Allocation of Plug-In Vehicles' Parking Lots in Distribution Systems Considering Network-Constrained Objectives

Nilufar Neyestani, *Student Member, IEEE*, Maziar Yazdani Damavandi, *Student Member, IEEE*,
Miadreza Shafie-Khah, *Member, IEEE*, Javier Contreras, *Senior Member, IEEE*, and
João P. S. Catalão, *Senior Member, IEEE*

***Abstract*—A recent solution to tackle environmental issues is the electrification of transportation. Effective integration of plug-in electric vehicles (PEVs) into the grid is important in the process of achieving sustainable development. One of the key solutions regarding the need for charging stations is the installation of PEV parking lots (PLs). However, contrary to common parkings, PLs are constrained by various organizations such as municipalities, urban traffic regulators, and electrical distribution systems. Therefore, this paper aims to allocate PLs in distribution systems with the objective of minimizing system costs including power loss, network reliability, and voltage deviation as possible objectives. A two-stage model has been designed for this purpose. PLs' behavior considering market interactions is optimized at the first stage to provide profit to the PL owner. At the second stage, the PL allocation problem is solved considering various network constraints. Conclusions are duly drawn with a realistic example.**

***Index Terms*—Market interactions, parking lot allocation, plug-in electric vehicle (PEV), reliability, voltage deviation.**

NOTATION

Capital letters denote parameters and small ones denote variables.

Subscripts

$j, \acute{j}$	Bus number.
l	Power line.
ω, Ω	Scenario and scenario set.
t, h	Time interval.

Superscripts

aff	Affected nodes due to a contingency.
ar	Arrived PEVs.
Cap	Capacitor.
Cd	Cost of equipment depreciation.
Cha	Battery charging.
Con	Contingency.
D	Demand.
E	Energy.
EMI	Energy market interactions.
del	Probability of a reserve call.
dep	Departed PEVs.
$dCha$	Battery discharging.
$down, up$	SOC with respect to a scenario's SOC.
EV	Electric vehicle.
fix	Fixed cost.
$G2V$	Grid to vehicle.
in	Power injected into the system or the PL.
inj	Energy injected from resources (used in EENS).
ins	Installation cost.
$Loss$	Loss of power lines.
$Line$	Power line.
out	Power injected from the PL into the system.
$outage$	Outage.
POI	PEV owner interaction.
PL	Parking lot.
PLA	Parking lot at the second stage.
Pr	Price.
PV	Photovoltaic resource.
Re	Reserve.

Manuscript received April 25, 2014; revised August 12, 2014; accepted September 20, 2014. This work was supported by FEDER funds (European Union) through COMPETE and by Portuguese funds through FCT, under Projects FCOMP-01-0124-FEDER-020282 (Ref. PTDC/EEA-EEL/118519/2010) and PEst-OE/EEI/LA0021/2013. Also, the research leading to these results has received funding from the EU Seventh Framework Programme FP7/2007-2013 under grant agreement no. 309048. Paper no. TPWRS-00564-2014.

N. Neyestani, M. Y. Damavandi, M. Shafie-Khah, and J. P. S. Catalão are with the University of Beira Interior, Covilha, Portugal, with INESC-ID, Lisbon, Portugal, and with IST, University of Lisbon, Lisbon, Portugal (e-mail: catalao@ubi.pt).

J. Contreras is with E.T.S. de Ingenieros Industriales, University of Castilla—La Mancha, 13071 Ciudad Real, Spain (e-mail: Javier.Contreras@uclm.es).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TPWRS.2014.2359919

$Reli$	Reliability.
RMI	Reserve market interaction.
Sc	Scenario.
$Shed$	Load shedding.
Sys	Upstream system.
$Tariff$	Tariff paid by PEV owners arriving at the PL.
Var	Variable cost.
VD	Voltage deviation.
$V2G$	Vehicle to grid.
W	Wind resource.

Operators

$\underset{\sim}{\vartriangle}$	Change in variable amount.
$\_$	Quadratic variable.
$\_,$	Minimum and maximum amount of a variable.

Variables and Parameters

B	Susceptance (Ω^{-1}).
C	Cost (€).
ca, Ca	Capacity of a PL (kW).
Can	Candidate site of PL.
CDC	Customer damage cost (€).
$EENS$	Expected energy not served (kWh).
FOR	Forced outage rate (%).
i, I	Line current (A).
n, N	Number of parked PEVs.
ns, NS	Number of PEV stations.
p, P	Active power (kW).
q, Q	Reactive power (kW).
re, RE	Reserve (kW).
rep	Repair time (h).
R, X	Resistance and reactance of a line (Ω).
si	Binary variable indicating the site of a PL.
soc, SOC	State of charge (kWh).
T	Operation system lead-time (h).
v, V	Voltage (V).
μ	Contract of a PEV owner for a minimum SOC.
λ	Failure rate (%).
η	Charge and discharge efficiency (%).
ρ	Scenario probability (%).
π	Price (€).
γ	Rate of charge and discharge of a PL (%).

I. INTRODUCTION

A. Motivation and Background

FORTHCOMING urban systems will be equipped with high-tech infrastructures that could make difficult to deal with both operational and planning aspects. Emerging facilities such as plug-in electric vehicles (PEVs) offer a vast spectrum of possibilities for future systems. As well as enhancing system's efficiency and operational conditions, other issues such as greenhouse gas emissions and fossil fuel shortages will be met if higher penetration of PEVs in both transportation and electrical systems is encouraged. On the other hand, renewable energy resources (RERs) are among the most used choices for sustainable development paths.

The presence of these two resources in the system provides the distribution system operator (DSO) with both generating and storage units that can be used profitably. Therefore, the problem of planning the optimal location of PEVs and RERs has to be solved by power system operators like any other resource in the system.

Managing the power needed for charging vehicles in a parking lot (PL) and the potential of PEVs to inject power into the grid is a challenging issue that may have conflicting impacts on the network. As a result, the DSO has to study the effects of PL network integration while considering the use of PL as a network resource in the most efficient way. This can be achieved through the optimal allocation of PLs in the system. Usually, PLs are connected to distribution networks, thus, the responsibility of the DSO is to investigate possible effects of this integration. High penetration of storage devices such as PEVs can have adverse impacts on the grid because of their randomly located charging loads or unmanaged additions [1]. On the contrary, the optimal allocation of PLs can provide benefits both to its owner and the DSO. To achieve all the advantages of PLs, both the optimal sizes and sites are needed. Therefore, the optimal allocation of PLs is one of the most important issues to be considered while trying to minimize undesirable effects on the distribution system.

B. Literature Review

Literature on the subject is limited. Among the related studies, a comprehensive overview of the inclusion of plug-in hybrid electric vehicles (PHEVs) has been provided in [2].

In [3], the optimal sites for electric vehicle (EV) charging stations are identified through a two-step screening method. However, the study has only considered charging stations focusing on the battery package effect and environmental issues affecting site selection. In [4], the optimal sizing and siting of EV charging stations is studied in distribution networks. Then, again in [4], charging stations are allocated instead of using a PL. Besides, charging stations are only considered as loads.

The authors in [5] have considered network topology and traffic constraints simultaneously for optimal planning of charging stations. However, like previously mentioned studies, the authors in [5] have only considered the charging stations and the grid to vehicle (G2V) mode. Moreover, the only discharge of PEV batteries is due to consumption on road travel, not through a network interface.

In [6], a genetic algorithm (GA) is used for a multi-objective optimization of the PL allocation problem. However, there are certain differences between [6] and the present work, since, in [6], the outputs of all EVs are considered in a simplified model (practically deterministic), whereas in this paper not only the uncertain behavior of PEVs has been modeled, but also the overall behavior of PL in energy and reserve markets is modeled. Moreover, in this paper, the voltage has been modeled in the objective function, whereas it has only been considered as a constraint in [6]. In addition, most of the above-mentioned works have considered the G2V mode of PEVs, whereas this work considers both G2V and vehicle to grid (V2G) modes.

Although the integration of distributed generation (DG) resources and their impact has been widely studied, major differences between PL and DG considered as network resources are apparent. Regarding the network integration impact, few attempts have been made to investigate its effects. In [7], the impact of various penetration levels of PEVs on distribution networks has been assessed. However, [7] only considers PEV integration adding loads to the grid. Although [8] studies two states of coordinated and uncoordinated charging of PEVs in a radial distribution network and reports the possible effects, the authors only consider the charging stations and their effects on power quality.

Although in [9] a reliability cost evaluation model is proposed for a distribution system with both wind generation and PEVs, it does not consider the V2G mode of PEVs in the reliability study. Reference [10] has studied the real-time coordinated operation of PEVs in order to minimize distribution network effects, including voltage and loss. However, the study in [10] is more concentrated on the load management aspect of the coordinated charging of PEVS. As a result, this approach is mostly used by the PEV aggregator.

In [11], both V2G and G2V modes of PEVs are studied at different penetration levels to reach acceptable bus voltages and power loss in the grid. The study in [11] has introduced a stochastic model for PEV behavior. In the present study not only the PEV's stochastic behavior is modeled, but also PL behavior is derived from market interactions considering a profit maximization objective. This approach may fulfill some of the PL owner's investment concerns. Moreover, in [11], simultaneous V2G and G2V states are not considered, whilst both states are simultaneously considered in the present study.

The authors in [12] have studied the allocation of PLs in a distribution network, but they have just addressed the technical aspect of the problem and not the economic concerns. Instead, this paper investigates the allocation of PL from both technical and economic points of view.

C. Contributions

Although many previous studies assume that the controlled management of PEVs can be beneficial for the distribution system, most of them have considered individual charging stations as PEVs interfaces to the grid. However, it should be noted that the nature of PLs provides some opportunities that cannot be obtained through charging stations. The duration of numerous vehicles' batteries that are available in a PL provides a potential that should be studied in order to be used in the most beneficial way. First, the stochastic behavior of PEVs is modeled. Then, based on this behavior in order to achieve PL owner's profit maximization, the optimal PL interaction with the energy and reserve markets is derived. Finally, the allocation of PLs in the distribution network is studied with several objectives: power loss, bus voltages, and network reliability. Hence, the paper's main contributions are threefold:

- To propose a two-stage model that determines the optimal behavior of PLs at the first stage. Then, this behavior is subject to network-constrained objectives in order to allocate PLs at the second stage;
- To model the integrated behavior of PLs through PEVs' arrivals and departures and also PLs interaction with energy and reserve markets;
- To linearize the PLs stochastic behavior at stage 1 and the nonlinear terms at stage 2 (voltage deviation, power flow, and loss).

D. Paper Organization

The rest of the paper is organized as follows. Section II explains the main assumptions of the problem. The two-stage mathematical optimization model is described in Sections III and IV. Numerical results are shown in Section V. Finally, Section VI concludes with the main achievements of the study.

II. PROBLEM OVERVIEW

The growing tendency towards the electrification of transportation has fostered the use of PEVs in the distribution grid. One way to do it is to use PEVs through the installation of PLs in the system. The DSO should benefit more from PLs if they could be operated in a V2G mode. Consequently, the operational planning of PLs as well as their allocation should be comprehensively analyzed.

A. Procedure and Assumptions

The main purpose of the current study is to investigate the optimal location of PLs in a distribution network in order to gain the maximum benefit of these resources. It is assumed that urban studies need the installation of PLs in a distribution network. As a result, individual PL operators own and operate PLs in the system. However, the allocation of PLs is assigned to the DSO. This idea starts from the fact that, in future sustainable distribution networks, the installation of PL stations with high charging requirements of PEVs will be inevitable.

As a result, it is assumed that new system agents such as PL owners/operators need to be introduced. Accordingly, a two-stage optimization problem is defined for this purpose. Fig. 1 shows the procedure that has been adopted to solve the problem. The flowchart in Fig. 1 showcases the optimization problem procedure, the scenarios assumed, the controlling variables and the input/outputs at each stage.

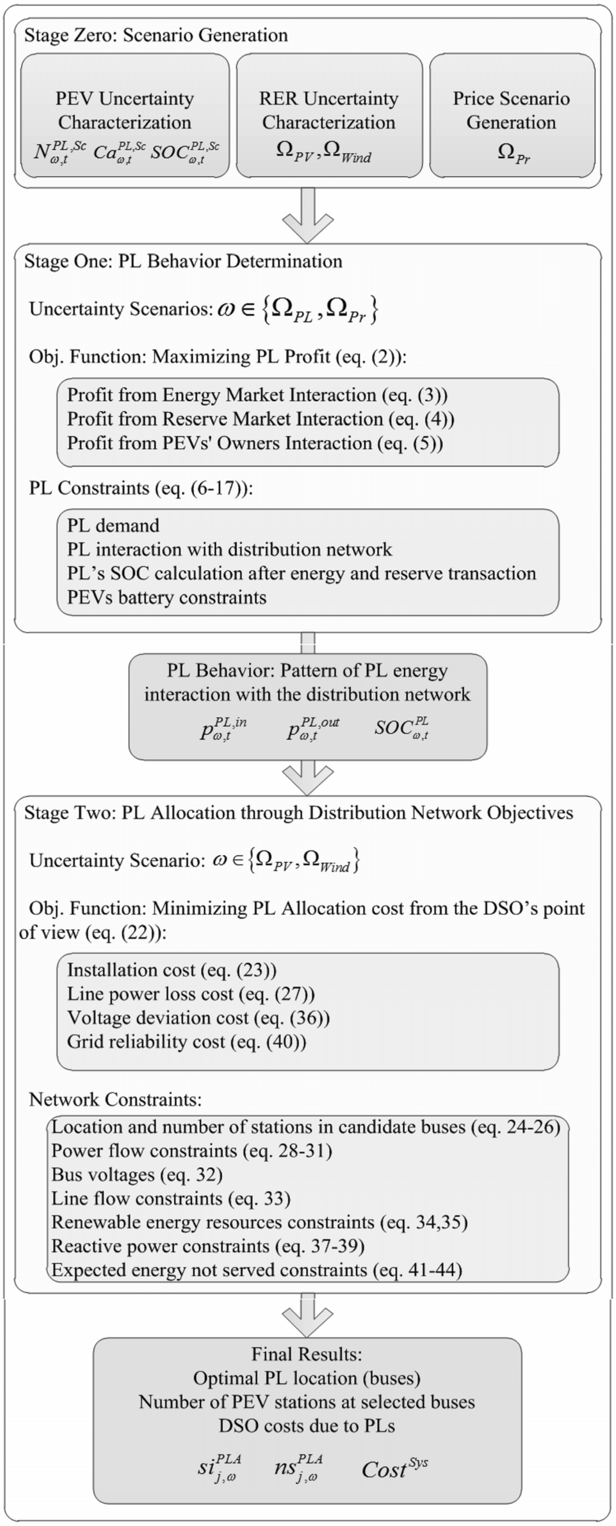

Fig. 1. Flowchart of the overall algorithm.

As shown, the uncertain characteristics of the problem (PEVs, RERs, and prices) are solved generating various scenarios at the first stage. These scenarios are the main inputs of the study. More explanations about scenario generation are presented in the following subsection.

The first stage of the problem is dedicated to model PLs' behavior based on the input scenarios given by PL uncertainty characterization. At this stage, based on PL traffic patterns and electricity market price scenarios, PLs' energy trade behavior, including input power to the PLs and the power purchased from PEV batteries, as well as the total PLs SOC, is computed. At this step, the PL operator maximizes his/her profit via market interaction along with the revenue from contracts with those PEV owners that use PLs. This means that PLs participate in both energy and reserve markets, while demonstrating the best possible behavior through interacting with PEV owners (based on their preferences and requirements). This is an input for the next stage, which is the PL allocation problem.

Managing a PL is a challenging issue due to the uncertain behavior of PEVs. Although it is difficult to derive a pattern for a vehicle's arrival/departure behavior, it is possible to characterize PL behavior. In case of a PEV, it should be noticed that the PEV's batteries have an SOC that is the main source to be utilized by a PL or system operator. Therefore, uncertainty characterization of PLs has been studied for a better illustration of the PL behavior.

The second stage is the PL allocation problem that determines the optimum locations for PLs based on network-constrained objective functions. It is executed through the separate minimization of the costs of reliability, power loss, and bus voltage deviation.

The presence of PEVs in PLs brings in both challenges and opportunities to the system. Those PEVs that are parked in a PL not only can be utilized as battery resources but also need to be charged, at least up to their minimum required SOCs. Accordingly, PLs are energy resources that may also be considered as controllable loads. By controllable loads it is meant that the PL owner can control the amount of energy that is needed to fuel up the PEV batteries during the period of their stays at the PL. The reason is that this time interval gives the PL the opportunity to see market prices and decide when to charge the batteries and when to sell energy to the grid. This makes PLs different from other distribution resources, such as conventional DGs. Consequently, their planning should be performed over a period of time.

Other assumptions are also imposed to examine various cases and to make the problem more compatible with the distribution grid. For example, it is assumed that PEVs that agree to be in a V2G mode sign a contract with the PL and determine a minimum amount of SOC before they leave the PL. Moreover, in this study, PEVs that use PLs do not necessarily have to be part of this network. This means that they can come from neighboring networks. As a result, they will not increase the total load of the system during the hours that they are not at a PL.

As shown in Fig. 1, each stage of the problem is solved in different environments. The first stage is solved in a market environment (energy and reserve) to maximize the PL owner's profit.

At the second stage, the problem is solved under network constraints considering the power generated from RERs. At this second stage, three network-constrained objective functions are solved, as also shown in Fig. 1.

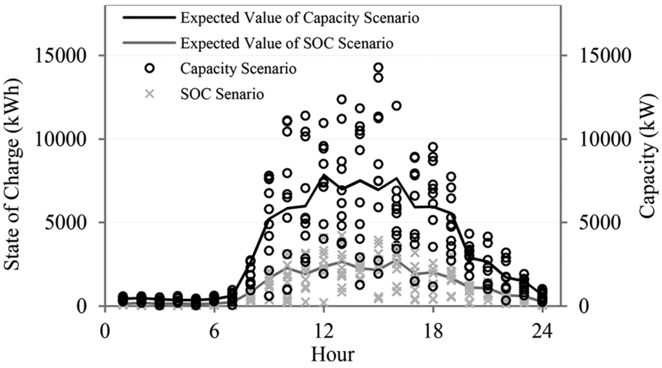

Fig. 2. Capacity and SOC scenarios of PEVs.

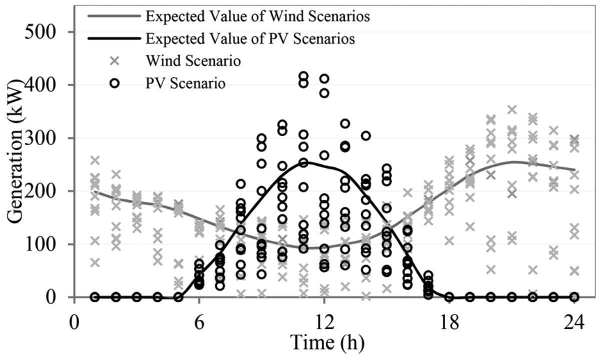

Fig. 3. Output generation of RERs.

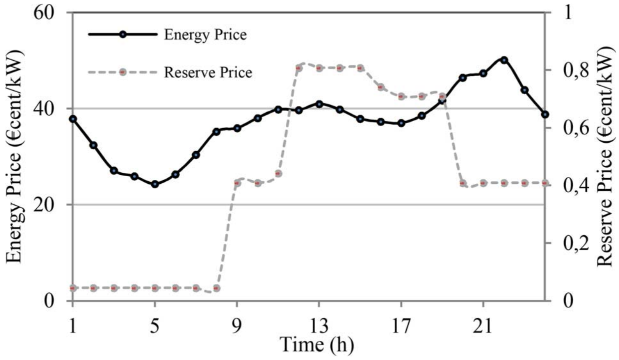

Fig. 4. Average price of energy and reserve.

The results indicate the optimum location for installing PLs as well as the number of stations at each bus. The results are obtained by optimizing the cost function for each of the objectives mentioned.

B. *Uncertainty Characterization*

In this paper the behavior of PEVs, RERs generation and energy market prices are considered uncertain. As a result, in order to model the stochastic behavior of these elements, a scenario generation approach has been used.

In order to investigate the uncertain behavior of PEVs, a stochastic model is used to provide the required scenarios for the number, SOCs, and battery capacities of the PEVs in each hour. The total aggregated capacity and SOC for EVs plugged-in at the PL are derived from the model. It should be emphasized that PEV scenarios are generated for the whole network. In other words, it is assumed that the PEVs in a certain geographical area, e.g., a district of a city, follow a certain behavior.

The pattern of available PEVs is extracted from real data in [13]. Since the SOC depends on each PEV's type and the daily distance driven, 24 different classes have been considered for PEV batteries [14]. Furthermore, a lognormal distribution function is used to generate the probabilistic traveled distance daily [15] and other general assumptions for generating scenarios are based on [13].

The scenarios that have been generated in this study are shown in Fig. 2. As it can be seen, the expected value of the scenarios is used in the calculations.

In order to characterize the uncertainty of RERs, the same method is utilized for both resources: wind power and photovoltaic (PV). Wind speed distributions are characterized by Weibull distributions [16] and the probability distribution function (PDF) is calculated. Different realizations of wind power generation are modeled through a scenario generation process based on the roulette wheel mechanism (RWM).

First, the distribution function is divided into several class intervals. Hence, each interval is associated with a probability. Subsequently, according to the different intervals and their probabilities obtained by the PDF, RWM is applied to generate scenarios for each hour. Finally, in a similar way, the RWM technique is applied for scenario generation at each hour. It is clear that a higher number of scenarios produces a more accurate model to consider the mentioned uncertainties. However, this may yield an unmanageable optimization problem. Hence, a scenario reduction technique is considered, namely the K-means clustering technique, resulting in a scenario tree with three independent scenarios. The reduced scenarios that are generated for RERs are shown in Fig. 3.

Four price scenarios are used in the process to enable a more comprehensive study. These scenarios are based on day-ahead market prices. Each scenario represents the average price of 90 days for each season. As a result, price scenarios are the average seasonal prices that are applied to the problem. The average prices of the energy and reserve markets based on these scenarios are shown in Fig. 4.

III. FIRST STAGE: PL MODEL

The first stage models the behavior of PEV's PLs as stochastic storage devices. Here, the nonlinear formulation is presented, while the model has been linearized for solving the problem. The problem is solved with various price and PEV traffic scenarios (1):

$$\omega \in \{\Omega_{\mathrm{PL}}, \Omega_{\mathrm{Pr}}\}. \tag{1}$$

A. *Objective Function*

The objective function at this stage maximizes the profit from operating the PLs from the PL operator's perspective. As shown in (2), the profit is obtained through energy and reserve market interactions as well as individual contracts with PEV owners that use the PLs in a V2G state. For a better illustration of the objective function terms, a separate formulation for each interaction is presented in (3)–(5).

The energy market interaction provides revenue to the PL from selling energy to the upstream network minus the cost of purchasing energy (3):

$$Max\left\{\mathrm{profit}^{\mathrm{PL}}\right\} = Max\left\{\sum_{\omega}\rho_{\omega}\sum_{t}\left(\mathrm{profit}^{\mathrm{EMI}} + \ \mathrm{profit}^{\mathrm{RMI}} + \mathrm{profit}^{\mathrm{POI}}\right)\right\} \tag{2}$$

$$\mathrm{profit}^{\mathrm{EMI}} = p_{\omega,t}^{\mathrm{PL,out}}\pi_{\Omega_{\mathrm{Pr}},t}^{E} - p_{\omega,t}^{\mathrm{PL},in}\pi_{\Omega_{\mathrm{Pr}},t}^{E}. \tag{3}$$

The revenues and costs from reserve market interaction are shown in (4). The income from reserve declaration and the income from selling power in the reserve market multiplied by the probability of a reserve call are the revenues from reserve market interaction. On the other hand, the penalty for not being ready whenever a PL is called to take part in the reserve market is the cost produced by reserve market interaction. In (4), $\mathrm{FOR}^{\mathrm{PL}}$ is the forced outage rate, which indicates the inability of a PL to deliver power to the upstream grid and may be caused by a system failure or by the PL itself:

$$\mathrm{profit}^{\mathrm{RMI}} = re_{\omega,t}^{\mathrm{PL}}\pi_{t}^{\mathrm{Re}} + re_{\omega,t}^{\mathrm{PL,in}}\rho_{t}^{\mathrm{del}}\pi_{\Omega_{\mathrm{Pr}},t}^{E} - re_{\omega,t}^{\mathrm{PL,in}}\rho_{t}^{\mathrm{del}}\,\mathrm{FOR}^{\mathrm{PL}}\pi_{t}^{\mathrm{Outage}}. \tag{4}$$

The revenue and income due to the interactions of the PLs with PEV owners that use PLs is shown in (5). The revenues are caused by the amount received from the PEVs for charging their batteries and the parking usage tariff. Besides, the costs of PEV owner interactions come from the value that should be paid to vehicle owners when they participate in a V2G interaction in the reserve and energy markets, respectively. However, it should be noted that the decreased SOC from PEV batteries is the amount that should be paid as the power contributing in the V2G mode. Another cost is the battery depreciation cost, which is calculated based on the amount of power taken from PEV batteries and sold to the energy and/or reserve markets multiplied by the cost of equipment depreciation:

$$\begin{aligned}\mathrm{profit}^{\mathrm{POI}} = {} & \mathrm{soc}_{\omega,t}^{\mathrm{PL,up}}\pi_{t}^{G2V} + n_{\omega,t}^{\mathrm{PL}}\pi^{\mathrm{Tariff}} \\ & - re_{\omega,t}^{\mathrm{PL,in}}\rho_{t}^{\mathrm{del}}\pi_{t}^{V2G} - \mathrm{soc}_{\omega,t}^{\mathrm{down}}\pi_{t}^{V2G} \\ & - \left(p_{\omega,t}^{\mathrm{PL,out}} + re_{\omega,t}^{\mathrm{PL,in}}\rho_{t}^{\mathrm{del}}\right)C^{Cd}.\end{aligned} \tag{5}$$

B. Constraints

The total power that can be injected into a PL or purchased from it is restricted to fixed charging and discharge rates, as shown in (6) and (7).

A PL is also restricted to these rates based on the characteristics of the charging stations, as well as the number of stations:

$$p_{\omega,t}^{\mathrm{PL,in}} \le \gamma^{\mathrm{EV}}\,n_{\omega,t}^{\mathrm{PL}} \tag{6}$$

$$p_{\omega,t}^{\mathrm{PL,out}} + re_{\omega,t}^{\mathrm{PL}} \le \gamma^{\mathrm{EV}}\,n_{\omega,t}^{\mathrm{PL}}. \tag{7}$$

Each PEV owner that agrees to participate in a V2G mode at a PL may have expectations based on its usage pattern. Mainly, these expectations are declared as the minimum required SOC.

On the other hand, the PL owner may expect an approximate duration of the stay at a PL in order to reduce uncertainty. It is assumed that a contract is signed between the PL owner and the PEVs that want to contribute in a V2G mode. In that case, a PL should aggregate the expected minimum SOC assigned in the contracts for each hour to put a limit to the maximum power exchange with the grid. The term μ denotes this aggregated percentage. The calculation of μ can be done using various probabilistic methods that are used for discrete probability problems. In this study a constant term is considered for μ.

In (8), it is shown that the total PL interaction with the grid should be less than required SOC of the PL due to the contracts with the PEV owners:

$$p_{\omega,t}^{\mathrm{PL,out}} + re_{\omega,t}^{\mathrm{PL}} \le \mu_{t}^{\mathrm{PL}}\,\mathrm{soc}_{\omega,t}^{\mathrm{PL}}. \tag{8}$$

In order to specify the SOC and the power capacity of a PL, it is necessary to estimate the approximate number of PEVs at a PL in each hour. On the other hand, as the study is based upon certain PL scenarios (number of PEVs, SOC, and capacity), the allowed number of stations in a PL has to be scaled on this basis. For this reason, (9) is defined, showing that if the total number of PEVs in a scenario is less than the number of stations, is fine, but, when it exceeds the number of stations, the presumed amount of PEVs will be limited by the number of stations at the PL:

$$n_{\omega,t}^{\mathrm{PL}} = \begin{cases}\mathrm{NS}^{\mathrm{PL}} & \text{if } \mathrm{NS}^{\mathrm{PL}} \le N_{\omega,t}^{\mathrm{PL},Sc} \\ N_{\omega,t}^{\mathrm{PL},Sc} & \text{if } N_{\omega,t}^{\mathrm{PL},Sc} < \mathrm{NS}^{\mathrm{PL}}.\end{cases} \tag{9}$$

The total capacity of a PL has to be scaled. It is assumed that the ratio of vehicle numbers in a PL with respect to the number of vehicles in a scenario is proportional to the PL capacity (10):

$$ca_{\omega,t}^{\mathrm{PL}} = Ca_{\omega,t}^{\mathrm{PL,SC}}\,n_{\omega,t}^{\mathrm{PL}}\Big/N_{\omega,t}^{\mathrm{PL},Sc}. \tag{10}$$

A PL's SOC at each hour depends on the remaining SOC of the PL from the previous hour, the power exchanged with the upstream network multiplied by the charge/discharge efficiency and the SOCs of arriving or departing vehicles (11). Moreover, the amount of SOC is restricted by the capacity of the PL in each hour and cannot exceed this limit (12):

$$\begin{aligned}\mathrm{soc}_{\omega,t}^{\mathrm{PL}} = {} & \mathrm{soc}_{\omega,t-1}^{\mathrm{PL}} + p_{\omega,t}^{\mathrm{PL,in}}\,\eta^{\mathrm{PL},Cha} \\ & - p_{\omega,t}^{\mathrm{PL,out}}\Big/\eta^{\mathrm{PL},dCha} \\ & + \mathrm{soc}_{\omega,t}^{\mathrm{PL},ar} - \mathrm{soc}_{\omega,t}^{\mathrm{PL,dep}}\end{aligned} \tag{11}$$

$$\mathrm{soc}_{\omega,t}^{\mathrm{PL}} \le ca_{\omega,t}^{\mathrm{PL}}. \tag{12}$$

The total SOC of a PL cannot exceed the minimum and maximum SOC of each PEV multiplied by the number of PEVs at each PL (13):

$$\underline{\mathrm{SOC}}^{\mathrm{EV}}\,n_{\omega,t}^{\mathrm{PL}} \le \mathrm{soc}_{\omega,t}^{\mathrm{PL}} \le \overline{\mathrm{SOC}}^{\mathrm{EV}}\,n_{\omega,t}^{\mathrm{PL}}. \tag{13}$$

The number of vehicles that arrive at a PL and depart from it in each hour provides the initial SOC of the PL. Moreover, the available SOC in each hour is the main factor that affects the behavior of the PL.

As a result, it is important to estimate its amount based on the stochastic behavior of PEVs. In order to have an approximation of the SOC in each hour, the approximated number of arrivals and departures in each hour should be specified. In this study, PEV scenarios that have been generated are used as a benchmark to indicate arrival/departure patterns. In each hour, the SOC in a scenario is compared with the SOC of the previous hour. If the SOC increases, this means that several PEVs have arrived at the PL (because no interaction is considered between the PL and the grid in the scenarios and the only change in the SOC is due to PEVs' arrivals and departures). However, in order to implement this increase in the SOC, it has to be scaled based on the number of the stations that are installed in the PL. For this purpose, (14) has been designed. In (14), it is shown that, if the SOC does not increase in the following hour, no arrival is considered for the PL. However, if the SOC in a scenario is higher than in the previous hour, the increase in the PL's SOC is calculated by scaling the SOC increase by the ratio between the number of PEVs in the PL and the ones in the scenario:

$$\begin{cases} \text{if } \mathrm{SOC}_{\omega,t}^{\mathrm{PL},Sc} \le \mathrm{SOC}_{\omega,t-1}^{\mathrm{PL},Sc} \Rightarrow \quad \mathrm{soc}_{\omega,t}^{\mathrm{PL},ar} = 0 \\ \text{if } \mathrm{SOC}_{\omega,t-1}^{\mathrm{PL},Sc} < \mathrm{SOC}_{\omega,t}^{\mathrm{PL},Sc} \Rightarrow \\ \mathrm{soc}_{\omega,t}^{\mathrm{PL},ar} = \left(\mathrm{SOC}_{\omega,t}^{\mathrm{PL},Sc} - \mathrm{SOC}_{\omega,t-1}^{\mathrm{PL},Sc}\right) n_{\omega,t}^{\mathrm{PL}} \Big/ N_{\omega,t}^{\mathrm{PL},Sc}. \end{cases} \tag{14}$$

On the other hand, when the SOCs between two consecutive hours decrease, this does not indicate that the number of vehicles has decreased. The reason is that, in some cases, fewer vehicles with higher SOCs may depart from the PL and more PEVs with lower SOCs may arrive at the PL in the same hour. As a result, the scaling procedure used for the SOCs related to PEVs arrivals cannot be used for determining the SOCs related to PEVs departures. Therefore, in (15), the same comparison is used, but the SOC of a PL is calculated scaling the amount of SOC decrease by the ratio between the SOC in the PL and the one in the scenario.

$$\begin{cases} \text{if } \mathrm{SOC}_{\omega,t-1}^{\mathrm{PL},Sc} \le \mathrm{SOC}_{\omega,t}^{\mathrm{PL},Sc} \Rightarrow \quad \mathrm{soc}_{\omega,t}^{\mathrm{PL,dep}} = 0 \\ \text{if } \mathrm{SOC}_{\omega,t}^{\mathrm{PL},Sc} < \mathrm{SOC}_{\omega,t-1}^{\mathrm{PL},Sc} \Rightarrow \\ \mathrm{soc}_{\omega,t}^{\mathrm{PL,dep}} = \left(\mathrm{SOC}_{\omega,t}^{\mathrm{PL},Sc} - \mathrm{SOC}_{\omega,t-1}^{\mathrm{PL},Sc}\right) \mathrm{soc}_{\omega,t}^{\mathrm{PL}} \Big/ \mathrm{SOC}_{\omega,t}^{\mathrm{PL},Sc}. \end{cases} \tag{15}$$

In scenario generation, the PL does not have any interaction with the network. As a result, the PEVs will enter the PL with a certain amount of SOC and will depart with the same amount. However, as the PL trades with the grid, the total SOC of the PEVs leaving the PL may be higher or lower than the SOC in the same hour for the scenario. The reason is that, while the PEVs stay in the PL, they may be charged or discharged, having a SOC different from the one that they had when they arrived at the PL. The extra charge or discharge of the initial SOC of the PEVs is the basis that produces the PL's profit. Therefore, in order to calculate the revenue/cost of a PL, it is necessary to compute the surplus SOC that remains within the PEVs when they depart. This can be achieved through (16) and (17). In (16), if the SOC of the departed PEVs that have left is higher than the scaled amount of the departed SOCs in a scenario, this means that the PEVs have been overcharged comparing to their initial SOCs.

Hence, the owners have to pay for the excess charge ($\mathrm{SOC}^{\mathrm{up}}$). On the other hand, in (17), if the SOC of the departed PEVs is lower than the one of the initial scenario, the owners should be paid by the PL based on $\mathrm{SOC}^{\mathrm{down}}$. See (16) and (17) at the bottom of the page.

IV. SECOND STAGE: ALLOCATION OF PEV'S PARKING LOTS

At the second stage, the allocation of PLs in a distribution network is modeled based on various network-constrained objectives. In this study the objectives are to minimize the costs of power loss, voltage deviation, and network reliability. The study examines various PL scenarios and RERs, including wind generation and photovoltaic (PV) sources (18):

$$\omega \in \{\Omega_{\mathrm{PLA}}, \Omega_W, \Omega_{\mathrm{PV}}\}. \tag{18}$$

As mentioned before, the outputs of the first stage are treated as inputs at the second stage. This means that the optimal trading behavior of the PLs based on maximizing the PL owner's profit

---

$$\begin{cases} \text{if } \mathrm{soc}_{\omega,t}^{\mathrm{PL,dep}} \le \left(\mathrm{SOC}_{\omega,t-1}^{\mathrm{PL},Sc} - \mathrm{SOC}_{\omega,t}^{\mathrm{PL},Sc}\right) n_{\omega,t}^{\mathrm{PL}} \Big/ N_{\omega,t}^{\mathrm{PL},Sc} \Rightarrow \\ \quad \mathrm{soc}_{\omega,t}^{\mathrm{PL,up}} = 0 \\ \text{if } \left(\mathrm{SOC}_{\omega,t-1}^{\mathrm{PL},Sc} - \mathrm{SOC}_{\omega,t}^{\mathrm{PL},Sc}\right) n_{\omega,t}^{\mathrm{PL}} \Big/ N_{\omega,t}^{\mathrm{PL},Sc} < \mathrm{soc}_{\omega,t}^{\mathrm{PL,dep}} \Rightarrow \\ \quad \mathrm{soc}_{\omega,t}^{\mathrm{PL,up}} = \mathrm{soc}_{\omega,t}^{\mathrm{PL,dep}} - \left(\mathrm{SOC}_{\omega,t-1}^{\mathrm{PL},Sc} - \mathrm{SOC}_{\omega,t}^{\mathrm{PL},Sc}\right) n_{\omega,t}^{\mathrm{PL}} \Big/ N_{\omega,t}^{\mathrm{PL},Sc} \end{cases} \tag{16}$$

$$\begin{cases} \text{if } \left(\mathrm{SOC}_{\omega,t-1}^{\mathrm{PL},Sc} - \mathrm{SOC}_{\omega,t}^{\mathrm{PL},Sc}\right) n_{\omega,t}^{\mathrm{PL}} \Big/ N_{\omega,t}^{\mathrm{PL},Sc} \le \mathrm{soc}_{\omega,t}^{\mathrm{PL,dep}} \Rightarrow \\ \quad \mathrm{soc}_{\omega,t}^{\mathrm{PL,down}} = 0 \\ \text{if } \mathrm{soc}_{\omega,t}^{\mathrm{PL,dep}} < \left(\mathrm{SOC}_{\omega,t-1}^{\mathrm{PL},Sc} - \mathrm{SOC}_{\omega,t}^{\mathrm{PL},Sc}\right) n_{\omega,t}^{\mathrm{PL}} \Big/ N_{\omega,t}^{\mathrm{PL},Sc} \Rightarrow \\ \quad \mathrm{soc}_{\omega,t}^{\mathrm{PL,down}} = \mathrm{soc}_{\omega,t}^{\mathrm{PL,dep}} - \left(\mathrm{SOC}_{\omega,t-1}^{\mathrm{PL},Sc} - \mathrm{SOC}_{\omega,t}^{\mathrm{PL},Sc}\right) n_{\omega,t}^{\mathrm{PL}} \Big/ N_{\omega,t}^{\mathrm{PL},Sc} \end{cases} \tag{17}$$

is considered as an input at this stage. The second stage is conducted from the DSO's point of view using the PLs to enhance network operation as much as possible. It should be mentioned that, at the first stage, PEVs are considered as a whole and assumed to belong to a single owner.

However, at the second stage, the DSO tries to distribute the PEVs among network buses, thus, the SOC and power injected from/into the PLs should be scaled based on the number of stations that are allocated at each bus.

The interface between the first and second stages is done through (19)–(21):

$$p^{\text{PLA,in}}_{j,\omega,t} = p^{\text{PL,in}}_{\omega,t} ns^{\text{PLA}}_{j,\omega} \Big/ \text{NS}^{\text{PL}} \tag{19}$$

$$p^{\text{PLA,out}}_{j,\omega,t} = p^{\text{PL,out}}_{\omega,t} ns^{\text{PLA}}_{j,\omega} \Big/ \text{NS}^{\text{PL}} \tag{20}$$

$$\text{soc}^{\text{PLA}}_{j,\omega,t} = \text{soc}^{\text{PL}}_{\omega,t} ns^{\text{PLA}}_{j,\omega} \big/ \text{NS}^{\text{PL}}. \tag{21}$$

The objective function shown in (22) denotes that the DSO wants to minimize the total cost subject to network constraints:

$$\begin{aligned} &Min\left\{\text{Cost}^{\text{Sys}}\right\} \\ &\quad = \sum_{\omega} \rho_\omega \left(\text{cost}^{\text{ins}}_\omega + \text{cost}^{Reli}_\omega + \text{cost}^{\text{VD}}_\omega + \text{cost}^{\text{loss}}_\omega\right). \end{aligned} \tag{22}$$

Each of the cost functions in (22) is described in the next subsections.

A. Installation Costs

The installation cost consists of the fixed and variable costs to install the PL (23):

$$\text{cost}^{\text{ins}}_\omega = \sum_j si^{\text{PLA}}_{j,\omega} C^{\text{PLA,fix}}_j + ns^{\text{PLA}}_{j,\omega} C^{\text{PLA,var}}_j. \tag{23}$$

The fixed costs refer to site-dependent costs such as the municipal license payment to install the PL and other wiring or construction licenses. Variable costs refer to the installation cost of the PL, which varies because the optimal number of parking stations in each PL can differ. The variable cost includes the cost of purchasing a station, land needed for installing the station, wiring costs, and vehicle on-board device costs.

To select a node for installation of a PL, (24) is used:

$$si^{\text{PLA}}_{j,\omega} \le \text{Can}^{\text{PLA}}_j \tag{24}$$

where si is a binary variable indicating whether a bus is selected for the installation of a PL and Can is a binary parameter representing whether a bus is a candidate for PL location or not. However, this selection can be based on electrical or urban planning issues. In the process of selecting a bus when a bus is a candidate, then, the binary variable si shows whether the candidate bus is also selected by the optimization model.

If a bus is selected for PL installation $(si = 1)$, then the number of stations that will be allocated at this bus should not exceed the limit of the total number of available stations in the network (25). Moreover, the total number of stations distributed along network buses should be equal to the whole number of stations to be installed in the system (26):

$$ns^{\text{PLA}}_{j,\omega} \le si^{\text{PLA}}_{j,\omega} \text{NS}^{\text{PL}} \tag{25}$$

$$\sum_j ns^{\text{PLA}}_{j,\omega} = \text{NS}^{\text{PL}}. \tag{26}$$

B. Loss Costs

The equation denoting the cost of loss is given by (27):

$$\text{cost}^{\text{loss}}_\omega = \sum_t \sum_l R_{j,j',\omega,t} (i_{j,j',\omega,t})^2 C^{\text{loss}}. \tag{27}$$

In order to calculate the above-mentioned function, a power flow is solved. In this study, a linear power flow is obtained based on [17] and [18]. The power flow model linearization takes into account the radial nature of the distribution network. For this purpose, the term $\tilde{\imath}$ is considered as a block to avoid nonlinearities. The formulation of the active and reactive power balance is shown in (28) and (29):

$$\begin{aligned} &p^{\text{Sys,in}}_{j,\omega,t} + p^{W}_{j,\omega,t} + p^{\text{PV}}_{j,\omega,t} + p^{\text{PLA,out}}_{j,\omega,t} \\ &\quad - p^{\text{PLA,in}}_{j,\omega,t} + \sum_l p^{\text{Line}}_{j,j',\omega,t} + R_{j,j'} (i_{j,j',\omega,t})^2 = p^{D}_{j,t} \end{aligned} \tag{28}$$

$$q^{\text{Sys,in}}_{j,\omega,t} + \sum_l q^{\text{Line}}_{j,j',\omega,t} + X_{i,j} (i_{j,j',\omega,t})^2 = q^{D}_{j,t}. \tag{29}$$

The relations to obtain $\tilde{\imath}$ and $\tilde{v}$ are shown in (30) and (31):

$$\begin{aligned} &(v_{j,\omega,t})^2 - 2\left(R_{j,j'} p^{\text{Line}}_{j,j',\omega,t} + X_{j,j'} \cdot q^{\text{Line}}_{j,j',\omega,t}\right) \\ &\quad - (Z_{j,j'})^2 (i_{j,j',\omega,t})^2 - (v_{j',\omega,t})^2 = 0 \end{aligned} \tag{30}$$

$$(i_{j,j',\omega,t})^2 = \frac{\left(p^{\text{Line}}_{j,j',\omega,t}\right)^2 + \left(q^{\text{Line}}_{j,j',\omega,t}\right)^2}{(v_{j',\omega,t})^2}. \tag{31}$$

As in any power flow, the voltage and current limits applied are shown in (32) and (33):

$$\underline{\tilde{v}}_j \le \tilde{v}_{j,\omega,t} \le \bar{\tilde{v}}_j \tag{32}$$

$$\underline{\tilde{I}}_{j,j'} \le \tilde{i}_{j,j',\omega,t} \le \bar{\tilde{I}}_{j,j'}. \tag{33}$$

RERs in the system should be also limited to the possible amount of generation defined in their scenarios (34) and (35), for wind and PV, respectively:

$$0 \le p^{W}_{j,\omega,t} \le P^{W,Sc}_{j,\omega,t} \tag{34}$$

$$0 \le p^{\text{PV}}_{j,\omega,t} \le P^{\text{PV},Sc}_{j,\omega,t}. \tag{35}$$

C. Voltage Deviation Costs

In this study, the cost imposed to the DSO for having the bus voltages within a specified range is calculated in (36). It is assumed that the voltage deviation is fixed by means of installing capacitors in the system.

Adding a capacitor to the system adds a variable cost term, based on the required VAR capacity and dependent on the amount of reactive power in the system, as well as a capacitor installation cost (fixed cost):

$$\mathrm{cost}_{\omega}^{\mathrm{VD}} = \sum_{j} si_{j,\omega}^{C}\, C^{\mathrm{Cap,fix}} + \Delta q_{j,\omega}\, C^{\mathrm{Cap,var}}. \tag{36}$$

The amount of reactive power required at each bus can be obtained from (37):

$$\Delta q_{j,\omega} = -\left|\Delta v_{j,\omega}\right| \cdot B_{j,j} \cdot \left|v_{j,\omega}\right|. \tag{37}$$

In order to minimize Δv at each bus, (38) is used. To keep the equation linear, the minimization of $\Delta \tilde{v}$ has been implemented based on (39):

$$\begin{aligned} \Delta q_{j,\omega} &= -B_{j,j}\left(\frac{\left(\underline{v}_{j}^{\mathrm{VD}}\right)^{2} - (v_{j,\omega})^{2}}{2}\right) - \frac{(\Delta v_{j,\omega})^{2}}{2} \\ &\approx -B_{j,j}\left(\frac{\Delta \tilde{v}_{j,\omega}}{2}\right) \end{aligned} \tag{38}$$

$$\begin{aligned} &Min\left\{\Delta v_{j,\omega}\right\} \\ &\Delta \tilde{v}_{j,\omega} \geq \begin{cases} 0 & \text{if } \left(\underline{v}_{j}^{\mathrm{VD}}\right)^{2} \leq (v_{j,\omega,t})^{2} \\ \left(\underline{v}_{j}^{\mathrm{VD}}\right)^{2} - (v_{j,\omega,t})^{2} & \text{if } (v_{j,\omega,t})^{2} < \left(\underline{v}_{j}^{\mathrm{VD}}\right)^{2}. \end{cases} \end{aligned} \tag{39}$$

D. Network Reliability Costs

As this study is conducted on a distribution network, the expected energy not served (EENS) index is used to measure reliability. Previous studies, such as [19], use the same concept, but the difference is that the battery is replaced instead of charged. The objective function implemented is shown in (40):

$$\mathrm{cost}_{\omega}^{Reli} = \mathrm{EENS}_{\omega}\, \mathrm{CDC} \tag{40}$$

where the cost of reliability is calculated through the payment of damages to end users for the period of time where the required energy is not supplied.

It is assumed that the PL operator has an extra contract with the PEV owners, whereby the operator can use more of the PEV's SOC during contingencies compared to the normal condition. This leads to a higher amount of power injection of the PLs into the grid, based on (41):

$$p_{j,\omega,t}^{\mathrm{inj,PLA}} = \mathrm{soc}_{j,\omega,t}^{\mathrm{PLA}}\, \mu_{t}^{\mathrm{PL,Con}}. \tag{41}$$

Whenever a contingency occurs in the system, the DSO aims to reduce load shedding by using the energy injected from PLs, wind farms, and PV units. However, it should be noted that all of these resources (PL, wind, and PV) are time-dependent with variable output amounts. On the other hand, a contingency is resolved after the required repair time. Thus, the total power that can be injected by these resources should be computed during the repair time period (42):

$$\begin{cases} p_{l,\omega,t}^{\mathrm{inj,Res}} = \sum\limits_{i} p_{j,\omega,t}^{\mathrm{inj,PL}} + \sum\limits_{h=t}^{h=t+\mathrm{rep}_{l}} p_{j,\omega,h}^{W} + \sum\limits_{h=t}^{h=t+\mathrm{rep}_{l}} p_{j,\omega,h}^{\mathrm{PV}} \\ p_{l,\omega,t}^{\mathrm{aff},D} = \sum\limits_{j} \sum\limits_{h=t}^{h=t+\mathrm{rep}_{l}} P_{j,t}^{D} \end{cases} \tag{42}$$

where, for each interruption (l), the summation of possible injections is made for the buses affected by the interruption, starting from the time when the interruption starts (t) until the repair time is finished $(t + r_l)$. The same procedure is performed for those loads that exist in affected buses. Finally, the amount of load shedding is obtained from (43) [19]:

$$p_{l,\omega,t}^{\mathrm{Shed}} = Max\left(0, p_{l,\omega,t}^{\mathrm{aff},D} - p_{i,\omega,t}^{\mathrm{inj,Res}}\right). \tag{43}$$

The total energy not supplied due to contingencies in a network is related with the probability of failure in the network multiplied by the load that has been shed (44):

$$\mathrm{EENS}_{\omega,t} = \frac{1}{T} \sum_{t} \sum_{l} p_{l,\omega,t}^{\mathrm{Shed}}\, \lambda_{l}. \tag{44}$$

V. NUMERICAL RESULTS

The proposed model of the problem explained above is tested on the IEEE 13-bus radial distribution test system [20]. Various references, including [21] and [22], have previously used the same network for studying the allocation of DG and PLs or PEV stations. All data used are based on real data from Madrid, Spain. Data for the day-ahead market are obtained from the Spanish electricity market [23] and data for wind and PV resources are taken from [24]. It is assumed that only one kind of charging station can be used. Based on [25] and [26], it is assumed that the PL owner purchases the quick charging station at a charging rate of 11 kW per hour. The tariff for PL contracts with PEV owners is based on [27].

The network load is adapted to the hourly-based load of the Spanish market for two reasons: first, the operation problem is calculated for each hour of the day, and second, the hourly load has to follow the same pattern as market prices; thus, the Spanish market load is used.

This process has been conducted for both active and reactive loads assuming that the system power factor is constant (0.85). In the original version of the IEEE 13-bus system, there is a switch between buses 671 and 692. However, in this study the switch between buses 671 and 692 is considered to be closed. As a result, bus 692 is eliminated from the figures. In addition, the transformer between buses 633 and 634 is assumed not to change the voltage level between these two nodes. The problem is modeled as a mixed integer linear programming (MILP) problem. The problem is implemented in GAMS utilizing CPLEX12 solver [28]. The CPLEX 12 solver, which has proved to be an efficient solver in previous studies, is used. In order to profit from its efficiency, the formulation presented in previous sections has been linearized.

A. PL Behavior Results

In order to determine the most profitable behavior of the PLs' owner in market transactions, the first stage of the problem has been computed in two cases. In the first case, the PL owner participates in both energy and reserve markets. In the second case, it is assumed that only the energy market is available to the PL owner. The purpose is to compare these two different

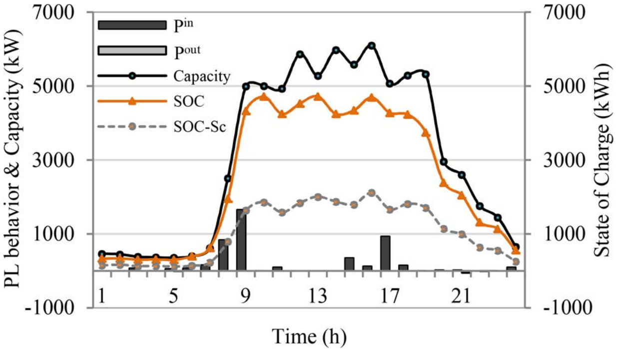

Fig. 5. PL behavior, capacity, and state of charge in case 1.

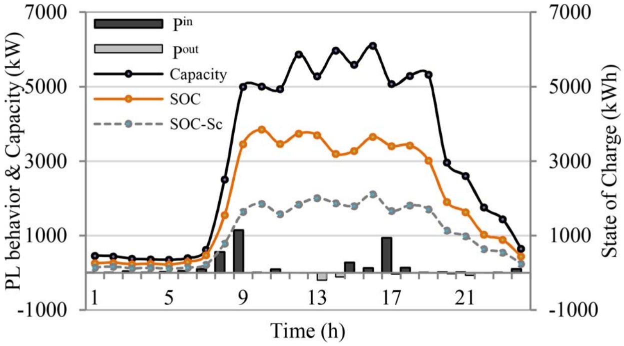

Fig. 6. PL behavior, capacity, and state of charge in case 2.

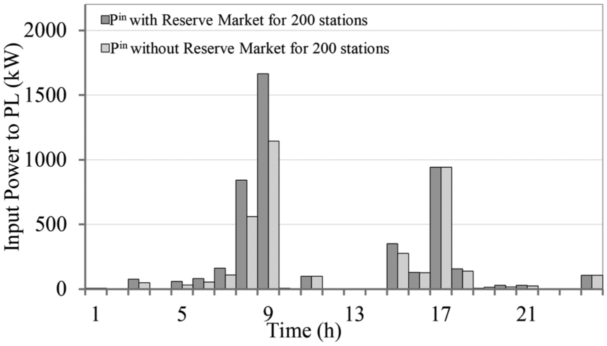

Fig. 7. Comparison of PL input power in cases 1 and 2.

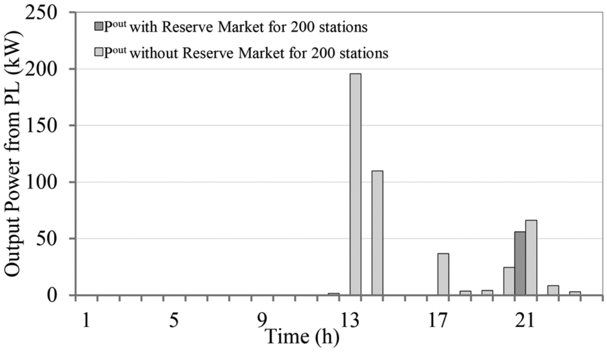

Fig. 8. Comparison of PL output power in cases 1 and 2.

situations and observe the PLs behavior and if either the reserve or the energy market is more profitable for the PLs owner.

The main results of this stage are shown in Figs. 5 and 6 for cases 1 and 2, respectively. These results are reported for 200 parking stations. The derived capacity, SOC, and power exchanged with the grid (input and output) are shown in each case. As it can be seen in both figures, a higher SOC is achieved in case 1 (where a reserve market exists). This shows a specific behavior in the case of having a reserve market. In case 1, more power is purchased from the grid and, hence, a higher SOC is achieved to be offered in both energy and reserve markets. In addition, in both Figs. 5 and 6, the PLs' SOCs is considerably higher than in a scenario. This is due to the power exchange of the PL with the grid, which is not considered in the process of scenario generation.

The comparison of the input power in the two cases is illustrated in Fig. 7. It is shown that, in case 1, where the possibility of participating in the reserve market exists, a higher amount of input power is purchased from the energy market. As can be seen in the figure, where both energy and reserve markets are available, the PL owner tries to buy more energy from the grid in order to maximize its SOC, thus, it has more power available to offer in the market. In case 2, where only the energy market is available to the PL, the owner also charges the battery's SOC but less than in the first case.

However, results in Fig. 8 indicate that there is a considerable difference in the output power of the two cases. It shows that the amount of energy sold to the grid in case 2 is significantly higher than in the case 1. This means that PLs tend to offer most of its available power in the reserve market. On the contrary, when it cannot participate in the reserve market, it sells most of its SOC to the energy market. The reason is revealed by analyzing the details of cost and revenue in each case. It appears that in case 1, the PLs' owner can earn more profit through both reserve declaration and tariff for charging PEV batteries, other than selling energy to the grid.

As a result, it manages its operation by charging the batteries and provides a sufficient degree of SOC to participate in the reserve market. Then, instead of discharging the batteries, it profits from reserve declaration, reserve call, and the extra benefit of charging PEV batteries.

The comparison of profits in two cases is shown in Fig. 9. The results for four price scenarios and the expected values of profit in the two cases are shown. These results are presented without the revenue from the PEV entrance tariff with the aim of having a better analysis of the behavior. It is clear that in case 2, although a higher amount of input energy is purchased from the market (Fig. 7) and less energy is sold to the market (Fig. 8), yet a higher profit can be obtained in this case. This is due to the reserve market. A considerable increase in the profit of the PLs indicates that, although they can participate in the market as energy resources, they can gain more profit participating in the reserve market. In this case, PLs are more likely to behave as loads that offer a potential reserve service to the DSO. The analysis denotes that in order to make a PL installation profitable to the owner apart from governmental incentives, it is better to rely on PL storage as a reserve element than as an energy source. Moreover, studies are conducted at this stage for an increasing number of available stations at the PLs, from 50 to 400. However, as it can be seen in Fig. 9, from a certain number

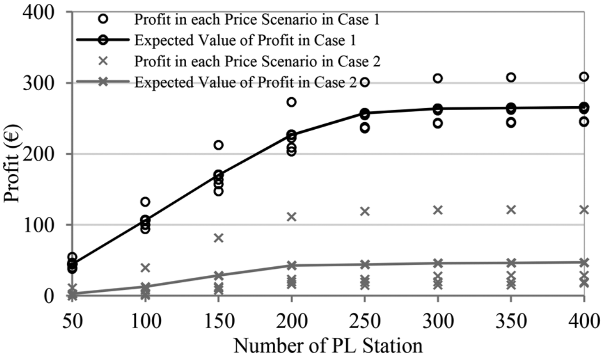

Fig. 9. PL profit comparison in the two cases.

of stations the amount of profit is saturated. This implies that a higher number of stations does not specifically produce a higher profit for the PLs owner. In case 1, where both energy and reserve markets exist, with more than 330 stations, no more profit is gained. As a result, the rest of the study is conducted for numbers between 50 and 250 in order to make sure that the behavior of the PLs is not affected by the saturation in the profit.

B. *PL Allocation*

At the second stage, three different allocation objectives are defined, including grid power loss, network reliability, and bus voltage deviation. In each of these case studies based on a network-constrained objective, a cost function has been defined. The purpose of the DSO is to minimize the cost of each objective.

The assumption in all cases is that there are two kinds of RERs (wind and PV) at bus number 680 simultaneously. Bus 680 is rather near to the load center, so if the RERs are located at this bus, part of the load can be supplied by these resources. Moreover, by assuming RERs at bus 680, the input symmetry of the system is somehow maintained. In addition, as wind and PV have different generation patterns, we have a smoother renewable generation pattern as well. It is also assumed that, except for buses 650 and 632, all other buses can be candidates for PL allocation. The cases are studied for an increasing number of available charging stations: from 50 up to 250. No limitation has been applied to the problem for the possible number of buses that can be selected for installing PLs. As a result, based on the number of available stations, the model decides how many locations should be selected to keep costs at a minimum level, as well as installing the predefined number of stations. However, the maximum amount of possible power injection from each PL into the grid is limited to 1 MW, based on [29]. The results are obtained solving the problem with individual objectives as well as concurrently.

1) Case I: Power Loss Cost Minimization: In Fig. 10, the selected buses and the number of stations in each PL are shown for the grid power loss cost function. As can be observed, bus number 633 is the preferred choice for installing a PL. This is probably due to the load-like behavior of PLs. Considering the distribution of loads, the major loads are located in the lower half of the system. As a result, extra loads, such as PLs, tend to be placed in the upper section of the system.

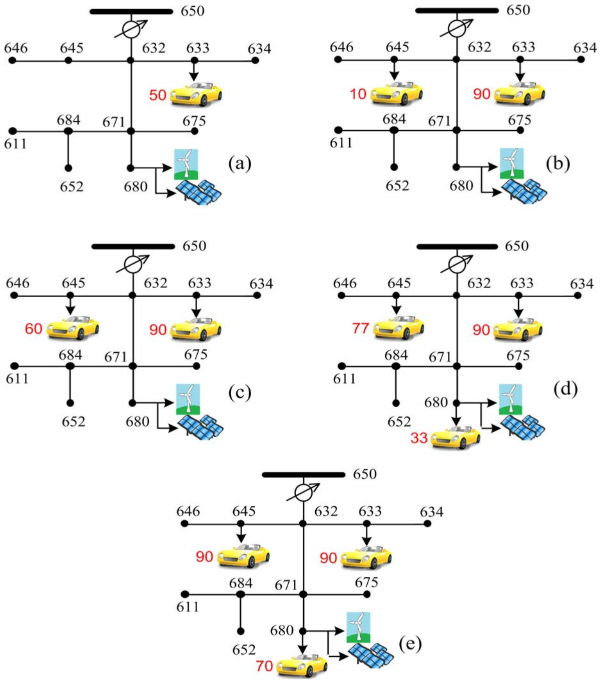

Fig. 10. PL distribution in the network with a loss cost function: (a) 50 stations; (b) 100 stations; (c) 150 stations; (d) 200 stations; (e) 250 stations.

However, as seen in Fig. 10, the model mostly locates PLs at buses near an energy resource. This is more obvious when the number of stations increases. In Fig. 10(d) and (e), it is shown that the third location for installing a PL is at the same bus as the RERs.

2) Case II: EENS Cost Minimization: To determine PL locations with a reliability cost function, it is assumed that the PL operator has a secondary contract with the PEV owners who can use the excess amount of their SOCs in case of a contingency. This means that, when a contingency occurs, the PL operator will be able to inject more power into the grid to help the DSO to minimize its EENS costs. In addition, a PL will not charge the PEV batteries during a contingency but will use the remaining SOC up to the limit defined in the secondary contract with the PEV owners. This situation results in the distribution of PLs as in Fig. 11. Differently from the grid power loss case, when the objective function consists of minimizing reliability costs, the lower section of the network is mostly selected for PL locations. The reason is that, when a contingency occurs, the DSO tries to use each possible resource in the system to reduce the amount of energy that cannot be served. In this case, according to aforementioned assumptions, PLs are considered as resources that can supply part of the isolated load.

The results show a reduction in the amount of EENS in the system (Fig. 12). Although the PL owner has to spend more money because of the secondary contract (which means it will buy PEV's excess SOC at a higher price than in normal condition), this is still profitable for the DSO. This can serve as a guide for designing incentives to encourage investors to install PLs, considering also contingency situations.

Based on Fig. 12, in a system with PLs and no RERs, a lower number of stations at the PLs may increase EENS as PLs act mostly as loads in the system. However, with an increase in the

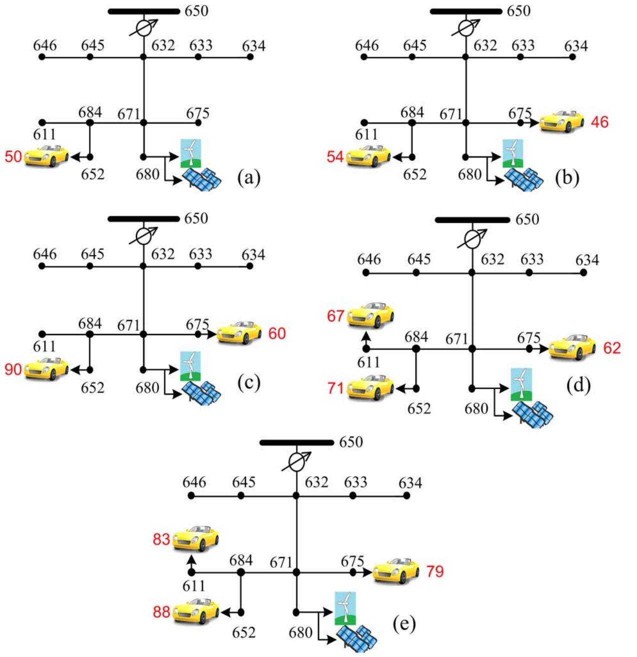

Fig. 11. PL allocation with a reliability cost function: (a) 50 stations; (b) 100 stations; (c) 150 stations; (d) 200 stations; (e) 250 stations.

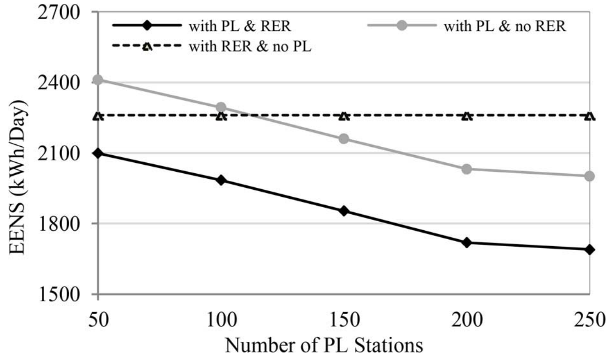

Fig. 12. EENS for various numbers of PL stations.

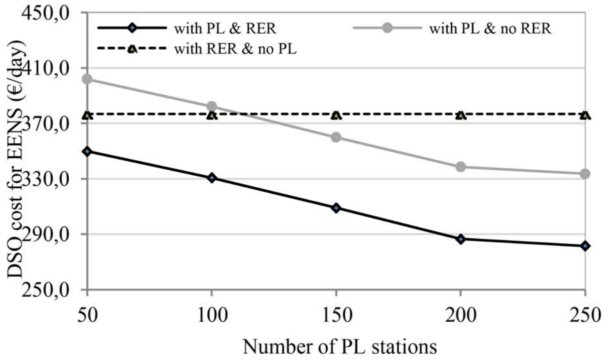

Fig. 13. DSO cost for EENS only.

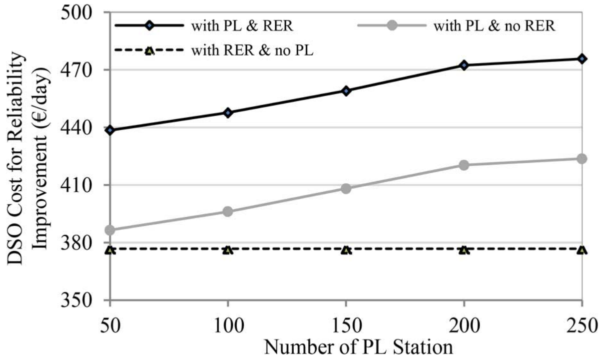

Fig. 14. Total system cost for reliability improvement.

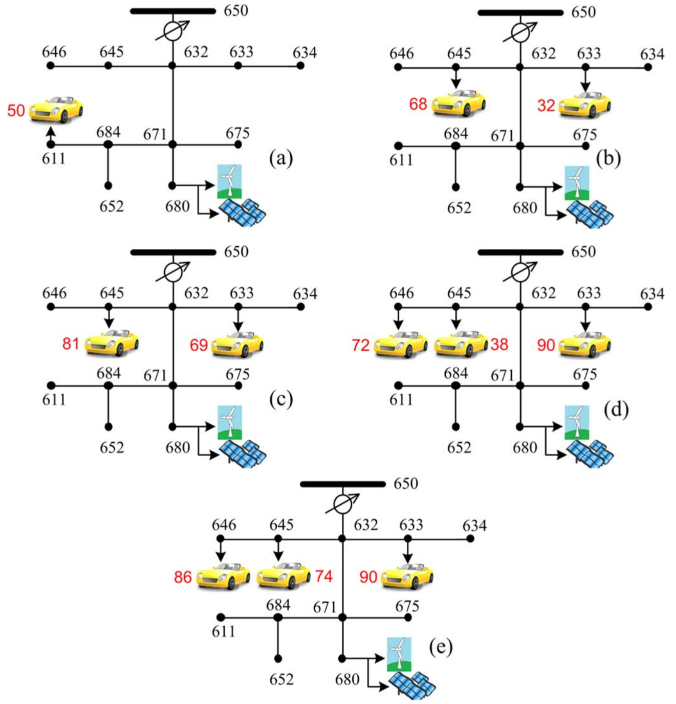

Fig. 15. PL allocation with a voltage deviation cost function: (a) 50 stations; (b) 100 stations; (c) 150 stations; (d) 200 stations; (e) 250 stations.

number of stations, EENS can decrease significantly. Figs. 13 and 14 show the costs imposed on the system for enhancing reliability. Although the total system cost (including the DSO and the PL owner) has increased, the DSO cost for reducing the amount of EENS has decreased. This shows that not only PLs are useful for enhancing reliability, but also they have positive interactions with RERs. This proves that PLs are fundamental elements towards sustainable energy systems. Adding PEV-based PLs to renewable-based electric systems can bring in major improvements to the system, such as reliability.

3) Case III: Voltage Deviation Cost Minimization: The study examines PL allocation with a voltage deviation cost function. It is assumed that a capacitor will be installed at the same bus where voltage deviates to overcome this problem. Cost data for installing the appropriate capacitor are obtained from [30]. As mentioned before, PLs behave mostly load-like; therefore, the results show that it is better to locate PLs in the upper section of the network, as seen in Fig. 15.

This is due to the topology of the network and lines' current limit. According to the test system data, the line between buses 632 and 671 has the highest current limit in the system. Hence, if more loads are added to the lower section of the network, more voltage deviation may occur at those buses. As it is shown, with a higher numbers of stations, there is a tendency to allocate the PLs at buses with shorter line lengths and lower current limits.

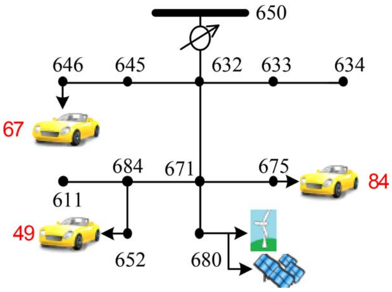

Fig. 16. PL allocation with a total cost function.

TABLE I
RESULTS FOR EACH OBJECTIVE FUNCTION

		Individual optimization	Overall optimization
Objective (€)	Loss	437	440
	Reliability	420	432
	Voltage Deviation	105	120
Location	Loss	633, 645, 680	646, 652, 675
	Reliability	611, 652, 675	
	Voltage Deviation	633, 645, 646	

One thing should be noted in studying the results in Fig. 15. As it is shown, the location of a PL with 50 stations differs from the other results. This is due to the behavior of the PL with various numbers of stations. As mentioned before, PLs mostly behave like loads, but also have the capability of injecting power into the grid. With a PL with 50 stations, the amount of load that is added to the system is still lower than the system's peak load. Therefore, it does not cause the voltage to deviate. However, when the number of stations is higher, the approach is different and the allocation will be done in order to reduce the voltage deviation.

4) Case IV: Total Cost Minimization: For the last case study, the overall system's cost minimization is conducted. In this case, all three objectives (loss, reliability, voltage deviation) are solved simultaneously. The selected buses for PL installation with 200 stations are shown in Fig. 16. Moreover, the objective function for each of the individual objectives in both the individual and the collective cases is compared in Table I. By comparing the locations of the PLs in all cases, the locations that are chosen for the individual reliability study are similar to the ones obtained in the collective case. However, comparing the objective functions, there is a change in the amount of the objective function. This indicates that the buses have higher sensitivities to the reliability index of the problem. The same conclusion can be obtained for voltage deviation.

VI. CONCLUSION

In this study, various cases of PL integration in a distribution network have been studied. Interconnecting resources in the network has effects on the system that should be carefully examined. A holistic view towards PL allocation has been presented. On one hand, PL installation should fulfill different traffic or urban considerations. On the other hand, installing numerous charging stations at a PL may cause problems for the electric system. In this study, it is assumed that different regulatory conditions or urban considerations will address the installation of various numbers of stations in the system. As a result, the problem is solved for an increasing number of available stations. The results show that a PL, due to its nature as a charging station, will behave more likely like a load in the system. However, in certain situations, the V2G mode can be used and the PL will act as a resource in the system. When optimizing the market behavior of PLs, it is concluded that when the PL owner participates in the reserve market instead of the energy market, this can be more profitable because the V2G costs are avoided. Also, more revenue from PEV owners can be obtained due to a higher SOC that will remain in the PEV batteries. Regarding network-constrained objectives, despite the low costs of V2G for PL owners, the DSO can profit significantly from the presence of PLs in the system, not only to reduce its EENS costs, but also to improve system reliability. PLs' interaction with the grid greatly affects the allocation of PLs in the network. Moreover, the overall solution considers all the objectives simultaneously, suggesting that the sensitivity of each bus to each objective imposes the right location of the PLs. In this study, it was shown that an optimal allocation of PLs can produce a significant profit for the DSO when considering reliability criteria.

REFERENCES

[1] P. Kadurek, C. Ioakimidis, and P. Ferrao, "Electric vehicles and their impact to the electric grid in isolated systems," in *Proc. Int. Conf. Power Engineering, Energy and Electrical Drives (Powereng)*, 2009, pp. 49–54.

[2] M. D. Galus, M. Zima, and G. Andersson, "On integration of plug-in hybrid electric vehicles into existing power system structures," *Energy Policy*, vol. 38, pp. 6736–6745, 2010.

[3] Z. Liu, F. Wen, and G. Ledwich, "Optimal planning of electric-vehicle charging stations in distribution systems," *IEEE Trans. Power Del.*, vol. 28, no. 1, pp. 102–110, Jan. 2013.

[4] Z. Hu and Y. Song, "Distribution network expansion planning with optimal siting and sizing of electric vehicle charging stations," in *Proc. UPEC*, 2012, pp. 1–6.

[5] G. Wang, Z. Xu, F. Wen, and K. P. Wong, "Traffic-constrained multi-objective planning of electric-vehicle charging stations," *IEEE Trans. Power Del.*, vol. 28, no. 4, pp. 2363–2372, Oct. 2013.

[6] M. Moradijoz, M. P. Moghaddam, M. R. Haghifam, and E. Alishahi, "A multi-objective optimization problem for allocating parking lots in a distribution network," *Elect. Power Energy Syst.*, vol. 46, pp. 115–122, 2013.

[7] L. P. Fernández, T. G. S. Román, R. Cossent, C. M. Domingo, and P. Frías, "Assessment of the impact of plug-in electric vehicles on distribution networks," *IEEE Trans. Power Syst.*, vol. 26, no. 1, pp. 206–213, Feb. 2011.

[8] K. Clement-Nyns, E. Haesen, and J. Driesen, "The impact of charging plug-in hybrid electric vehicles on a residential distribution grid," *IEEE Trans. Power Syst.*, vol. 25, no. 1, pp. 371–380, Feb. 2010.

[9] C. X. Wu, C. Y. Chung, F. S. Wen, and D. Y. Du, "Reliability/cost evaluation with PEV and wind generation system," *IEEE Trans. Sustain. Energy*, vol. 5, no. 1, pp. 273–281, Jan. 2014.

[10] S. Deilami, A. S. Masoum, P. S. Moses, and M. A. S. Masoum, "Real-time coordination of plug-in electric vehicle charging in smart grids to minimize power losses and improve voltage profile," *IEEE Trans. Smart Grid*, vol. 2, no. 3, pp. 456–467, Sep. 2011.

[11] S. Rezaee, E. Farjah, and B. Khorramdel, "Probabilistic analysis of plug-in electric vehicles impact on electrical grid through homes and parking lots," *IEEE Trans. Sustain. Energy*, vol. 4, no. 4, pp. 1024–1033, Oct. 2013.

[12] M. H. Amini and A. Islam, "Allocation of electric vehicles' parking lots in distribution network," in *Proc. IEEE PES Innovative Smart Grid Technologies Conf. (ISGT)*, 2014, pp. 1–5.

[13] Z. Liu, F. Wen, and G. Ledwich, "Optimal siting and sizing of distributed generators in distribution systems considering uncertainties," *IEEE Trans. Power Del.*, vol. 26, no. 4, pp. 2541–2551, Oct. 2011.

[14] A. D. Domínguez-García, G. T. Heydt, and S. Suryanarayanan, Implications of the Smart Grid Initiative on Distribution Engineering (Final Project Report-Part 2), PSERC Document 11-05, Sep. 2011.

[15] R. van Haaren, "Assessment of electric cars' range requirements and usage patterns based on driving behavior recorded in the national household travel survey of 2009," Earth and Environmental Engineering Department, Columbia Univ., Fu Foundation School of Engineering and Applied Science. New York, NY, USA, Dec. 2011, Study of the Solar Journey USA..

[16] F. Nemry, G. Leduc, and A. Muñoz, "Plug-in Hybrid and Battery-Electric Vehicles: State of the research and development and comparative analysis of energy and cost efficiency," European Communities, 2009 [Online]. Available: http://ftp.jrc.es/EURdoc/JRC54699_TN.pdf

[17] A. C. Rueda-Medina, J. F. Franco, M. J. Rider, A. Padilha-Feltrin, and R. Romero, "A mixed-integer linear programming approach for optimal type, size and allocation of distributed generation in radial distribution systems," *Elect. Power Syst. Res.*, vol. 97, pp. 133–143, Apr. 2013.

[18] J. F. Franco, M. J. Rider, M. Lavorato, and R. Romero, "A mixed-integer LP model for the reconfiguration of radial electric distribution systems considering distributed generation," *Elect. Power Syst. Res.*, vol. 97, pp. 51–60, Apr. 2013.

[19] L. Cheng, Y. Chang, J. Lin, and C. Singh, "Power system reliability assessment with electric vehicle integration using battery exchange mode," *IEEE Trans. Sustain. Energy*, vol. 4, no. 4, pp. 1034–1042, Oct. 2013.

[20] W. H. Kersting, "Radial distribution test feeders," in *Proc. IEEE Power Eng. Soc. Winter Meeting*, 2001, vol. 2, pp. 908–912.

[21] A. Jiménez and N. García, "Unbalanced three-phase power flow studies of distribution systems with plug-in electric vehicles," in *Proc. NAPS*, 2012.

[22] U. C. Chukwu and S. M. Mahajan, "Real-time management of power systems with V2G facility for smart-grid applications," *IEEE Trans. Sustain. Energy*, vol. 5, no. 2, pp. 558–566, Apr. 2014.

[23] Red Eléctrica de España, "Maximum average hourly power demand and daily energy," [Online]. Available: http://www.ree.es

[24] Spanish Power System Archive, 2010 [Online]. Available: http://www.esios.ree.es

[25] A. Briones, J. Francfort, P. Heitmann, M. Schey, S. Schey, and J. Smart, "Vehicle-to-grid(V2G) power flow regulations and building codes review by the AVTA," Idaho National Lab., Idaho Falls, ID, USA, Sep. 2012 [Online]. Available: http://www1.eere.energy.gov

[26] Y. K. Jemal, "Plug-in electric vehicle charging impacts on power systems," M.Sc.thesis, Dept. of Energy and Environment, Chalmers Univ. of Technol., Goteborg, Sweden, 2010.

[27] W. Kempton and J. Tomic, "Vehicle-to-grid power fundamentals: Calculating capacity and net revenue," *Power Sources*, vol. 144, pp. 268–279, Jun. 2005.

[28] A. Brooke, D. Kendrick, A. Meeraus, and R. Raman, GAMS Development Corp. Washington, DC, USA, GAMS/CPLEX 12.0. User Notes, 2014.

[29] M. Kim, R. Hara, and H. Kita, "Design of the optimal ULTC parameters in distribution systems with distributed generations," *IEEE Trans. Power Syst.*, vol. 24, no. 1, pp. 297–305, Feb. 2009.

[30] ETAP Company, Optimal Capacitor Placement Costs Benefits Due to Loss Reductions [Online]. Available: http://etap.com

Nilufar Neyestani (S'09) received the M.Sc. degree in electrical engineering from Iran University of Science and Technology, Tehran, Iran, in 2010. She is currently pursuing the Ph.D. degree in the laboratory of Sustainable Energy Systems with Prof. J. P. S. Catalão, University of Beira Interior (UBI), Covilha, Portugal.

Her research interests include electric vehicles, smart grids, power system planning, power system optimization, multi-energy systems, and energy hub.

Maziar Yazdani Damavandi (S'08) received the M.Sc. degree in electrical engineering from the Tarbiat Modares University (TMU), Tehran, Iran, in 2010. He is currently pursuing the Ph.D. degree in the Energy Management laboratory in the TMU.

He is working as a researcher in the SiNGULAR project in the University of Beira Interior (UBI), Covilha, Portugal. His research interests include optimization models in power system studies and multi-energy system modeling.

Miadreza Shafie-Khah (S'08–M'13) received the M.Sc. and Ph.D. degrees in electrical engineering from Tarbiat Modares University, Tehran, Iran, in 2008 and 2012, respectively. He is currently pursuing the Ph.D. degree in the laboratory of Sustainable Energy Systems with Prof. J. P. S. Catalão, University of Beira Interior (UBI), Covilha, Portugal.

His research interests include power market simulation, market power monitoring, power system optimization, operation of electricity markets, price forecasting, and smart grids.

Javier Contreras (SM'05) received the B.S. degree in electrical engineering from the University of Zaragoza, Zaragoza, Spain, in 1989, the M.Sc. degree from the University of Southern California, Los Angeles, CA, USA, in 1992, and the Ph.D. degree from the University of California, Berkeley, CA, USA, in 1997.

He is currently Full Professor at the University of Castilla-La Mancha, Ciudad Real, Spain. His research interests include power systems planning, operations and economics, and electricity markets.

João P. S. Catalão (M'04–SM'12) received the M.Sc. degree from the Instituto Superior Técnico (IST), Lisbon, Portugal, in 2003, and the Ph.D. degree and Habilitation for Full Professor ("Agregação") from the University of Beira Interior (UBI), Covilha, Portugal, in 2007 and 2013, respectively.

He is currently a Professor at UBI and Researcher at INESC-ID. He is the Primary Coordinator of the EU-funded FP7 project SiNGULAR. He is an author or co-author of more than 250 papers published in journals, book chapters, and conference proceedings, having supervised more than 20 post-docs, Ph.D., and M.Sc. students. His research interests include power system operations and planning, distributed renewable generation, demand response, and smart grids. He is the Editor of the book entitled *Electric Power Systems: Advanced Forecasting Techniques and Optimal Generation Scheduling* (Boca Raton, FL, USA: CRC Press, 2012), also translated into Chinese in 2014.

Prof. Catalão is an Editor of the IEEE TRANSACTIONS ON SUSTAINABLE ENERGY, an Editor of the IEEE TRANSACTIONS ON SMART GRID, and an Associate Editor of *IET Renewable Power Generation*.