with the economic viability of the proposed EVSPL.

Accordingly, this study highlights an intersection of four different fields which are at the forefront of the progression towards cleaner and more sustainable societies: the design of green/sustainable transport systems, design of green/sustainable buildings, energy efficiency, and energy use and consumption. Thus, the design of the EVSPL helps to promote the uptake of electric vehicles and sustainable buildings to boost sustainable transport systems and buildings. The EVSPL also promotes energy efficiency and the increase of sustainable electricity production and consumption.

The remaining manuscript is prepared as follows: Section 2 presents the proposed architecture model considering the different mathematical models of PVs modeling as well, EVSPL modeling, and the distribution system modeling. Section 3 presents the proposed case study, the results, and a detailed analysis considering multiple scenarios and conditions. Section 4 discusses the main conclusions of the proposed work.

2. Modeling

The main objective of the current work is to investigate the optimal operation of an EVSPL to gain the maximum benefit for the EVSPL's operator. Based on this, a three-layer optimization problem is designed for this purpose. The first layer of the problem is dedicated to the energy market. The second layer focuses on the EVSPL behavior based on input data such as EVSPL traffic patterns and electricity market prices from the first layer.

The EVSPL operator's profit is maximized through market interactions along with the revenues from the EVs owner's contracts with the EVSPL. This objective was targeted as a financially viable EVPSL will also demonstrate numerous environmental benefits such as reduced air pollution, (Silva et al, 2020). These results are based on the EVSPL participating in both energy and reserve markets. The second layer also includes the distribution system. The distribution system provides the energy to the EVSPL charging stations which are in different areas. EVs are connected to the distribution power system to charge/discharge EVs through the charging stations.

At the distributions system, the problem is solved under network constraints considering the power generated from the rooftop PV from EVSPL. The third layer is dedicated to the construction of different PV power generation scenarios according to the uncertainty related to the weather conditions. The impact of the different weather conditions was studied as changes in weather have a large impact on the amount of solar irradiance available to the PV system and thus the fluctuations in the output of the Solar PV system. The proposed model is based on an hourly simulation that calculates energy output (V2G, and grid-to-vehicle (G2V)), incomes, and EVSPL operation costs. The proposed model and inputs considered in this analysis are shown in Fig. 1. The model inputs are fourfold:

- EV – arrival/departure time, EV battery capacity, and SoC,
- PV panels – hourly solar irradiance considering the season and location,
- Economic – electricity tariff, parking usage tariff,
- Electricity market – energy price, the reserve price, and regulation up/down price.

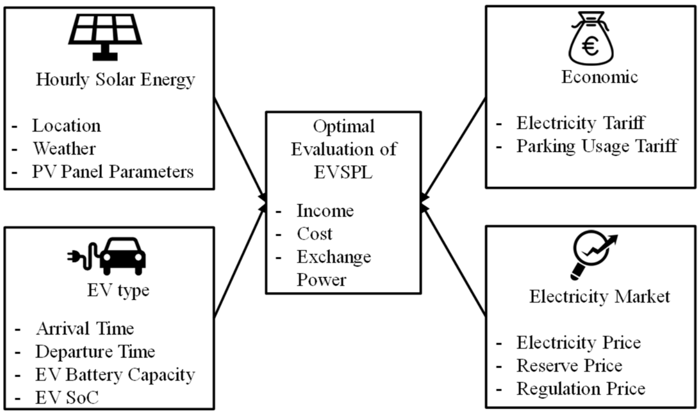


Figure 1
Proposed model and its inputs.

2.1. EVSPL Rooftop PV Modeling

During the day, solar irradiance varies which caused the PV generation to be extremely dependent on the local weather conditions. Based on the PV module parameters specified by the manufacturer, the maximum output at hour t can be obtained through Equations (1)-(5) (Goli and Shireen, 2014):

$$P_{t,\beta}^{PV} = V_{t,\beta}^{OC} \times I_{t,\beta}^{SC} \times FF \quad (1)$$

$$V_{t,\beta}^{OC} = V_{STC}^{OC} - K_v \times T_t^c \quad (2)$$

$$V_{t,\beta}^{OC} = \{I_{STC}^{SC} + K_I \times [T_t^c - 25°\mathrm{C}]\}\frac{G_{t,\beta}}{1000} \quad (3)$$

$$T_t^c = T^{amb} + (T^{NOCT} - 20°\text{C}) \times \frac{G_{t,\beta}}{800} \tag{4}$$

$$FF = \frac{P_{MPP}}{V_{oc} \times I_{sc}} \tag{5}$$

The total power output from the EVSPL rooftop is presented in Equation (6):

$$P_{t,\beta}^{rooftop} = \eta^{PV} \times N^S \times N^P \times P_{t,\beta}^{PV} \tag{6}$$

where, respectively, N^S is the number of PV modules connected in series and N^P is the number of PV modules connected in parallel. To limit the injection of power from the rooftop PV to the parking lot (PV2PL), one additional constraint, presented in Equation (7) has been added. Further details concerning solar energy conversion mechanisms can be found in Al-Shahria et al., (2021).

According to the maximum SoC of the EVSPL, the maximum power that can be injected into the EVSPL depends on the SoC from the previous hour and the state of energy (SOE) from newly arrived/departed EVs, imposing that the injected energy to the EVSPL must be higher than the rooftop PV power.

$$P_{t,\beta}^{rooftop} \leq P_{w,t}^{En,PV2PL} \leq SOC^{max} \times PLCapcom_t - (SOC_{w,t-1} + PLSOEnet_t) \tag{7}$$

where $PLCapcom_t$ represent the EVS sum capacity in the EVSPL and $PLSOEnet_t$, which consist of the net EVs SoC, i.e., $PLSOEnet_t = PLSOEin_t - PLSOEout_t$. The rooftop PV is sized according to the characteristics of the Hanwha QCELLS PV panel (Hanwha, 2017). By placing the PV system on top of the roof structure of the parking lot, no additional land will need to be used by the PV system and this could reduction in land required can be seen as an additional environmental benefit, (Silva, et al., 2020).

2.2. EVSPL Modeling

The operation of the EVSPL must be limited by several constraints, due to EVs uncertainties such as the arrival/departure times of each EV, and EV SoC at the arrival time. These constraints are modeled next. The power limit injection from the grid-to-PL (G2PL) is limited by Equation (8) according to the rate of charge of EV's batteries. The limit of power injection back from the PL-to-grid (PL2G), based on the discharge rate of EV batteries is presented in Equation (9).

It has been assumed a ramp-up/down of 3.3 kWh. The inequality from Equation (10) guarantees that the EVSPL cannot exchange and inject power at the same time (Gil et al., 2015).

$$P_{w,t}^{En,G2PL} + P_{w,t}^{En,PV2PL} + P_{w,t}^{R-down} \leq \gamma^{charge} \times n_{w,t} \tag{8}$$

$$P_{w,t}^{En,PL2G} + P_{w,t}^{R-up} + P_{w,t}^{Res,Act} \leq \gamma^{discharge} \times n_{w,t} \tag{9}$$

$$U_t^{G2PL} + U_t^{PL2G} \leq 1 \tag{10}$$

The EV state-of-charge (SoC) is defined as the remaining capacity of the battery. By implementing this constraint to the EVSPL, the SoC of EVSPL at each hour t, presented in Equation (11), is dependent on the SoC from the previous hour, the power interactions with the grid, in both directions (G2PL and PL2G), and the EVs SoC from both the arrived/departed EVs.

$$soc_{w,t}^{PL} = soc_{w,t-1}^{PL} + soc_{w,t}^{arrival} - soc_{w,t}^{departure} + \left(P_{w,t}^{En,PL2G} + P_{w,t}^{En,PV2PL} + P_{w,t}^{R-down} \right) \times \eta^{charge} - \frac{P_{w,t}^{En,PL2G} + P_{w,t}^{Res,Act} + P_{w,t}^{R-up}}{\eta^{discharge}} \tag{11}$$

In turn, the SoC of the arriving EV is presented in Equation (12) and the SoC for the departing EV is shown in Equation (13).

$$soc_{w,t}^{arrival} = \begin{cases} 0, & SOC_{w,t}^{Scenario} \leq SOC_{w,t-1}^{Scenario} \\ SOC_{w,t}^{Scenario} - SOC_{w,t-1}^{Scenario}, & SOC_{w,t}^{Scenario} < SOC_{w,t-1}^{Scenario} \end{cases} \tag{12}$$

$$soc_{w,t}^{departure} = \begin{cases} 0, & SOC_{w,t-1}^{Scenario} \leq SOC_{w,t}^{Scenario} \\ \dfrac{\left(SOC_{w,t-1}^{Scenario} - SOC_{w,t}^{Scenario}\right) \times soc_{w,t}}{SOC_{w,t}^{Scenario}}, & SOC_{w,t}^{Scenario} < SOC_{w,t-1}^{Scenario} \end{cases} \tag{13}$$

where $SOC_{w,t}^{Scenario}$ represents the stored energy in the EVSPL obtained from the input scenarios, and it is formulated by Equation (14):

$$SOC_{w,t}^{Scenario} = \sum Cap_{w,t}^{EV} \times SOC_{w,t}^{EV} \tag{14}$$

To better understand the constraint in Equation (14), Fig. 2 presents the EVSPL's SoC and capacity between the hours of 7:00 am and 16:00, which is the period considered for the occupation of the EVSPL.

As it can be seen, $SOC_{w,t}^{Scenario}$ depends on the two mentioned parameters from the input scenarios. In this case, Fig. 2 represents the input scenarios from the Faculty of Engineering of the University of Porto (FEUP)'s parking lot (this is described further in the next sections).

Equation (15) presents the added EV SoC during EV stay in the EVSPL, denoting the amount of energy that is injected into an EV. Equation (16) represents the amount of energy that is absorbed from an EV:

$$soc_{w,t}^{up} = \begin{cases} 0, & soc_{w,t}^{departure} \leq SOC_{w,t}^{Scenario} - SOC_{w,t-1}^{Scenario} \\ soc_{w,t}^{departure} - SOC_{w,t}^{Scenario} - SOC_{w,t-1}^{Scenario}, & Otherwise \end{cases} \tag{15}$$

$$soc_{w,t}^{down} = \begin{cases} 0, & SOC_{w,t}^{Scenario} - SOC_{w,t-1}^{Scenario} \leq soc_{w,t}^{departure} \\ soc_{w,t}^{departure} - SOC_{w,t}^{Scenario} - SOC_{w,t-1}^{Scenario}, & Otherwise \end{cases} \tag{16}$$

EVSPL's SoC is limited by Equation (17). It has been considered a minimum SOC of 20% and a maximum of 80%, for each EV.

$$\sum SOC^{EV,min} \leq soc_{w,t} \leq \sum SOC^{EV,max} \tag{17}$$

Input Scenarios																														
	SOC Parking Lot										Parking Lot Capacity										$SOC^{Scenario}$									
	7	8	9	10	11	12	13	14	15	16	7	8	9	10	11	12	13	14	15	16	7	8	9	10	11	12	13	14	15	16
16	0	41	48	0	0	0	0	0	0	0	0	60	30	0	0	0	0	0	0	0	0	24,6	14,4	0	0	0	0	0	0	0
17	0	62	41	48	41	0	0	0	0	0	0	120	150	210	60	0	0	0	0	0	0	74,4	61,5	100,8	24,6	0	0	0	0	0
18	54	50	42	59	21	0	0	0	0	0	30	210	510	210	60	0	0	0	0	0	16,2	105	214,2	123,9	12,6	0	0	0	0	0
19	46	51	44	49	0	0	0	69	0	0	60	60	180	120	0	0	0	30	0	0	27,6	30,6	79,2	58,8	0	0	0	20,7	0	0
20	0	53	67	42	0	0	48	59	33	48	0	30	30	30	0	0	30	150	90	30	0	15,9	20,1	12,6	0	0	14,4	88,5	29,7	14,4
21	0	0	0	0	0	0	50	38	58	55	0	0	0	0	0	0	60	180	90	60	0	0	0	0	0	0	30	68,4	52,2	33
22	0	0	0	0	0	0	0	47	43	53	0	0	0	0	0	0	0	210	60	60	0	0	0	0	0	0	0	98,7	25,8	31,8
23	0	0	0	0	0	0	0	59	0	0	0	0	0	0	0	0	0	30	0	0	0	0	0	0	0	0	0	17,7	0	0
24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure 2
Input scenarios and $SOC_{w,t}^{Scenario}$ from FEUP's parking lot.

2.3. Distribution System Modeling

The proposed model of the EVSPL must meet and keep the distribution system's integrity, which is modeling through energy balance equations. This section presents the mathematical distribution system model under network constraints, power flow, bus voltages, and reactive power, considering the rooftop PV generated power. The objective is the minimization of losses (Gil, et al., 2015).

Equation (18) represents the power flow equation related to the active power of the system which depends on the flow of the active powers of the branch *ij* when going upstream and downstream $\left(P_{i,j,t,w}^{+}, P_{i,j,t,w}^{-}\right)$. Similarly, Equation (19) represents the reactive power balance, which depends on the reactive power flow of the branch *ij* shown in the upstream $\left(Q_{i,j,t,w}^{+}\right)$ and downstream directions $\left(Q_{i,j,t,w}^{-}\right)$. The four terms represent non-negative auxiliary variables.

$$P_{i,t,w}^{S} + P_{i,t,w}^{RN} - \sum_{j}\left[\left(P_{i,j,t,w}^{+} - P_{i,j,t,w}^{-}\right) + R_{i,j} \times I2_{i,j,t,w}\right] + \sum_{j}\left(P_{j,i,t,w}^{+} - P_{j,i,t,w}^{-}\right) + P_{w,t}^{En,PL2G} = P_{i,t}^{D} + P_{w,t}^{En,G2PL} \tag{18}$$

$$Q_{i,t,w}^{S} + Q_{i,t,w}^{RN} - \sum_{j}\left[\left(Q_{i,j,t,w}^{+} - Q_{i,j,t,w}^{-}\right) + X_{i,j} \times I2_{i,j,t,w}\right] + \sum_{j}\left(Q_{j,i,t,w}^{+} - Q_{j,i,t,w}^{-}\right) + P_{w,t}^{En,PL2G} = Q_{i,t}^{D} + P_{w,t}^{En,G2PL} \tag{19}$$

Note that $I2$ in Equations (18) and (19), and thereafter, refers to an auxiliary variable representing the square root flow $I2$ in each branch *ij*. It is worth mentioning that each flow is expressed as the difference of two auxiliary variables.

In the interest of completeness, the auxiliary variable of active and reactive power flows is constrained by the maximum apparent power. The inequality shown in Equation (20) is related to the constraints of the active power while Equation (21) corresponds to the constraints of reactive power (Gil, et al., 2015):

$$0 \leq \left(P^{+}_{i,j,t,w} - P^{-}_{i,j,t,w}\right) \leq V^{NOM} \times I^{MAX}_{i,j} \tag{20}$$

$$0 \leq \left(Q^{+}_{i,j,t,w} - Q^{-}_{i,j,t,w}\right) \leq V^{NOM} \times I^{MAX}_{i,j} \tag{21}$$

where $V^{NOM} \times I^{MAX}_{i,j}$ expresses the maximum transfer capacity. Note that constraints Equations (20) and (21) may be redundant since the apparent power flow in each line should not exceed the maximum transfer capacity. The voltage balance in the system is represented in Equation (22). Note that $I2$ and $V2$ are auxiliary variables representing the squared current flow and the squared voltage relations, respectively:

$$V2_{i,t,w} - V2_{j,t,w} - Z^{2}_{i,j} \times I2_{i,j,t,w} - 2R_{i,j}\left(P^{+}_{i,j,t,w} - P^{-}_{i,j,t,w}\right) - 2X_{i,j}\left(Q^{+}_{i,j,t,w} - Q^{-}_{i,j,t,w}\right) = 0 \tag{22}$$

The linearization constraints to the active and reactive power are presented in Equation (23):

$$V2^{NOM}_{i,t,w} \times I2_{i,j,t,w} = \sum_{f}\left((2f-1) \times \Delta S_{i,j,f,t,w} \times \Delta P_{i,j,f,t,w}\right) + \sum_{f}\left((2f-1) \times \Delta S_{i,j,f,t,w} \times \Delta Q_{i,j,f,t,w}\right) \tag{23}$$

Equations (24)-(28) represent the flow constraints piecewise linearization:

$$\left(P^{+}_{i,j,t,w} - P^{-}_{i,j,t,w}\right) = \sum_{f} \Delta P_{i,j,f,t,w} \tag{24}$$

$$\left(Q^{+}_{i,j,t,w} - Q^{-}_{i,j,t,w}\right) = \sum_{f} \Delta Q_{i,j,f,t,w} \tag{25}$$

$$0 \leq \Delta P_{i,j,f,t,w} \leq \Delta S_{i,j,f,t,w} \tag{26}$$

$$0 \leq \Delta Q_{i,j,f,t,w} \leq \Delta S_{i,j,f,t,w} \tag{27}$$

$$\Delta S_{i,j,f,t,w} = \frac{V^{NOM} \times I^{MAX}_{i,j}}{F} \tag{28}$$

The distribution system model also includes the constraints related to voltage limits, through $V2 \leq {V^{NOM}}^{2}$ (Gil, et al, 2015). Inequalities Equations (29) and (30) represent the power factor constraints, where $\theta = 0.95$ is considered.

$$P^{RN}_{i,t,w} \times \tan\left(arcos(-0.95)\right) \leq Q^{RN}_{i,t,w} \leq P^{RN}_{i,t,w} \times \tan\left(arcos(0.95)\right) \tag{29}$$

$$P^{C}_{i,t,w} \times \tan\left(arcos(-0.95)\right) \leq Q^{C}_{i,t,w} \leq P^{C}_{i,t,w} \times \tan\left(arcos(0.95)\right) \tag{30}$$

2.4. Proposed Optimization Model

The objective function, presented in Equation (31), aims to maximize the profit for EVSPL operator. The profit results from the difference of nine income terms and nine cost terms. These are affected by the different market interactions (electricity, reserve, and regulation) between the grid and EV owners that decided to participate in the V2G mode.

$$\begin{aligned} &\underset{P_{w,t}^{En,PV\,2PL},P_{w,t}^{n,PL\,2G},P_{w,t}^{En,G\,2PL},P_{w,t}^{Res},P_{w,t}^{Res,Act},soc_{w,t}^{up},soc_{w,t}^{down}}{Maximize} \{profit^{PL}\} = \\ &Max \sum_{w} \pi_{w} \sum_{t} \{ P_{w,t}^{En,\,PL2G} \times \lambda_{t}^{En} + P_{w,t}^{Res} \times \lambda_{w,t}^{Cap,Res} + P_{w,t}^{R\text{-}up,\,Act} \times \lambda_{t}^{R\text{-}up} + P_{w,t}^{R\text{-}down,\,Act} \times \lambda_{t}^{R\text{-}down} \\ &+ P_{w,t}^{Res,\,Act} \times \lambda_{t}^{En} + soc_{w,t}^{up} \times \lambda_{t}^{Tariff,\,G2V} + n_{t}^{PL} \times \lambda_{t}^{Tariff,stay} - P_{w,t}^{En,\,G2PL} \times \lambda_{t}^{En} \\ &- \left(P_{w,t}^{Res,\,Act} \times \Gamma^{Res} + P_{w,t}^{R\text{-}up} \times \Gamma^{R-up} + P_{w,t}^{R\text{-}down} \times \Gamma^{R-down}\right) \lambda_{t}^{En} \times \pi^{unvail.} \\ &- P_{w,t}^{Res,\,Act} \times \lambda_{t}^{Tariff,\;V2G} - soc_{w,t}^{down} \times \lambda_{t}^{Tariff,\,V2G} - \left(P_{w,t}^{En,\,PL2G} + P_{w,t}^{Reg,\,Act}\right) \times Cd^{En} - P_{w,t}^{R\text{-}up} \times Cd^{Reg} \} \end{aligned} \tag{31}$$

The first income term, Equation (32), results from providing energy to the electricity market, i.e., the injection of energy considering the PL2G model, paid at the Portuguese electricity market λ_t^{En}:

$$IncomePL1 = \sum_{t} P_{w,t}^{En,PL2G} \times \lambda_{t}^{En} \tag{32}$$

The second income term, illustrated in Equation (33), is a result of the participation in the capacity reserve payment, which has been extracted from SIMEE, Information Market, (2020):

$$IncomePL2 = \sum_{t} P_{w,t}^{Res,PL2G} \times \lambda_{t}^{Cap,Res} \tag{33}$$

The third income term, Equation (34), is related to the probability of EVSPL being called by the system operator to generate the offered reserve. The hourly reserve prices have been extracted from Simee, (2020):

$$IncomePL3_{t,w} = \sum_{t} P_{w,t}^{Res,PL2G} \times \pi^{call} \times \lambda_{t}^{Res} \tag{34}$$

The fourth income term, Equation (35), is caused by the EV charging process, i.e., it represents the amount that EV owners pay the PL to charge their EV batteries.

$$IncomePL4_{t,w} = \sum_{t} (P_{w,t}^{En,PV2PL} + P_{w,t}^{En,G2PL}) \times \lambda_{t}^{Tariff,G2V} \tag{35}$$

where $\lambda_t^{Tariff,G2V}$ represents the charging tariff from the Portuguese grid network, and it has been extracted from GalpElectric, (2020).

The fifth- and sixth-income terms, Equations (36) and (37), describe the EVSPL profit from providing up/down-regulation to the grid in the regulation market. It has been considered a capacity payment for both regulations up $\left(\lambda_t^{Cap,R-up}\right)$ and down $\left(\lambda_t^{Cap,R-down}\right)$ market, and has been extracted from SIMEE, Information Market, (2020):

$$IncomePL5_{t,w} = \sum_{t} P_{w,t}^{Reg,PL2G} \times \lambda_{t}^{Cap,R-up} \tag{36}$$

$$IncomePL6_{t,w} = \sum_{t} P_{w,t}^{Reg,G2PL} \times \lambda_{t}^{Cap,R-down} \tag{37}$$

The seventh term, Equation (38), represents the EVSPL usage tariff, i.e., the amount that EVs owners pay to the EVSPL for parking in the EVSPL:

$$IncomePL7_{t,w} = \sum_{t} n_{t}^{PL} \times \lambda^{Tariff,stay} \tag{38}$$

where $\lambda^{Tariff,stay}$ corresponds to an average EVSPL usage tariff from Oporto city, and has been extracted from Porto, (2020). n_{t}^{PL} represents the number of EVs in the EVSPL at each hour.

The eighth- and ninth-income terms, presented in (39) and (40), are related to the probability of being called by the system operator to generate the offered regulation. It has been assumed hourly regulation prices equal to regulation capacity payment, extracted from SIMEE, Information Market, (2020):

$$IncomePL8_{t,w} = \sum_{t} P_{w,t}^{Reg,PL2G} \times \pi^{call} \times \lambda_{t}^{R-up} \tag{39}$$

$$IncomePL9_{t,w} = \sum_{t} P_{w,t}^{Reg,G2PL} \times \pi^{call.} \times \lambda_{t}^{R-down} \tag{40}$$

Regarding the cost terms, the first cost term, Equation (41), results from the EVs battery degradation due to the V2G operation mode in the reserve market:

$$CostPL1_{t,w} = \sum_{t} P_{w,t}^{Res,PL2G} \times \pi^{unvail.} \times Cd^{En} \tag{41}$$

The second cost term, Equation (42), presents the cost of buying energy from the grid, i.e., due to the injection of power from the grid to the parking lot (G2PL):

$$CostPL2_{t,w} = \sum_{t} P_{w,t}^{En,G2PL} \times \lambda_{t}^{En} \tag{42}$$

The third cost term, Equation (43), describes the paying EVs owner's cost due to discharge the EVs batteries, to participate in the V2G mode:

$$CostPL3_{t,w} = \sum_{t} P_{w,t}^{En,PL2G} \times \lambda_{t}^{Tariff,G2V} \tag{43}$$

The fourth cost term, Equation (44), results in the EVSPL's unavailability to deliver the offered reserve. If the EVSPL is not able to provide the reserve that has been offered, EVSPL suffers a penalty cost. It has been assumed Γ^{Res} equal to the unit:

$$CostPL4_{t,w} = \sum_{t} P_{w,t}^{Res,PL2G} \times \pi^{unvail.} \times \lambda_{t}^{Cap,Res} \times \Gamma^{Res} \times FOR^{PL} \tag{44}$$

where FOR^{PL} represents the EVSPL forced outage rate, considered equal to 0.02. The fifth cost term, Equation (45), is caused by the EVs batteries discharging during participating in the reserve market as needed by the grid system operator:

$$CostPL5_{t,w} = \sum_{t} P_{w,t}^{Res,PL2G} \times \pi^{unvail.} \times \lambda_t^{Tariff,G2V} \quad (45)$$

Like the reserve market, the sixth and seventh terms, Equations (46) and (47), resulting from the EVs batteries' degradation due to the operation in V2G mode in the energy and regulation market:

$$CostPL6_{t,w} = \sum_{t} P_{w,t}^{En,PL2G} \times Cd^{En} \quad (46)$$

$$CostPL7_{t,w} = \sum_{t} P_{w,t}^{Reg,PL2G} \times Cd^{Reg} \quad (47)$$

where Cd^{En} and Cd^{Reg} represents the EV batteries degradation cost due to operation in either the energy market or regulation V2G mode. It should be noted that the operation in energy and reserve markets requires deep discharging of the EVs batteries', whereas shallow discharges are needed in the regulation-up market.

The eighth and ninth cost terms, Equations (48) and (49), resulting from the EVSPL's unavailability to deliver the offered energy in the regulation market. If the EVSPL is not able to provide the regulation that has been offered, EVSPL suffers a cost penalty. It has been assumed Γ^{R-up}, and Γ^{R-down} equal to the unit.

$$CostPL8_{t,w} = \sum_{t} P_{w,t}^{Reg,PL2G} \times \pi^{unvail.} \times \lambda_t^{En} \times \Gamma^{R-up} \times FOR^{PL} \quad (48)$$

$$CostPL9_{t,w} = \sum_{t} P_{w,t}^{Reg,PL2G} \times \pi^{unvail.} \times \lambda_t^{En} \times \Gamma^{R-down} \times FOR^{PL} \quad (49)$$

3. Case Study and Results

3.1. Case Study

The proposed EVSPL management model was implemented in the General Algebraic Modeling System (GAMS), (Gams, 2020) using the Mixed Integer Linear Program (MILP) solver. The network used for the proposed model is composed of 15 buses, including RES and conventional generation (Espassandim, et al., 2019). To evaluate the proposed EVSPL management model, the Staffs' parking lot from FEUP, Porto, has been considered. To fully analyze the interaction of the proposed EVSPL with the different electricity markets, a distinct pattern between the prices of energy, reserve, regulation, and capacity payment has been considered.

Three different approaches have been used. The first one consists of three different scenarios, considering the variability of the solar irradiance between hours and seasons and without considering the capacity payment. Scenario I represent the base case where no PV generation is modeled. In Scenario II, a 100kW rooftop PV (with a PV panel area of approximately 558m^2) on a typical winter day has been analyzed. In Scenario III a 100kW rooftop PV (with a PV panel area of approximately 558m^2) in a typical summer day has been investigated.

The second approach consists of the three same scenarios, but it considers the capacity payment. The third approach consists of a tenfold increase in the capacity payment. Fig. 3 illustrates the load curve. It can be divided into three different periods:

- The valley-period from 2:00h to 8:00h,
- The off-peak period from 16:00h to 18:00h and from 23:00h to 1:00h,
- The peak-period from 9:00h to 15:00h and from 19:00h to 22:00h.

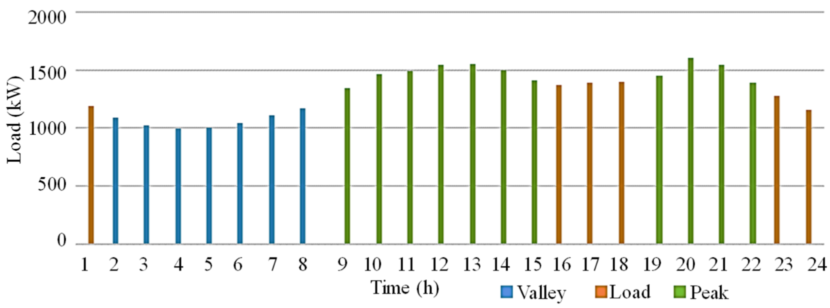


Figure 3
Hourly load curve considered.

To test the proposed EVSP management model, several assumptions had to be made. The climate data were obtained from the Satellite Application Facility on Climate Monitoring, which has a resolution of one hour. Moreover, global in-plane irradiance, $G_{t,\beta}$, and ambient temperature T^{amb} were obtained from Jrc, (2020) for the year of 2016, more specifically for January 2016 and July 2016.

As for the electricity prices, an individual pattern between the energy and reserve prices have been considered to analyze the EVSPL contributions in the electricity market. For this purpose, the data obtained from July 2016 and January 2016 of the Portuguese electricity market has been used, SIMEE, Information Market, (2020). The considered energy and reserve market prices and capacity payments for both months are presented in Fig. 4 and Fig. 5, respectively.

All EVs (for the sake of simplicity modeling) were Nissan Leafs, the third best-selling EV globally in 2018 (CleanTechnica, 2020). The Nissan Leaf's features are presented in Table 1 (NewMotion, 2020). The EVs batteries were assumed to be identical with a capacity of 30 kWh each (Nissan, 2020). With regards to EV charging the following assumptions were made:

- The charging efficiency is 90% for all EVs,
- The discharging efficiency is 81% for all EVs,
- The minimum and maximum EVs SoC is 20% and 80%, respectively.

While the environmental benefits of EVs are well known, using electricity generated from a mixture of fossil-fuel dependent power stations, renewable energy sources, and hydroelectric power means that there are still emissions associated with charging EVs. By using the proposed EVSPL and charging the EVs solely using the PV system, these emissions are eliminated thus increasing the environmental benefits of EVs.

This was investigated using the lifecycle carbon intensity of the Portuguese low voltage network and comparing it to the lifetime emissions of solar PV systems in Portugal. All data relating to the carbon intensities were obtained from Tranberg et al, (2019). The emissions from the electricity generated by the EVSPL were compared to the emissions for the same amount of electricity from the existing network to estimate the reduction in emissions that the EVSPL could provide.

Also, it was assumed that the EV owners pay 0.246€/kWh to charge their cars, which is the current rate from one of the Portuguese electrical operators (GalpElectric, 2020). In comparison, EVs home charging could be more economical (around 0.17 €/kWh, according to Erse, (2020). Charging EVs at the EVSPL is still an attractive opportunity for owners as they avoid the need to have access to a charging station at home. It is assumed that the EVs owners must pay 0.60€ for EVSPL usage, which is the current rate in Porto parking system (Porto, 2020). Further details are available in Table 2.

The case study is focused on the Staff's PL from FEUP, in Porto (41º 10' 40.8'' N, 8º 35' 52.8'' W), Portugal (Fig. 6). For the study, only the permanent Staff PL (P1) was considered which has a capacity of 450 "official" parking spaces without any type of roof structure. For the numerical study, the occupation data of six rows, highlighted in the red line, of the PL occupation data was gathered, as can be seen in Fig. 6. This highlighted area makes up a total of 108 parking spaces. As can be seen in Fig. 6, there is a limited amount of open land near the parking lot which increases the need to install the PV system on top of the parking lot roof structure.

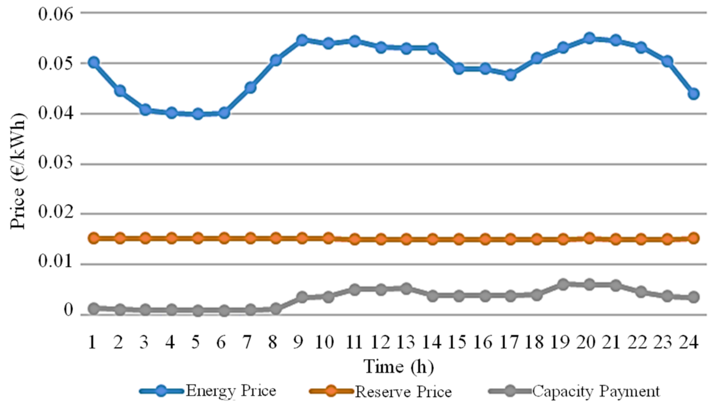


Figure 4
Considered electricity market prices (January 2016).

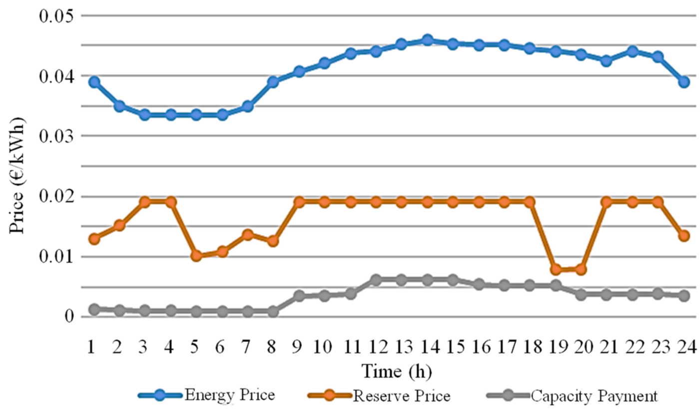


Figure 5
Considered electricity market prices (July 2016).

Table 1.
Nissan Leaf specifications.

EV Model	Battery Capacity	Real Electric Driving Range	Efficiency	Charge Power	Charging Costs
Nissan Leaf	30 kWh	170 km	16.5 kWh/100km	3.3 kW	6.00 € (fully charged)

Table 2.
Breakdown of charging tariff parameters.

	Reference Price	Excise Duty	Value Added Tax (VAT)	Charging Station Tax	Total
Galp Electric	0.1989 €/kWh	0.001 €/kWh	23 %	0 €/kWh	0.24587 €/kWh

According to a behavioral study of the considered PL, the EVs arrival/departure times are randomly distributed based on a normal distribution, where arrival times are divided into two groups, as indicated in Table 3. It is assumed that the PL is not monitored during the night or weekends. In these periods EVs were not registered. The arrival/departure patterns of the EVs are shown in Fig. 7 where blue dots mark the arrival time of an EV and red dots denote the departure time. For the EVSPL's PV rooftop, two seasonal PV power curves were obtained, obtained through the real solar irradiance and ambient temperature data (Fig. 8).

Moreover, the daily power PV generation, for both, typical winter, and summer days, is presented in Fig. 9. A good correlation between the PV generation and the EVSPL's occupation data is essential to directly use PVs for EVs charging, in this sense; the correlation was calculated as 71% for the winter day and 88% for the summer day. These correlations present lower values due to the presence of EVs in the evening, combined with a low/null PV generation.

Figure 6
FEUP’s PL and the considered area for the case study.

Table 3.
EVs probability distribution parameters.

		Mean	Standard deviation	Max
Type 1	Arrival Time	9	0.83	11.5
	Departure Time	18		-
Type 2	Arrival Time	14	0.83	16.5
	Departure Time	21		-

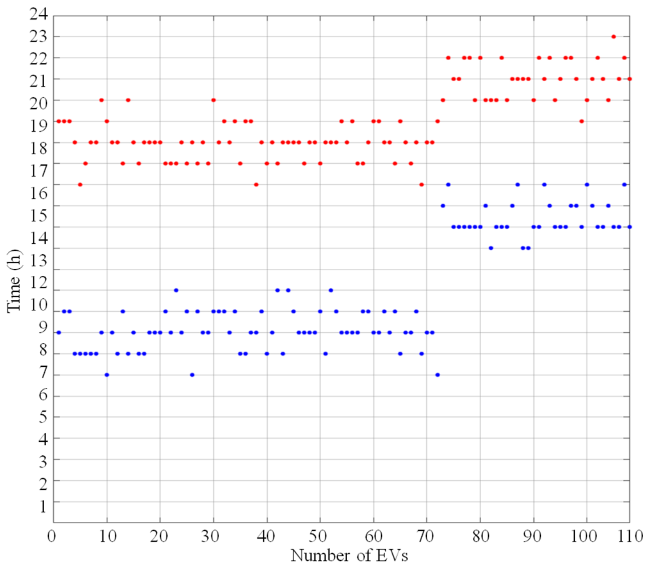


Figure 7
EVs arrival (blue dots)/departure (red dots) times at FEUP’s parking lot.

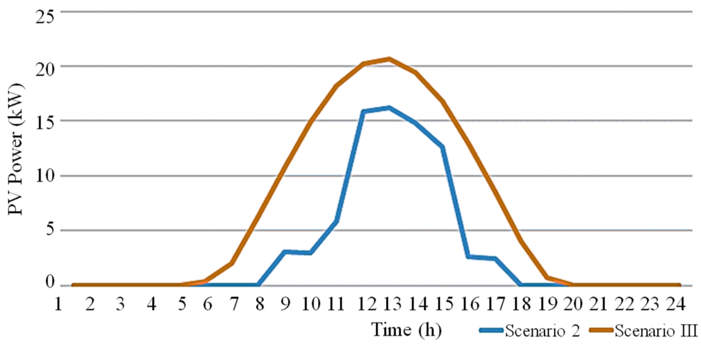
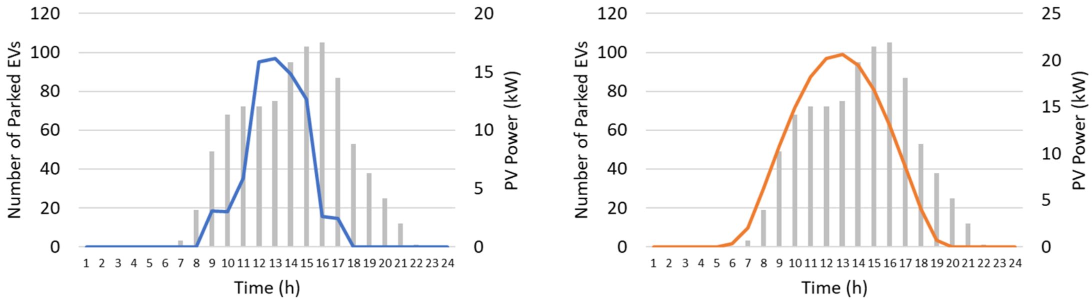


Figure 8
EVSPL's PVs power output.



(a) (b)

Figure 9
Seasonal PV production profile (full line) and FEUP EVSPL occupation (bars) corresponding to (a) typical winter day; (b) typical summer day.

3.2. Results Analysis without a Capacity Payment

A total of three case studies were defined, considering different weather conditions. Scenario I was defined as a reference/base case with no rooftop PV system. It is divided into two scenarios: winter and summer days to have a comparison basis for the next scenarios.

In Scenario II, a 100 kW rooftop PV was simulated for a winter day. Scenario III considers a 100 kW rooftop PV for a typical summer day. While in Scenario II, the EVSPL injects energy to the grid a larger amount of energy at hour 14, in Scenario III the EVSPL transfers a higher amount of energy for a prolonged period, more particularly, from 13:00h to 16:00h. This means that in the presence of a higher solar irradiance, the EVSPL has a higher capability to benefit from selling energy to the grid at solar peak hours.

These sales of electricity generated from the PV system may displace electricity generated from fossil-fuel reliant power stations, thus reducing the overall emissions of the electricity grid. It can be noticed that the grid does not sell and buy energy at the same time. Moreover, in Scenario II, in hour 8, there is not enough energy generated from the rooftop PV to satisfy the EVs charging requests, the EVSPL buys a higher amount of energy from the energy market. In the middle of the day, when PV generation is high, the EVSPL delivers more energy to the grid.

Another factor that influences the amount of energy that is bought from the electricity market is the number of EVs in the EVSPL. In contrast, in hour 14, there is an excess generation. This surplus generation is sold back to the grid. Similarly, in Scenario III, the EVSPL becomes more active between 13:00h and 16:00h, while in morning and evening hours it buys a higher amount of energy from the grid.

In Scenario II, the contribution in the regulation-down market occurs during three periods: 10:00h to 12:00h, a peak-period at 14:00h, and from 18:00h to 20:00h, while in Scenario III the EVSPL participates in the regulation-down market for a continuous period of five hours, more particularly from 12:00h to 16:00h. Although both scenarios have the potential to contribute to the regulation market, Scenario III presents a higher potential to participate in regulation markets when compared to the cases where a winter day is considered (Scenario II).

The total hourly SoC of the EVSPL is presented in Fig. 10. Considering Scenario II, the highest commutative amount of EVs SoC in the EVSPL occurs between 16:00h and 17:00h. In Scenario III the highest amount of EVs SoC change occurs at 11:00h and 12:00h. In Scenario III, the EVSPL SoC is higher than the other scenarios in most of the hours, even though in Scenario II, a higher amount of energy (1432 kWh) is purchased from the grid, while in Scenario III the EVSPL buys a total amount of 1417 kWh. The distinction in the EVSPL SoC does not come from the amount of energy that is bought from the grid but from the rooftop PV power output, since the conditions are equal to both scenarios.

The different EVSPL profits terms are presented in Fig. 11. It should be noted that the reported results do not consider the income from the EVSPL through the usage tariff by EVs. Scenario III is the most profitable one for the EVSPL, while the winter baseline scenario is the least lucrative scenario. Considering the income resulted from the electricity market, Scenario II presents the highest income. This fact would be expectable since Scenario II presents the highest interaction between the EVSPL and the grid.

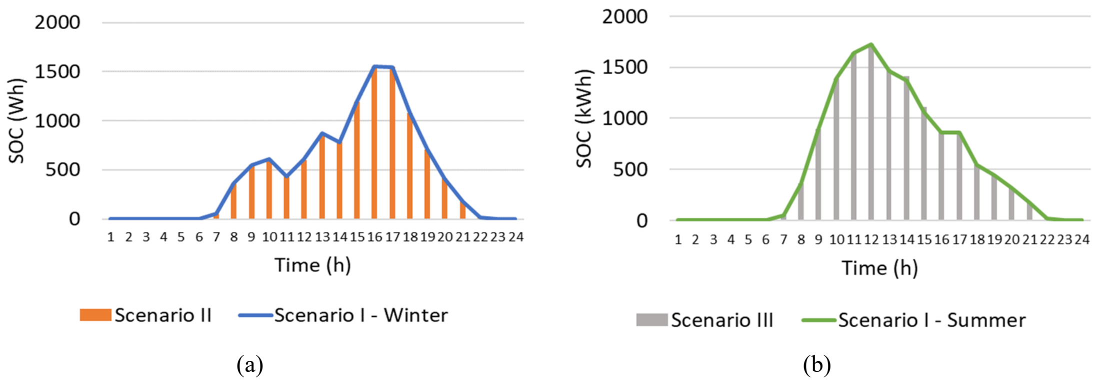


Figure 10
EVSPL SoC corresponding to (a) Scenario I – Winter and Scenario II; (b) Scenario I – Summer and Scenario III.

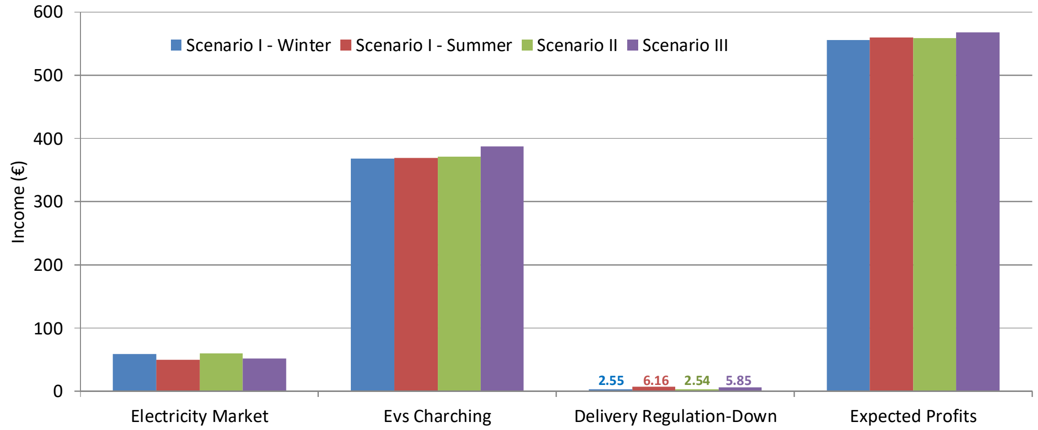


Figure 11
A breakdown of considered EVSPL profits corresponding to Scenario I (base case), Scenario II (Winter) and Scenario III (Summer) without a capacity payment.

Fig. 12 represents the hourly incomes for the EVSPL to better analyze the income differences resulting from EVs charging between scenarios that consider the rooftop PV system. As it can be observed, the distinction in this income comes from the charging in the morning, more particularly from 9:00h to 11:00h, and from the EVs charging during evening hours from 18:00h to 21:00h. On one hand, in hours 15:00h and 16:00h, Scenario II benefits the most from EVs charging as this process does not occur through the rooftop PV system but from purchasing from the grid. During the same hours, Scenario III has a significantly higher PV power generation, so the EVSPL does not need to buy energy from the grid, leading to a considerably lower income when compared with Scenario II.

Through the participation in the regulation market, the EVSPL may be required by the system operator to deliver the offered regulation and so benefiting from delivering it. This income represents a relatively small fraction of the global profit when compared with the remaining terms. The contributions of each term for the total income in each scenario are presented in Table 4. As it can be observed, the lowest contribution in all scenarios is the income from the delivery of the offered regulation services while the largest is the income from EVs charging.

Another point that can be observed from the results is that, in winter, the parking lot with and without the rooftop PV system participates equally in both the electricity market and in the EVs charging. The distinction in the expected profit does not come from the incomes but the costs. Moreover, in summer, there is a difference of 0.1% in both income streams, i.e., from EVs charging and from delivering the offered regulation. In Scenario III, the EV charging results in a higher income since it involves the rooftop PV. As for the offered regulation, Scenario III participates with a lesser amount of energy than its corresponding baseline scenario.

The EVSPL delivers a smaller amount of energy when it is called by the grid system operator. By comparing the scenarios with different weather conditions, it can be observed that in winter, the EVSPL benefits more from the electricity market than in summer. Despite that, the EV charging contribution is 1.2% higher in summer scenarios due to a higher PV power production in summer.

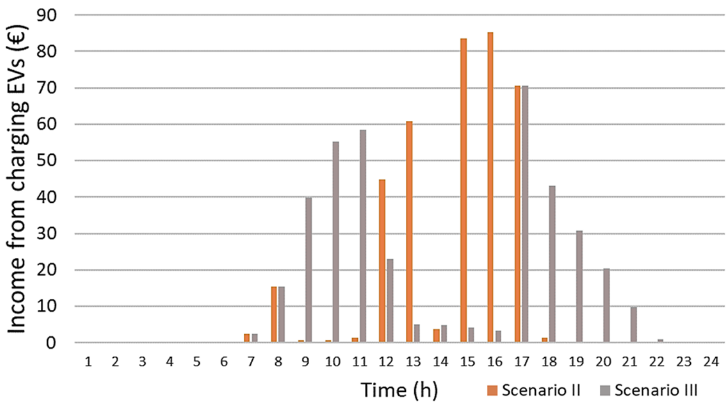


Figure 12
Income from the hourly EVs charging corresponding to Scenario II and Scenario III without a capacity payment.

Table 4.
Contribution of each income for the EVSPL global profit without a capacity payment (Part I).

	Winter (Scenario I)	**Summer (Scenario I)**	**Winter (Scenario II)**	**Summer (Scenario II)**
Charging EVs (%)	85.7	86.9	85.7	87.0
Electricity Market (%)	13.7	11.7	13.7	11.7
Offered delivery (regulation down) (%)	0.6	1.4	0.6	1.3

The different EVSPL's costs are presented in Fig. 13, where Scenario III represents the highest cost. The main reason is the higher cost related to the EVs discharge payment. Since there is a higher presence of PV power generation, EVs tend to discharge in the early morning and the evening, when the electricity market prices are high. A clear change is observed in the grid purchased energy.

As shown in Fig. 13, as the PV power generation increases (from Scenario II to Scenario III), the purchased energy cost decreases. This means with more PV power generation available, the EVSPL can fulfill more of the charging requirements, so it is not necessary to buy a high amount of energy from the grid, as in Scenario I. This reduces the dependence of the EVSPL on the existing grid and therefore reduces the emissions associated with charging the EVs.

As the EVSPL operator is interested in minimizing the cost (or maximizing the profit), the EVSPL operator increases the income from energy sales to the grid. A significant difference is detected in the EV batteries' degradation cost. It can be observed that a large interaction between the EVSPL and the grid harms the EVs batteries' degradation cost.

In Scenario I, with the lowest impact on EV batteries' degradation cost, EVs owners may not be interested in participating in PL2G activities as in Scenario III, where the cost is higher. Another point that can be observed from the results is that the EVSPL pays a penalty due to the unavailability to provide the offered regulation up/down energy, even though this cost represents a very small contribution to the total cost, not rising above 0.05% in the global cost.

The reason is that this cost is related to the probability of being called upon by the grid system operator to generate the offered regulation. The EVSPL's main objective is EV charging so it can choose not to participate in the energy regulation market, without suffering high-cost penalties. For a comprehensive analysis of each scenario, Table 5 demonstrates the contributions of each cost in terms of the total cost.

The highest cost in all scenarios results from paying for the EVs' discharge, while the lowest is represented by the EVs battery degradation costs due to the EVSPL participation in the energy market. By comparing the winter scenarios, it can be observed that in the scenario involving a rooftop PV system (Scenario II), the EVSPL buys a smaller amount of energy.

Consequently, since there are two sources for EV charging, i.e., grid and rooftop PV, the EVSPL is more willing to participate actively in the energy market by selling energy to the grid. This increases not only the EVs' battery degradation costs but also the payment to EVs' discharge cost. The same circumstances occur in summer scenarios.

By comparing both winter and summer scenarios, there is a smaller amount of energy purchased from the grid. The EVs' battery degradation costs and, the EVs' discharge costs are higher. This is mostly due to a higher injection of energy from the EVSPL to the grid between 13:00h and 16:00h.

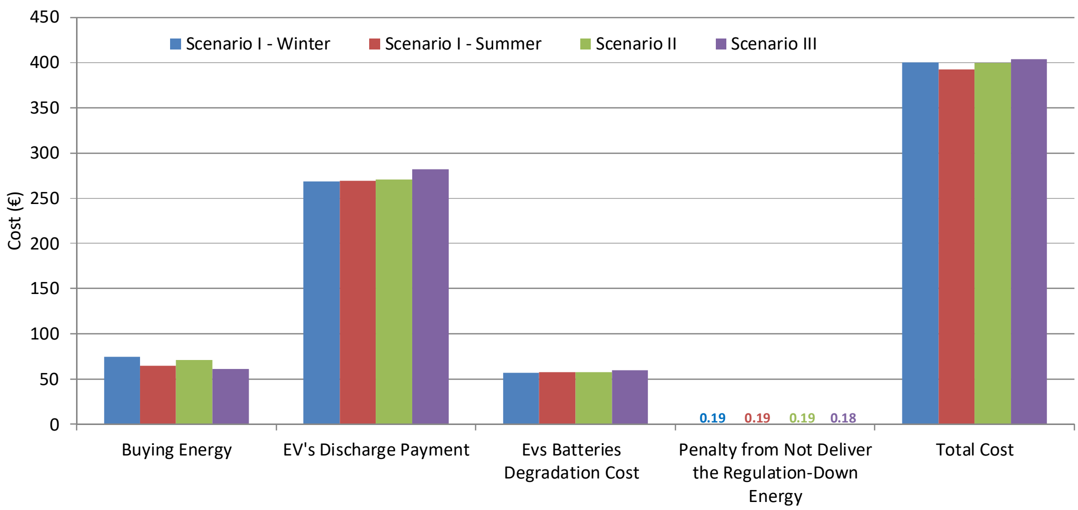


Figure 13
Breakdown of EVSPL's cost without a capacity payment corresponding to Scenario I – base-case; Scenario II – Winter; and Scenario III – Summer.

Table 5.
Contribution of each income for the EVSPL global profit without a capacity payment (Part II).

	Winter (Scenario I)	Summer (Scenario I)	Winter (Scenario II)	Summer (Scenario II)
Payment to EVs for discharge (%)	67.0	68.7	67.7	69.9
Battery degradation due to energy market (%)	14.3	14.7	14.4	14.9
Buying energy (%)	18.7	16.6	17.9	15.2

3.3. Results Analysis with a Capacity Payment

Similarly, as the previous section detailed, a total of three scenarios were defined, considering different weather conditions as well as the inclusion of the capacity payment. The scenario involving the rooftop PV system purchases a lower amount of energy than its baseline scenario. As it can be observed, the EVSPL sells back to the grid a larger amount of energy between 8:00h to 11:00h on a winter day (when the number of EVs parked increased from 19 to 72, increasing the EVSPL's occupation by approximately 279%).

In this scenario, the EVSPL has a higher potential to benefit from selling energy to the grid during peak hours preferring to sell the energy that is not used for EVs charging rather than participating in the electricity regulation market. In both scenarios, the EVSPL generates the same amount of electricity, on both the summer and winter days. The difference between the scenarios is where this electricity is directed to. For the summer day, the EVSPL generates 155.75 kWh of electricity.

Using a factor of 69.3 gCO_2eq/kWh, Tranberg et al., (2019), this equates to 4.3178 $kgCO_2eq$ emitted compared to 62.307 $kgCO_2eq$ if the EVSPL sourced electricity from the existing grid, using a factor of 400 gCO_2eq/kWh for the Portuguese system. For the winter day, the EVSPL generates 76.473 kWh which corresponds to 2.1198 $kgCO_2eq$ versus 30.589 $kgCO_2eq$ that would have been emitted if the EVSPL obtained all the electricity from the distribution grid. Thus, using the generation from the EVSPL reduced emissions by 93.07%, Tranberg et al. (2019). This is an important environmental aspect to consider.

In Scenario III there are only two hours where energy sales back to the grid occur (11:00h and 22:00h). At 11:00h, since the regulation-down price is a null value and combined with the fact that there is PV power available, the parking lot can inject 63 kWh back to the grid. In hour 22 even though there is not PV power available, and the regulation-down price remains null, there is only one EV parked at the EVSPL, which allows the EVSPL to sell 3.3 kWh to the grid. In Scenario III the EVSPL participates in the regulation-down market for an extended period, between 12:00h and 14:00h. This means that, at these specific hours, the offered price and capacity payment for the regulation-down is more rewarding in summer than in winter.

Both scenarios have the potentiality for contributing to the regulation market, but Scenario III is seen as the most promising in terms of participating in the electricity regulation markets. This is due to the higher PV power uncertainty in the system at peak hours. The EVSPL can benefit from supplying the regulation up/down to compensate for the unpredictability during these hours. By supplying regulation up/down services generated from renewable energy sources to the grid, the EVSPL is again reducing the emissions associated with the electricity mix.

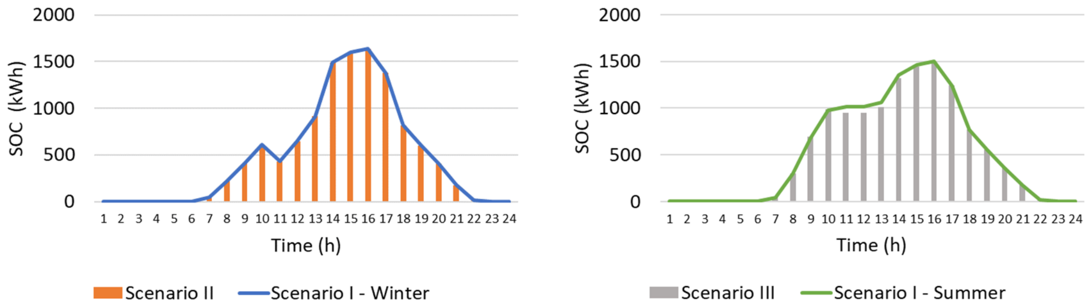
Another point that can be observed is that the EVSPL participates in the regulation-up market only in periods that the capacity payment can compensate for the costs of contributing to the electricity regulation market. As an example, at 10:00h in Scenario II, the EVSPL participates in the electricity regulation market, while in Scenario III the EVSPL does not participate. The capacity payment for the regulation-up in this hour is higher on the considered typical winter day than on the summer day.

The hourly EVSPL SoC is presented in Fig. 14. In Scenario II, the largest change in the SoC levels occurs between 14:00h and 16:00h when the EVSPL buys energy from the grid. Regarding Scenario III, the highest EVSPL SoC occurs between 14:00h and 16:00h. A higher SoC is achieved in Scenario III for most of the time.

Although in Scenario II more energy is purchased from the grid, Scenario III has a higher PV power output which leads to a higher SoC. The different EVSPL's profits are presented in Fig. 15. Scenario I (winter) is the least profitable, followed by Scenario II and, Scenario I (summer). The most lucrative is Scenario III due to the EVSPL participation in the regulation-down electricity market as this represents the largest contribution to the overall profit in Scenario III.

Another point that can be observed from the results is that there are no differences regarding incomes between the base-case winter Scenario I and Scenario II. The results demonstrate a null income from EVs charging in the summer base-case scenario, confirming that there is neither injection from the grid to the EVSPL nor PV generation. Regarding purchasing energy costs from the grid, the winter scenarios represent the highest costs, when compared with the summer scenarios.

Summer scenarios denote a null cost of buying energy from the grid, confirming that the EVSPL meets the EVs charging requirements through the electricity regulation-down market and not through the energy's purchase from the grid.



(a) (b)

Figure 14
EVSPL SoC considering a capacity payment corresponding to: (a) Scenario I – Winter, and Scenario II; (b) Scenario I – Summer and Scenario III.

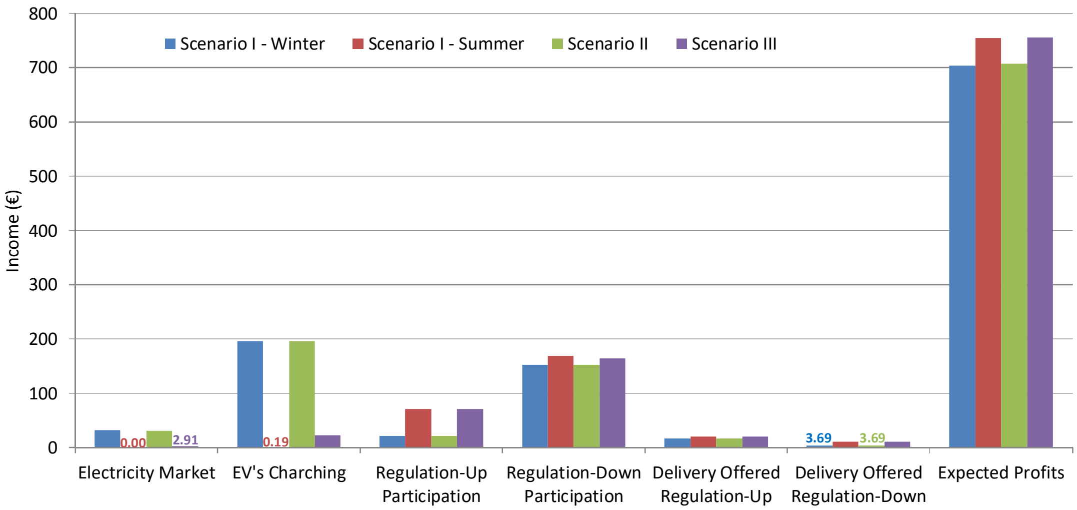


Figure 15
Breakdown of EVSPL's profit considering a capacity payment to: Scenario I (base-case); Scenario II – Winter; and Scenario III – Summer.

A significant difference is verified between Scenario II and Scenario III, regarding EVs batteries' degradation costs, both in terms of the energy and electricity regulation market. Scenario II presents a total EV batteries' degradation cost of nearly €57 during the analysed time. In Scenario III the same cost is €45, a difference of approximately 27%. Scenario III is a considerably more balanced scenario since the EVSPL participates in both electricity and regulation markets.

The total EV batteries' degradation costs represent 72% of Scenario's III total cost. The contribution of approximately 26% due to the EVs' payment for the discharge of the batteries is caused by the interaction with the grid at 11:00h and 22:00h, with an injection back to the grid of 63.3 kWh and 3.3 kWh, respectively. To better investigate the EVSPL penalties from failure to generate the offered energy regulation, Fig. 16 represents the hourly penalty cost for Scenarios II and III. As it can be observed, both scenarios pay a higher penalty in hours 15:00h and 16:00h, when the EVSPL has the highest occupation. The EVSPL participation in the reserve market is illustrated in Fig. 17.

The amount of the capacity payment significantly influences participation in the reserve market. The EVSPL only participates in the energy reserve market when the capacity payment is higher. This fact means that the EVSPL participates in this market only in periods that the capacity payment can remunerate the costs of operating in the energy market through V2G mode.

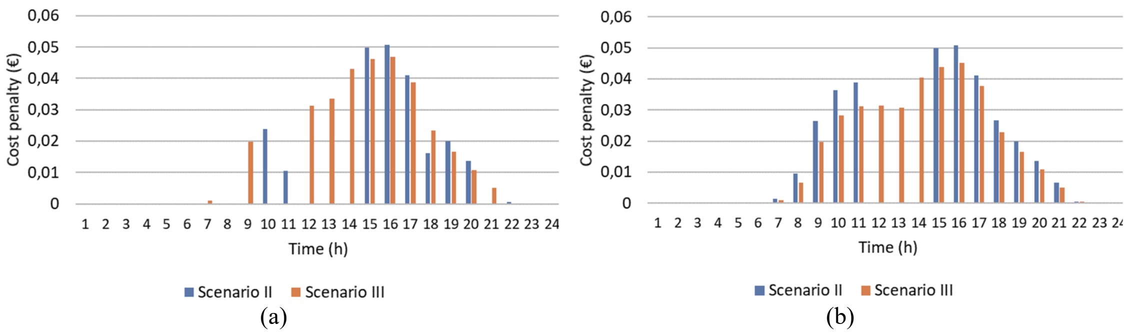


Figure 16
EVSPL's hourly penalty cost for not generate the offered energy regulation-up (a); and regulation-down (b).

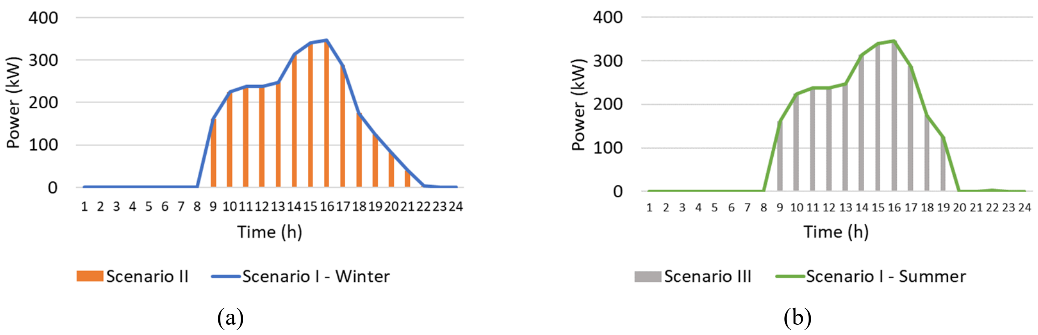


Figure 17
EVSPL's reserve market participation considering an increase of the capacity payment: (a) Scenario I – Winter and Scenario II; (b) Scenario I – Summer and Scenario III.

An investigation into the effects of the capacity payment on the financial viability of the EVSPL shows that including a capacity payment can both increase income (by an average of 29.79%) and reduce costs (by an average of 62.46%). These effects greatly improve the financial viability of the EVSPL and are shown in Fig. 18.

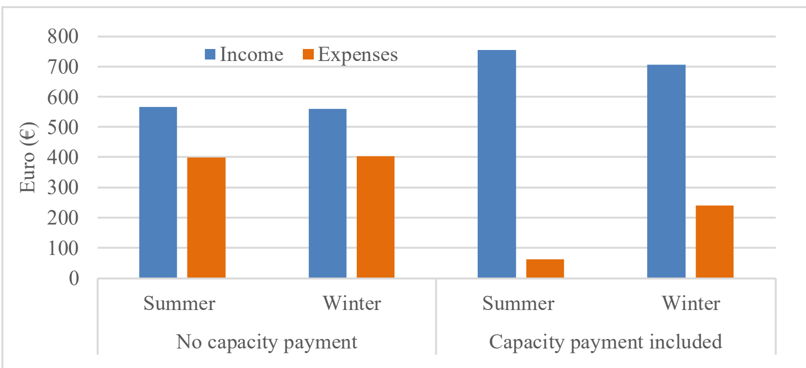


Figure 18
Financial performance of the EVSPL across both winter and summer days when there is no capacity payment (left) vs when there is a capacity payment (right).

4. Conclusions

This work presents a tri-level management and analysis model which shows the impacts of PV generation on the profits and behavior of an EVSPL, considering different weather conditions. This novel agent type can generate profits for itself and the owners of the EVs while providing energy trading and important ancillary markets. Results show that without an energy trading and ancillary services provision account for on average 12.7% of the income of the EVSPL across the four scenarios without a capacity payment and 74.5% of income on average across the scenarios with the capacity payment.

The model investigated the impacts of various types of uncertainty as well as the effects of a capacity payment. The electricity regulation market, or ancillary service market, appears to be a particularly valuable application of V2G power, especially in the presence of a capacity payment.

In these situations, the EVSPL is paid not only for having available and synchronized power capacity, but it receives additional payment for energy delivery. Incomes from the actual delivery of the available capacity ranges from 4-7% of the total income for the EVSPL agent. Including the ancillary services market in this model has provided interesting results and shown potential future opportunities for value creation from similar agents. The maximum penalty that the EVSPL suffered for not delivering the offered power regulation was approximately 0.38 € and 0.32 € in the regulation down/up market, respectively.

The EVSPL provides important environmental benefits in addition to the stated economic benefits. These benefits include the reduced need for open land to construct renewable energy projects, charging EVs with electricity generated by renewable energy sources, therefore, removing any emissions associated with the operation of the EVs, and importantly by selling electricity generated from the solar PV system as well as ancillary services, the EVSPL is lowering the average emissions associated with the electric grid.

This model can be used to incentivize the development of a larger EV charging network. This work shows a viable business model for EV charging stations through participating in ancillary services markets. The applicability of the EVSPL agent in different market conditions may provide interesting insights for further work.

Authors Contribution

G.J. Osório has worked on the proposed model, wrote, and revised the present manuscript. M. Lotfi and H.M.D. Espassandim have worked on the proposed model, collected the data, and performed the analysis. G.J. Osório, M. Lotfi, M. Shafie-khah, and J.P.S. Catalão have conceived the presented idea, supervised, and analyzed the results and findings of proposed work. M. Lotfi, M. Gough and M. Javadi have also contributed to improve and revise the contents and results reported in this work. All Authors have discussed the results and contributed to the final and proposed manuscript. All Authors have actively worked on this manuscript together and all Authors have read and approved the final manuscript.

Declaration of Competing Interest

The Authors declare no conflicts or competing interests, from financial, institutional, or personal domains.

Acknowledgements

M. Lotfi would like to acknowledge the support of the MIT Portugal Program (in Sustainable Energy Systems) by Portuguese funds through FCT, under grant PD/BD/142810/2018.

M. Shafie-khah would like to acknowledge the SolarX research project with financial support provided by the Business Finland, 2019-2021 (grant No. 6844/31/2018). J. P. S. Catalão acknowledge the support of the FEDER funds through COMPETE 2020 and by the Portuguese funds through FCT, under POCI-01-0145-FEDER-029803 (02/SAICT/2017).

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