

Location of Parking Lots for Plug-in Electric Vehicles Considering Traffic Model and Market Participation

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Abstract—This paper addresses the location of parking lots (PLs) to be used for plug-in electric vehicles (PEVs) by using a probabilistic traffic model and taking into account the PL participation in electricity markets. The PLs are used both for grid-to-vehicle and vehicle-to-grid. The system includes private or public charging stations only used for PEV charging. The traffic model considers the partitioning of the territory into areas. The case study is based on traffic and market data referring to Italy.

Index Terms— electricity market, electric vehicles, parking lot, traffic model.

I. INTRODUCTION

Environmental concerns are leading several countries to introduce policies for reducing greenhouse gases, also with the aim to improve air quality. The transport sector is responsible for a large amount of CO₂ emissions; therefore, substantial improvements are needed about environmental efficiency. In this context, the electrification of the vehicle fleet represents a significant opportunity [1]. Electric vehicles (EVs), compared to other types of propulsion, do not produce harmful emissions and have significantly higher efficiency and lower management and maintenance costs [2]. The JRC scenario studies confirm that the market share of *Electric Vehicles (EVs)* will be destined to grow. It is expected that in 2050 more than 80% of the vehicle fleet will consist of *Plug-in Hybrid Electric Vehicles (PHEVs)* and *Battery Electric Vehicles (BEVs)* [3].

EVs that can be connected to the network, commonly called *Plug-in Electric Vehicles (PEVs)*, could work as storage resources, especially if their diffusion will be significant. The availability of energy coming from PEVs would allow better integration with non-programmable renewable sources and would bring improvements in terms of reliability, efficiency and security of the electric system [4]. However, the introduction of PEVs brings a number of issues to the electrical network, referring to the possibility of exceeding the thermal limits of the lines, exceeding the node voltage limits, increasing the network losses, reducing the system reliability, and so on [5][6].

The unpredictability of PEVs does not allow determining the node active and reactive power in the network in a deterministic way. In fact, the contribution coming from PEVs is closely related to the usage of the PEVs and on the road traffic patterns. Therefore, probabilistic analysis of the electrical system is needed to investigate the effects of PEVs on the electrical network operation. The same issues appear in planning studies, with the further uncertainty due to the future scenarios of PEV introduction and energy prices.

One of the key challenges of the future is to integrate a large number of PEVs within the electric system. In general, there are multiple options for managing the PEV interaction with the grid. Considering the functional aspects of the PEV management, the following options can be identified:

- The PEV grid connection *location*, considering:
 - an individual *charging station (CS)* located in the house (for home charging) or in public spaces accessible from the roads; or,
 - a charging point locating in an organized (public or private) *parking lot (PL)*.
- The operation *mode*, with the possibility of using:
 - *Grid-to-Vehicle (G2V)* only;
 - *Vehicle-to-Grid (V2G)* only;
 - both G2V and V2G.
- The *managing entity*, enabling:
 - *individual* management of the PEV by the user (e.g., the PEV owner) or from a third party enabled by the owner;
 - *collective* management of a PL, a set of PLs, or a set of CSs, by an *aggregator*; or,
 - *global* management of all PLs only, or of all PLs and CSs, by a single *supervising* entity.

The *aggregator* is an intermediary between PEV owners, electricity markets, and network operators. The literature has proposed different strategies the aggregator may use to manage charging and discharging operations obtaining optimal scheduling of CSs and PLs, with objectives such as minimise of the network losses, improve the voltage profiles, increase the total load factor, obtain a better integration with non-programmable renewable sources, minimise the costs

from the viewpoint of the PEV owner, the aggregator or the system operator, provide frequency regulation and/or ancillary services, and so forth.

In the collective management, the aggregator and the PEVs owners have to subscribe a contract, in which each driver is committed to preliminarily communicate, for example, the arrival time to the CSs, the departure time from the CSs, the desired state of charge (SOC) at PEV departure, and whether the PEV will adhere to the V2G programme. This information allows the aggregator estimate the amount of energy to buy or sell in the electricity markets. In this way, the aggregator can organise the management of the charge/discharge of the PEVs. However, very often the drivers do not know where and when parking the vehicle, and therefore are not able to preliminarily indicate the time of arrival and departure from the CSs.

Various studies have been dedicated to model the PEVs in the system. However, few studies have focused on the traffic flow of PEVs in a system from both the electric system and the urban planning points of view. Furthermore, not all the studies have considered destinations in PLs. An interesting work in [7] adopts a Mixed-Integer Linear Programming (MILP) model for the traffic behaviour of PEVs in an urban environment. It assumes that any environment can be categorised into different zones based on their urban functions (residential and industrial); the model assumes that in each zone there is only one PL.

Issues concerning the optimal planning of PLs were also analysed in other works; but almost all of these ignored the simultaneous presence of CSs and the real traffic behaviour. Many studies only considered the G2V mode, neglecting the V2G mode. Other studies addressed only the optimal allocation problem, imposing the size of PLs. Further contributions studied the problem of optimal planning in order to reduce losses and/or to improve voltage profiles, regardless of economic feasibility, or solved the optimal planning problem from the aggregator point of view. Other papers estimated the profits regardless of the electricity markets trading. In particular, optimal location and sizing of PLs in addressed in [8], considering V2G provision to the distribution system within a multi-objective approach that takes into account power losses and network reliability. SmartParks placement is addressed in [9] with both V2G and G2V, with the aim of improving the system reliability and participating in the energy market. PL allocation is carried out in [10], considering cost minimization referring to network losses, reliability, and voltage deviations. A profit-based determination of the optimal number, capacity and location of PLs is presented in [11].

This paper addresses PL location by using a probabilistic traffic pattern model that can be used to estimate the energy quantities to buy or to sell in electricity markets, leaving free and independent the choice of drivers' destinations and considering infrastructural constraints. In this model, the geographical area is conceptually divided into zones with different characteristics of traffic (residential, commercial, industrial and rural). In this context, the probabilistic traffic model of PEVs is able to identify the behaviour of drivers in

the various zones, hour by hour. It is assumed that in each zone there are PLs and CSs. The PLs are directly managed by a single supervising entity and are used both for G2V and V2G. The private or public CSs, instead, are only used for PEVs charging. The number of PLs is not imposed, but it is influenced by the total capacity installed in each PL. The location and size of the PLs are not imposed, but are obtained by solving an optimisation problem.

The next sections of the paper contain the traffic model for PEVs (Section II), the market participation model and the formulation of the optimisation for PL location (Section III), the case study application (Section IV) and the Conclusions (Section V).

II. TRAFFIC MODEL FOR PEVS

A. Number of PEVs and division of the territory in zones

The probabilistic traffic model of PEVs proposed in this paper is able to identify the behaviour of drivers, hour by hour. The geographical area under analysis is conceptually divided into zones with different traffic characteristics (residential, commercial, industrial, and rural). The PEVs are partitioned into PHEVs and BEVs, and their number is strictly dependent on the number of inhabitants of the geographical area N_{inh} . By considering the number of vehicles per capita k_{cars} , and the market shares k_{PHEVs} for PHEVs and k_{BEVs} for BEVs, the equations (1) and (2) are used to determine the number of PHEVs N_{PHEVs} and the number of BEVs N_{BEVs} . Furthermore, the equivalent number of PEVs is obtainable through (3):

$$N_{\text{PHEVs}} = N_{\text{inh}} \cdot k_{\text{cars}} \cdot k_{\text{PHEVs}} \quad (1)$$

$$N_{\text{BEVs}} = N_{\text{inh}} \cdot k_{\text{cars}} \cdot k_{\text{BEVs}} \quad (2)$$

$$N_{\text{PEVs}} = N_{\text{PHEVs}} + N_{\text{BEVs}} \quad (3)$$

By crossing Italian data on demographic forecasts from the Italian National Institute of Statistics (ISTAT) [12] with information from the Italian Automobile Club (ACI) [13] about the vehicle fleet, it can be found that in Italy $k_{\text{cars}} = 0.60$. This is one of the highest values in Europe. For this reason, it is assumed that the k_{cars} trend will remain unchanged over the years of analysis. The market shares of BEVs and PHEVs, instead, are assumed to grow. It is confirmed by the JRC scenarios [3] considered in this work.

The number of PEVs in each zone (residential, commercial, industrial and rural) is influenced by many factors, such as:

- i) population composition by age group;
- ii) population composition by type of employment;
- iii) unemployment rate;
- iv) day hours.

By using this information, it is possible to estimate how PEVs are divided in each zone, hour by hour. Obviously, not all PEVs are located within the geographical area under consideration, but a part of them may be outside (external environment). The division rates of PEVs used in this paper, obtained by crossing statistical information on the above-indicated factors for the Italian case, are shown in Fig. 1.

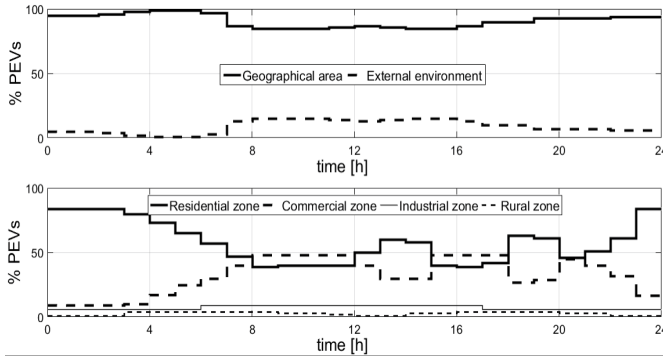


Fig. 1. Division rates of PEVs in each zone and in the external environment.

B. Consumption and Capacity of PEVs

Each PHEV or BEV model is characterized by different values of consumption and capacity. However, it is possible to determine the average values of consumption and capacity to assign to the entire fleet of PHEVs and BEVs. After that, consumption W and capacity C of the PEVs' fleet are obtainable through (4) and (5).

$$W_{PEVs} = \frac{W_{PHEVs} N_{PHEVs} + W_{BEVs} N_{BEVs}}{N_{PEVs}} \quad (4)$$

$$C_{PEVs} = \frac{C_{PHEVs} N_{PHEVs} + C_{BEVs} N_{BEVs}}{N_{PEVs}} \quad (5)$$

Technological improvements of batteries and the progressive reduction of the weight of vehicles tend to reduce consumption and increase the capacity. In this work, it is assumed that the improvements will be 1% per year until 2030, 0.75% per year in the period 2030-2040, and 0.5% per year in the period 2040-2050. The percentages are gradually reduced because the technologies gradually become mature. Table I shows the values of consumption and capacity adopted.

C. Desired and Real Destinations

Each PEV can choose to:

- i) reach a PL;
- ii) reach a CS;
- iii) continue to circulate or search a traditional parking.

The desired destinations are stochastic variables that can be obtained from appropriate probability distributions based on traffic data (different for each zone and for each hour).

This paper adopts probabilistic distributions related to the percentage of PEVs that wish to reach a PL. These distributions are shown in the figures from Fig. 3 to Fig. 6, depending on the zone.

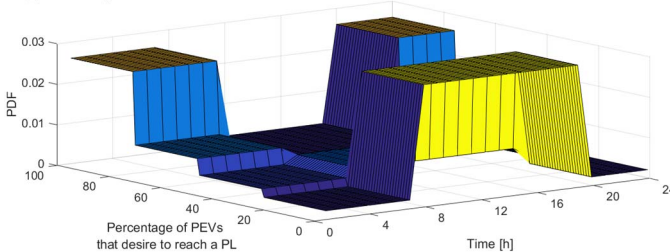


Fig. 3. Probability distribution of percentage of PEVs that desire to reach a PL in the residential zone.

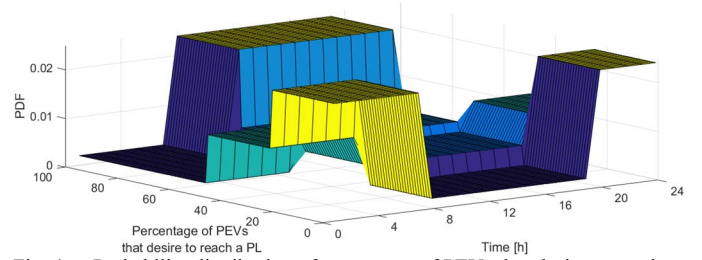


Fig. 4. Probability distribution of percentage of PEVs that desire to reach a PL in the commercial zone.

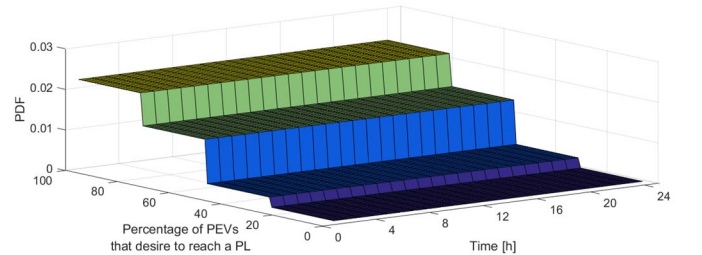


Fig. 5. Probability distribution of percentage of PEVs that desire to reach a PL in the industrial zone.

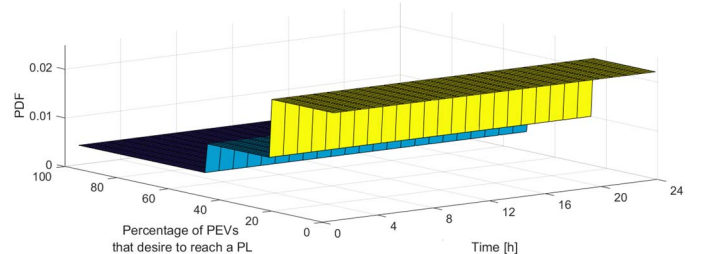


Fig. 6. Probability distribution of percentage of PEVs that desire to reach a PL in the rural zone.

The share of PEVs that do not want to reach PLs should be distributed among drivers who intend to reach a CS and drivers who prefer to continue to circulate.

Sometimes the desired destinations are different from the real destinations due to infrastructure constraints. Hence, it is important to verify the infrastructure constraints and proceed to the update of the destinations. The infrastructure constraints are the maximum number of charging points inside the PLs (selected by the optimal sizing solution), and the (given) maximum number of CSs. The destination update strategy used in this paper is:

- i) if PLs are full, drivers have to search a CS;
- ii) if CSs are full, drivers have to continue to circulate in order to search a traditional parking.

D. Battery Model

No prediction is made here on the evolution of future battery technologies. Thereby, PHEVs and BEVs are equipped with lithium-ion batteries, with charge and discharge characterized by constant power and linearly variable SOC [14].

E. Time interval and SOC needed to reach the destinations

The achievement of the desired destinations is not immediate but requires a certain time interval Δt . This time interval is a function of distance travelled L and speed v :

$$\Delta t = \frac{L}{v} \quad (6)$$

In [15] it is established that the average road speed in Italian municipalities is around 20 km/h. The distance has to be evaluated in a stochastic manner and substantially depends on the extension of the territorial zone considered. Probability distributions of the percentages of distances travelled are also connected to traffic data.

Let us denote with x the generic zone (residential, commercial, industrial or rural). According with the battery model, the SOC dissipated to reach the destination zone x is

$$\Delta SOC^{(x)} = W_{PEVs} N_{PEVs}^{(x)} L^{(x)} \quad (7)$$

Therefore, for every PEVs' aggregation, which the destination is PLs or CSs, the arrival SOC at zone x is

$$SOC_{arrival}^{(x)} = SOC_{initial}^{(x)} - \Delta SOC^{(x)} \quad (8)$$

F. Initial and Final SOC

The initial SOC cannot exceed the maximum energy storable within entire PEVs fleet (9) and is chosen with random extractions constrained by the observance of the energy conservation principle between the end of hour h and the beginning of hour $h+1$, considering the number $\Delta N_{PEVs}^{(ext)}$ of PEVs that come from the external environment. The initial SOC must satisfy the inequalities (10) and (11).

$$SOC_{initial}^{(x)} \leq C_{PEVs} N_{PEVs}^{(x)} \quad (9)$$

$$\sum_x SOC_{final}^{(x)}(h) - \Delta N_{PEVs}^{(ext)}(h) C_{PEVs} \leq \sum_x SOC_{initial}^{(x)}(h+1) \quad (10)$$

$$\sum_x SOC_{final}^{(x)}(h) + \Delta N_{PEVs}^{(ext)}(h) C_{PEVs} \geq \sum_x SOC_{initial}^{(x)}(h+1) \quad (11)$$

PLs are directly connected to Medium Voltage (MV) nodes, while the MV nodes see the CSs as additional loads. When PEVs arrive to PLs or CSs, they can exchange energy with the grid or they can balance the local loads. In particular, PEVs connected to the CSs can only receive energy, while PEVs connected to PLs can take part in both G2V and V2G programmes.

In this paper, it is assumed that each driver chooses, freely and independently of any other vehicle, the SOC threshold that separates the G2V mode from V2G mode. The variable $0 \leq \phi \leq 1$ models the choices of the entire fleet of PEVs. The equivalent SOC threshold that separates the operation in G2V mode from the operation in V2G mode is:

$$SOC^{threshold} = \phi \cdot C_{PEVs} \quad (12)$$

According of the above considerations, the final SOC is calculated. Let us consider the capacity C_{PL} of a single charging point and the capacity C_{CS} of a CS, while N_{PLs} is the total number of charging points and N_{CSs} is the total number of CSs.

In the generic zone x , for every PEV aggregation:

- if the destination is a PL:

$$SOC_{final}^{(x)} = SOC_{arrival}^{(x)} + C_{PL} \cdot N_{PLs}^{(x)} \quad (13)$$

$$SOC_{final}^{(x)} = SOC_{arrival}^{(x)} - C_{PL} \cdot N_{PLs}^{(x)} \quad (14)$$

- if the destination is a CS:

$$SOC_{final}^{(x)} = SOC_{arrival}^{(x)} + C_{CS} \cdot N_{CSs}^{(x)} \quad (15)$$

$$SOC_{final}^{(x)} = SOC_{arrival}^{(x)} \quad (16)$$

Furthermore, the final SOC cannot exceed the maximum energy that may be stored within PEVs that are placed in y (where y represents PLs or CSs).

$$0 \leq SOC_{final}^{(x)} \leq C_{PEVs} \cdot N_{PEVs,y}^{(x)} \quad (17)$$

The electricity exchanged at the generic hour between PLs and grid or between CSs and grid, is assessed as the difference between the final SOC and the SOC at the PEV arrival. It is assumed that the energy exchanged between CSs and the grid is evenly distributed among the nodes. It is further assumed that if in a zone there are more than one PL the energy exchanged between those and the grid is equally distributed. According of the above considerations, the average nodal powers in a generic hour are obtained.

III. MARKET PARTICIPATION

Optimal location of PLs is carried out to maximize the PLs owner profit, taking into account possible benefits on distribution system (loss reductions) and verifying that the solution is compatible with system constraints. A part of the profit comes from market trading. PLs owners purchase G2V energy on the day-ahead market, may sell V2G energy on the day-ahead market, and may offer V2G capacity on ancillary market (e.g., upward reserve). The part of profit coming from market trading can be only appraised after estimating the market prices and the real use of reserves. For this purpose, it is used a probabilistic electricity market model where the probability distributions are obtained from processing appropriate historical data.

The objective function includes the profits π^{Market} obtained by market trading, the revenues $R^{Parking}$ obtained by parking fees, the revenues R^{G2V} obtained by recharge payment, the costs C^{V2G} that come from possible V2G incentives, and the other costs $C^{inv\&main}$ including the discounted investment costs, the discounted maintenance costs, and the losses costs:

$$\pi = \pi^{Market} + R^{Parking} + R^{G2V} - C^{V2G} - C^{inv\&main} \quad (18)$$

IV. CASE STUDY APPLICATION

The application has been constructed by using the network described in [10], assuming a geographical area of 50 km² with 4500 inhabitants. Three different scenarios of PEV penetration are analysed, ending at year 2030, 2040 and 2050, respectively. In each scenario the percentage of CSs with respect to the total number of PEVs increases during time (Table I), taking into account an expected rate of technological development. The limits are set to 11 kW for the capacity of the single charging point in a PL, 5 MW to the total capacity installed in a PL, and 3 kW for the capacity of the single CS.

TABLE I. RELEVANT ENTRIES FOR THE SCENARIOS

year	2030	2040	2050
Market share of BEVs (%)	5	17	45
Market share of PHEVs (%)	12	15	41
Battery capacity of BEV (kWh)	23	25	27
Battery capacity of PHEV (kWh)	8	9	10
BEV consumption (kWh/km)	0.110	0.102	0.097
PHEV consumption (kWh/km)	0.163	0.152	0.144
Percentage of CS, residential zone (%)	80	90	100
Percentage of CS, commercial zone (%)	60	70	80
Percentage of CS, industrial zone (%)	40	50	60
Percentage of CS, rural zone (%)	20	30	40

The optimization at maximum profit is executed by considering different share of the aggregate capacity participating in the V2G (the parameter $\varphi = 0$ when the entire capacity is available for V2G, and $\varphi = 1$ with no V2G). One of the results obtained is shown in Fig. 2. The revenues and costs increase with the PEV penetration, but in the long term the profit tends to increase. The parking fees are a significant part of the total revenues, meaning that the number of PEVs accessing the PLs is relatively high. The costs of losses are almost negligible.

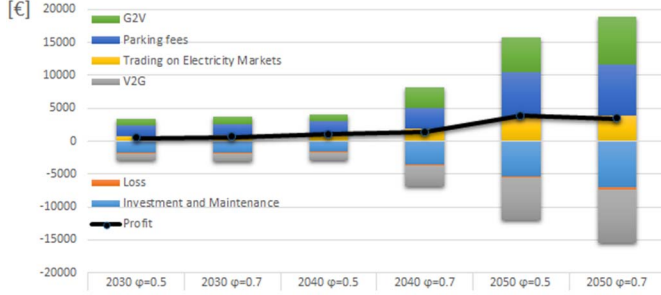


Fig. 2. Contributions to the determination of the profit.

The results indicated depend on a set of data (e.g., the economic data, the probability distributions of the traffic model and of the market-related quantities, and the costs considered in the objective function).

The optimization problem, for each scenario, is run several times, considering different values of the equivalent *SOC* threshold φ . In this way, it is possible to point out possible dependencies between the choices of the drivers and the planning of PLs. Specifically, analysis are made with $\varphi = 0.5$ and $\varphi = 0.7$. The results shown in Table II indicate the outcomes for the scenario at the year 2030. The number of PHEVs is 324, while the BEVs are 135. All the configurations analysed are acceptable. There is one PL in each area (the node location is indicated in the table), and the number of charging points is different from area to area. The residential area has the highest number (221 charging points), while the industrial area has the lowest number (31 charging points). The node in which the PL is located is the same with $\varphi = 0.5$ and $\varphi = 0.7$ only for the rural area. The daily profit is positive in both cases. The same information is provided in Table III for the year 2040, and in Table IV for the year 2050.

From an overall view of the results, the nodes to which the PLs are located and the numbers of PLs change in the three scenarios from the year 2030 to the year 2050.

TABLE II

RESULTS OF SCENARIO 2030 – EQUIVALENT *SOC* THRESHOLDS 0.5 AND 0.7

		PHEVs	BEVs	
		acceptable		unacceptable
Number of PEVs		324		135
Analysed configurations, case $\varphi = 0.5$		100%		0%
Analysed configurations, case $\varphi = 0.7$		100%		0%
$\varphi = 0.5$	Residential	Commercial	Industrial	Rural
n_{PLs}	1	1	1	1
N_{PLs}	221	53	31	74
nodes	2	16	23	28
$\varphi = 0.7$	Residential	Commercial	Industrial	Rural
n_{PLs}	1	1	1	1
N_{PLs}	221	53	31	74
nodes	1	11	27	28
		case $\varphi = 0.5$	case $\varphi = 0.7$	
Daily profit [€/day]		+215		+269
Daily losses [MWh/day]		3.61		3.63

TABLE III

RESULTS OF SCENARIO 2040 – EQUIVALENT *SOC* THRESHOLDS 0.5 AND 0.7

		PHEVs	BEVs	
		acceptable		unacceptable
Number of PEVs		405		459
Analysed configurations, case $\varphi = 0.5$		100%		0%
Analysed configurations, case $\varphi = 0.7$		100%		0%
$\varphi = 0.5$	Residential	Commercial	Industrial	Rural
case				
n_{PLs}	1	1	1	1
N_{PLs}	401	76	33	117
nodes	3	19	22	28
$\varphi = 0.7$	Residential	Commercial	Industrial	Rural
n_{PLs}	2	1	1	1
N_{PLs}	401	76	33	117
nodes	2	11	27	28
		case $\varphi = 0.5$	case $\varphi = 0.7$	
Daily profit [€/day]		+646		+831
Daily losses [MWh/day]		3.67		3.63

TABLE IV

RESULTS OF SCENARIO 2050 – EQUIVALENT *SOC* THRESHOLDS 0.5 AND 0.7

		PHEVs	BEVs	
		acceptable		unacceptable
Number of PEVs		1107		1215
Analysed configurations, case $\varphi = 0.5$		31%		69%
Analysed configurations, case $\varphi = 0.7$		73 (10%)		655 (90%)
$\varphi = 0.5$	Residential	Commercial	Industrial	Rural
case				
n_{PLs}	2	2	1	1
N_{PLs}	744	803	88	56
nodes	4, 8	12, 16	25	28
$\varphi = 0.7$	Residential	Commercial	Industrial	Rural
n_{PLs}	2	2	1	1
N_{PLs}	744	803	88	56
nodes	4, 9	15, 16	22	28
		case $\varphi = 0.5$	case $\varphi = 0.7$	
Daily profit [€/day]		+2070		+2101
Daily losses [MWh/day]		3.88		3.86

In order to reach a meaningful planning solution, it is important to consider that at the year 2050 there will be a relatively low number of acceptable configurations, while at the years 2030 and 2040 all the configurations were acceptable. This fact forces the planner to look at the solutions originated for the year 2050 also with the aim of identifying the most suitable nodes. In practice, a suitable combination of the solutions obtained in the different scenarios has to be determined, in order to develop a sound expansion plan in which the PLs are progressively added to the system without changing their location after they have been built.

Starting from the results at year 2050, the nodes involved are two in the locations of the residential area (indicated as P_R1 and P_R2), two in locations of the commercial area (indicated as P_C1 and P_C2), and one node per area in the locations of the other two areas (P_I for the industrial area, and P_Ru for the rural area). The PL location provides a relevant reduction in the network losses. Table V shows the expansion plan, consistent with the system constraints and able to bring positive profits for each value of ϕ . The plan starts with the construction of the PL in the rural area, with a number of charging points directly equal to the one that will be needed in the year 2050. In the industrial area the PL is constructed, but with a number of charging point lower than the full number that will be reached in the year 2050. The PL in the location P_R1 reaches its final structure in the year 2040, while the PL in the location P_R2 will be built to be ready for initial use in the year 2040, and will be completed by the year 2050. The PL in the location P_C1 will grow in time, while the PL in the location P_C2 will be built in the last period and will be ready by the year 2050. This result makes it possible to schedule the investments in a proper way, in some cases with a modular construction of the charging points that is in any case based on the acquisition of the territorial area needed to build the PL in its final structure.

TABLE V
EXPANSION PLAN (PL LOCATION AND NUMBER OF CHARGING POINTS)

	P_R1	P_R2	P_C1	P_C2	P_I	P_Ru
2030	221	--	53	--	31	56
2040	372	29	76	--	33	56
2050	372	371	402	401	88	56
node	4	9	12	16	22	28

V. CONCLUSIONS

The proposed approach provides a generalised tool to be used for planning purposes, aimed at determining the location of PLs with a predefined amount of CSs in each scenario.

From the results of the analyses carried out, the overall profit increases with the increase of the PEV penetration. The PL location and size change with the scenario, in particular depending on the occurrence of situations reaching the network constraints. The optimization may enable to discover viable solutions limiting the need for network reinforcement. Taking into account the long-term uncertainties involved, different results have been obtained in different scenarios. In

the presence of a progressive technological development, the choice of the planning solution requires the formulation of an expansion plan leading to a consistent final solution in the longest planning horizon considered.

Further analyses will be carried out by resorting to specific decision-making tools, weighting the importance of the scenarios considered.

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