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Optimal allocation of plug-in electric vehicle parking lots for maximum serviceability and profit in the coupled distribution and transportation networks

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Optimal allocation;
Parking demand;
Traffic pattern.

Abstract. Optimal planning and management of Electric Vehicle Parking Lots (EVPLs) can be an effective approach for improving the operation of both the distribution system and traffic networks. However, the limited land areas of cities can be an obstacle for constructing a large number of Parking Lots (PLs). This paper proposed a model for optimal siting and sizing of EVPLs as well as their charging schedule to maximize the total profit of their owners, while maximum parking demand of Plug-in Electric Vehicles (PEVs) can be satisfied. In the proposed model, the purpose of trips, number of PEVs, plus their arrival and departure time in different urban areas are considered. Distribution network constraints are also taken into account using linearized load flow equations. The proposed model is implemented in a 37-bus distribution system coupled with a 25-node transportation network which includes four different areas in terms of PEV travel type. The simulation results show the effectiveness of the proposed model to cover the parking demand of PEVs with a limited number of PLs.

1. Introduction

Because of the benefits of reducing fossil fuel consumption and greenhouse gas emissions as well as improving energy efficiency, Plug-in Electric Vehicles (PEVs) will be used extensively in future transportation systems [1]. However, for enhancing the penetration level of such vehicles into the system, the construction of charging infrastructure and the effect of their charging demand on the distribution network need to be addressed.

One of the most important solutions for charging PEVs in public places are Parking Lots (PLs), which provide a good opportunity to manage the State Of Charge (SOC) of PEVs. In addition, due to the development of Vehicle-to-Grid (V2G) technology, Electric Vehicle Parking Lots (EVPLs) can also inject energy into the system as a power source. However, inappropriate location and size of EVPLs can negatively affect their performance from the viewpoint of electrical and transportation networks. In this regard, we address the

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issue of optimal location and capacity of EVPLs in this article. In our proposed model, the requirements and limitations of both traffic and distribution networks are taking into account.

1.1. Literature review

Given the role that EVPLs will play in future smart cities, an extensive literature has been developed on the subject of optimal energy management in EVPLs or optimal location and size of EVPLs. For example, in [2], a two-step approach has been presented for optimal energy management in EVPLs. In [3], a mathematical model for the problem of charging and repositioning a fleet of shared PEVs has been introduced. However, the models presented in such articles examine the short-term operation of EVPLs rather than their location and capacity.

Ref. [4] located EVPLs in the presence of distributed generation for reducing the cost of power losses in the distribution network. In [5], allocation of EVPLs in the distribution system and charging scheduling of PEVs were proposed in order to improve the voltage profile of the network. In [6], siting of EVPLs in the distribution system was implemented based on a two-stage model for minimizing power loss and voltage deviations as well as maximizing network reliability. In the first stage, interactions of EVPLs with energy and reserve markets are specified to maximize the profit of EVPL owners. Then, locations of EVPLs are determined in the second stage regarding the constraints of the distribution network. Ref. [7] developed the model of [6] by taking into account the EVPL allocation and network constraints simultaneously with managing the interactions of EVPLs with electricity markets. In [8], a two-stage stochastic programming model was formulated to maximize the total profit of the EVPL owner. The first stage deals with the siting and sizing of EVPLs as well as contractual arrangements, while the second stage evaluates the operational performance of the suggested EVPLs under different scenario realizations of PEV behaviors. Other researchers have also located EVPLs for purposes such as reducing network losses [9–11], improving reliability [11–14], correcting voltage deviations [13], and obtaining economic benefits [14,15]. However, the PEV charging pattern in [10,11,13,14] was not optimized. In [9,16], the charging pattern and the optimal location of EVPLs were determined in separate optimization processes, which can lead to suboptimal solutions for the whole system and the EVPL owners. Moreover, most of the previous articles focused on the improvement of distribution network operation and did not examined the impact of EVPLs on the performance of traffic network.

When a limited number of EVPLs can be constructed in an area due to budget constraints or limitation of land areas, it will be important to maximize the availability of parking spots for PEVs. The optimal location of EVPLs from the viewpoint of distribution system may be unsuitable for satisfying the parking demand of vehicles, so drivers have to spend time in finding a vacant PL at nearest location of destination and keeps the vehicle on road for a long time. Thus, allocation of EVPLs in urban areas is becoming a major challenge as it should meet the objectives of EVPL owners, distribution system operator, and urban planners simultaneously. In [17], the issue of optimal location of PEV charging infrastructures was investigated for enhancing the mileage by vehicles and creating a suitable level of service with the minimum cost. In [18], an improved mathematical model for locating PEV charging stations was proposed which would maximize the charging demand supplied by the system under a constrained budget. In [19], the location of public EVPLs was investigated in two modes of slow and fast charging for reducing total cost and providing a certain level of charging demand in the zone. In [20], dynamic planning approach has been presented to determine the optimal number, location, capacity and time of construction or development of EVPLs in a distribution network to minimize both the time and energy required for PEVs to arrive at the EVPLs. However, most of these articles have not considered distribution network constraints and charging management of PEVs at the EVPLs.

1.2. Contribution

Table 1 compares the main features of some important articles on the EVPL allocation. According to the literature, little attention has been paid to the impact of EVPLs on the transportation network. Also, the related articles do not optimize the allocation of PEVs to EVPLs. Thus, this paper aims to introduce a more comprehensive framework that jointly optimizes the location and size of EVPLs, as well as management of parking spots and their charging/discharging schedule to maximize the profit of EVPL investors. In addition, the EVPLs are located in places that meet the maximum parking demand of PEVs in each zone thus enhancing the drivers' comfort. Further, a three-layered optimization approach is employed which combines the Genetic Algorithm (GA) and mathematical programming to reach the optimal solution. In short, the innovations of this paper are as follows:

- Formulating a new model for allocating PEVs to the PLs of each area to maximize the available parking spaces for PEVs;
- Optimal siting and sizing of EVPLs plus managing their charging schedule taking into account the parking space accessibility as well as the profit of EVPL investors;

Table 1. Comparison of the proposed models with previous studies in the field of EVPL planning.

Ref.	Distribution network	Traffic network	V2G capability	Driving pattern uncertainty	Objective function	Solution method	Allocation of PEVs to PLs
[3]	–	✓	–	–	Minimizing the cost	GA-MATLAB	–
[4]	✓	–	✓	–	Minimizing power loss	GA-MATLAB	–
[5]	✓	–	✓	–	Maximizing the revenue	GA-MATLAB	–
[6]	✓	–	✓	✓	Minimizing system costs	GAMS (CPLEX12)	–
[7]	✓	✓	✓	–	Maximizing the profit	GAMS (CPLEX12)	–
[8]	✓	–	✓	✓	Maximizing of the total net revenue	GA-MATLAB	–
[9]	✓	–	✓	–	Minimizing the overall energy cost	ABC-MATLAB	–
[10]	✓	–	✓	✓	Minimizing the loss value	GA & PSO-MATLAB	–
[11]	✓	✓	✓	–	Minimizing total cost	GA-MATLAB	–
[12]	✓	–	✓	✓	Maximizing the profit	SA-MATLAB	–
[13]	✓	–	✓	✓	Minimizing loss costs	COA-MATLAB	–
[14]	✓	–	✓	–	Maximizing the profit	GA-MATLAB	–
[15]	✓	✓	✓	✓	Maximizing the profit	GA-MATLAB	–
[16]	✓	–	✓	✓	Maximizing the profit	PSO-MATLAB	–
[17]	–	✓	–	–	Minimizing the total number of the missed trips	GA-MATLAB	–
[18]	–	✓	–	–	Maximizing the satisfied demand	MIP–Branch and bound	✓
[19]	–	✓	–	–	Minimizing total cost while satisfying certain charging demand	MILP–CPLEX12.6	✓
[20]	✓	✓	✓	✓	Maximizing the profit	GA-MATLAB	–
Current paper	✓	✓	✓	✓	Maximizing the profit	GA & GAMS (CPLEX12)	✓

– Employing a three-layered optimization algorithm including the combination of GA and Mixed-Integer Linear Programming (MILP) to solve the nonlinear and nonconvex problem.

The rest of the paper is organized as follows: Section 2 explains the main assumptions and the general framework of the problem. The mathematical optimization model for locating EVPLs is formulated in Section 3. The results of implementing the proposed model are presented in Section 4. Finally, Section 5 concludes the paper.

2. General framework of the proposed model

2.1. Modeling of traffic patterns

The potential of EVPLs for participating in electricity markets significantly depends on the number of PEVs, their battery capacity, and the PEV travel patterns. Depending on the characteristics of areas, the arrival and departure times as well as the stay period of vehicles are different. Thus, in several articles, a multi-zone traffic has been used to distinguish these differences [11,21]. According to Figure 1, the urban area is assumed to be divided into four areas including

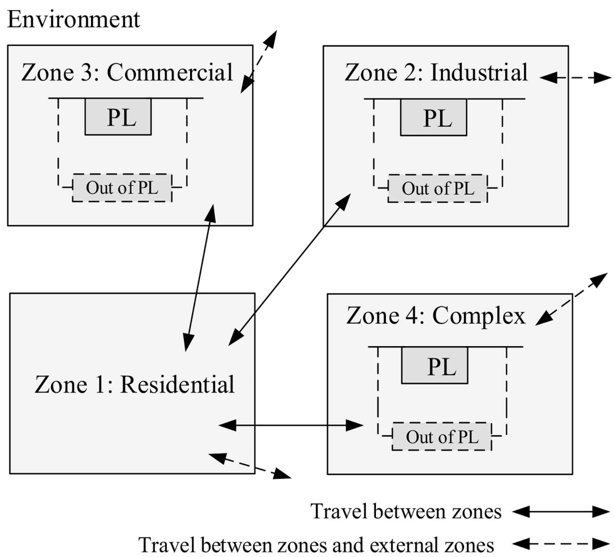


Figure 1. Travel types of vehicles across different areas.

residential, commercial, industrial, and complex zones. Regarding this classification, there are three main categories for trips across the transportation network:

- Travel type 1: Between residential and commercial zone;
- Travel type 2: Between the residential area and the industrial area;
- Travel type 3: From the residential area to the complex zone and vice versa.

It can be assumed that in each area, a number of vehicles have a destination or origin other than the designated areas, which is known as the external zone.

For enhancing the accuracy of the proposed model, the PEV driving patterns are considered as stochastic scenarios generated with normal probability distribution as shown by Eq. (1) [22]:

$$N_{i,j,t,\omega}^{PEV} = \mu_{i,j,t}^{PEV}\left(1 + e_{i,j,t,\omega}^{PEV}\right), \tag{1}$$

where, $\mu_{i.j.t}^{PEV}$ is the expected number of PEVs travelling from zone i to j at time t, and $e_{i.j.t.\omega}^{PEV}$ represents the forecasting error that is generated as a gaussian random variable with zero mean and standard deviation of $\sigma_{i.j.t}$. Regarding Eq. (1), one can generate a high number of scenarios that would best represent the stochastic process under study. However, the total number of scenarios can become too large to be tractable. Thus, a scenario reduction technique based on Kantorovich distance is applied to determine a subset of the initial scenarios and to assign new probabilities to the selected scenarios [23].

2.2. Assumptions about the interaction of EVPLs and PEVs

It is assumed that when PEVs participate in the V2G program, they will be paid for their battery depreciation. The owners of PEVs also set a minimum amount for their battery SOC before their departure. In each area, there are a number of nodes as vehicle reference nodes. Based on their desirability, they have a corresponding weight. That is, a node with a higher weight will attract more PEVs. The EVPL installed at each node can only serve the PEVs in the nodes of the same area, if their distance is less than a pre-specified walking distance. It is also assumed that EVPLs exchange power with the upstream network at the hourly electricity market price, but the price of energy sold to the PEVs is less than the average market price. Selling energy to PEVs at a lower price is considered as an incentive to enhance the presence of PEVs in the EVPLs.

2.3. Problem solving method

In the proposed optimization problem, the main decision variables are the location and capacity of EVPLs plus the hourly power exchanges with the network. In addition, the allocation of incoming PEVs to the PLs, revenue from power exchanges with the network and PEVs, and the cost of network losses are other outputs of the problem.

In the proposed model, the manner of allocating PEVs to EVPLs depends on the location and capacity of the PLs. However, the location and capacity of PLs are not initially known as input to the problem and are considered as decision variables. Thus, the proposed model includes nonlinear or conditional equations. Due to the complexity and non-linearity of the model, a combination of GA and the mathematical programming is employed to solve the proposed optimization model. However, to reduce the search space, a three-layer optimization technique inspired by Zheng et al. [24] has been used as displayed by Figure 2. In the first step called the outer layer, the location and capacity of the EVPLs are generated as populations in the GA. In the second step or the middle layer, the allocation of PEVs to the PLs is optimized to achieve the maximum parking demand coverage. The third step or the inner layer determines the optimal power exchanges between the EVPLs and the network by a MILP model to obtain maximum profit for the EVPL investors. In this way, the fitness function of each population is obtained from the total cost of installing EVPLs and exchanging power with the network and PEV owners as well as the cost of system losses. The process of population production and generation repetition in GA continues until the convergence criterion is met, i.e., when there is no significant improvement in the values of fitness function for a pre-specified number of consecutive generations or reaching the maximum number of generations. Figure 3 indicates the flowchart of the solving technique.

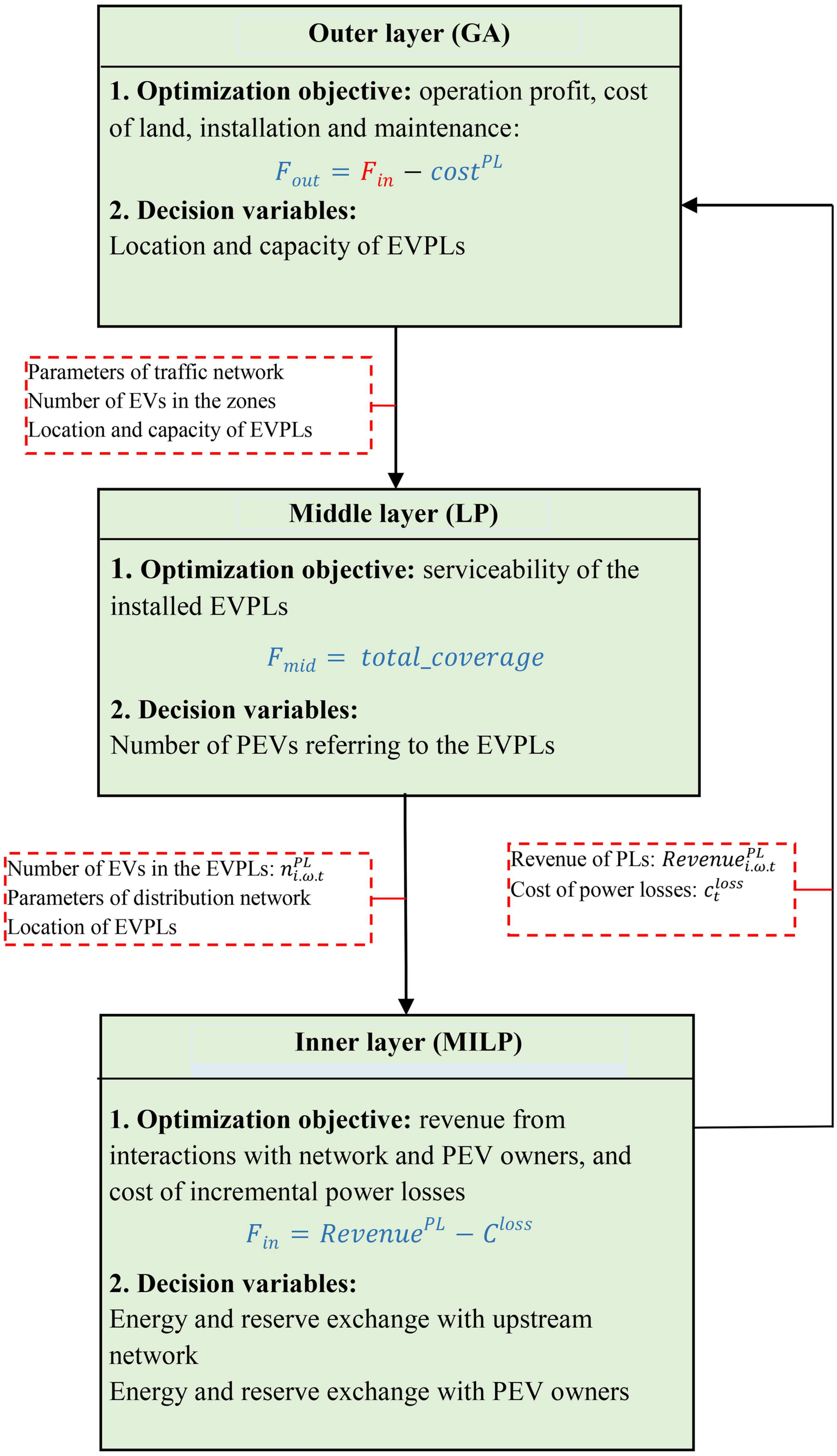


Figure 2. Three-layer optimization approach for the proposed method.

3. Mathematical formulation of the problem

3.1. Description of the outer layer (F_{out})

According to Eq. (2), the objective of the outer layer is the total profit of EVPL owners including their operating revenue minus the investment cost. Operating revenue comes from EVPL interactions with the network and PEV owners and is calculated in the inner layer after determining the number of PEVs at the EVPLs in the middle layer. Eq. (3) represents the investment cost which includes the fixed cost for installing an EVPL and the variable costs for purchas-

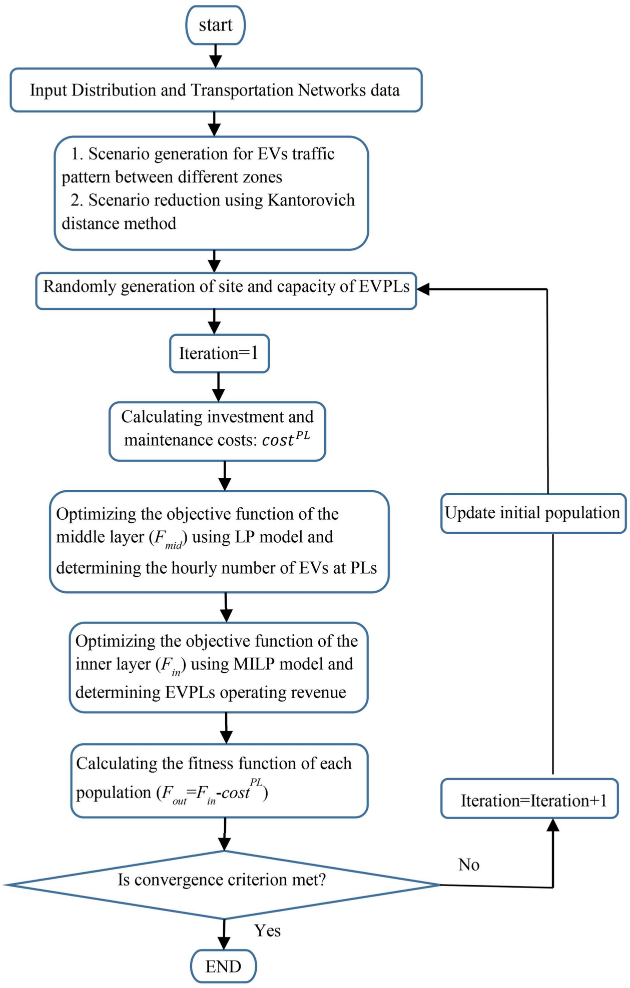


Figure 3. Flowchart of the problem solving method by combining GA and mathematical programming.

ing the land, installation of charging equipment, as well as their maintenance. In Eq. (4), capital recovery factor (κ) is used to convert investment expenses to the annual cost [25], where α indicates the number of years of returning capital and d denotes the annual rate of declining capital. The constraint of the minimum and maximum number of charging points in each EVPL is shown by Eq. (5). According to Eqs. (6) and (7), budget constraint and the maximum allowable EVPL installation can be applied to the optimization problem. The total capacity of the PLs in each area regarding the number of charging points of each EVPL is obtained by Eq. (8), except for the residential zone, where EVPL is not considered.

$$F_{out} = F_{in} - \cos t^{PL}, \tag{2}$$

$$\cos t^{PL} = \sum_n \left[\kappa.\left(c^{fix} u_n^{PL} + \left(c_n^{land} A + c^{eq}\right) nsPL_n\right) + c^M nsPL_n\right], \tag{3}$$

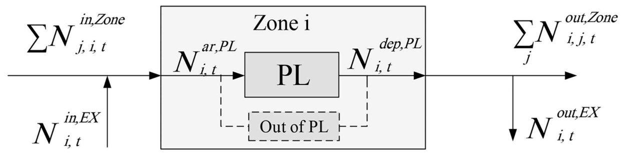


Figure 4. Model of entry and exit of vehicles in zone i [21].

$$\kappa = d/(1-(1+d)^{-\alpha}), \tag{4}$$

$$u_n^{PL} nsPL_n^{\min} \leq nsPL_n \leq u_n^{PL} nsPL_n^{\max}, \tag{5}$$

$$\sum_n \left(c^{fix} u_n^{PL} + \left(c_n^{land} A + c^{eq}\right) nsPL_n\right) \leq IC^{\max}, \tag{6}$$

$$\sum_n u_n^{PL} \leq N^{PL,\max}, \tag{7}$$

$$NPL_i^{zone} = \sum_{n \in \Omega_i} nsPL_n, \qquad i = 2, 3, 4. \tag{8}$$

3.2. Description of the middle layer (F_{mid})

This section introduces equations that model the distribution of PEVs in traffic zones and EVPLs to provide the maximum parking demand coverage. Figure 4 reveals the traffic flow in area i, with respect to the arriving/departing number of PEVs.

According to Eqs. (9) and (10), the total number of PEVs that reach/leave each area is equal to the number of vehicles from/to other areas and the external area. Eqs. (11) and (12) calculate the net number of vehicles entering each area per hour and the number of vehicles in each area up to time t, respectively. Eq. (13) determines the number of PEVs referring to each node at each time t regarding the hourly weights (importance) of transportation nodes for PEV drivers.

$$TN_{i,\omega,t}^{in,zone} = N_{i,\omega,t}^{in,EX} + \sum_j N_{j,i,\omega,t}^{in,zone} \forall i, \omega, t, \tag{9}$$

$$TN_{i,\omega,t}^{out,zone} = N_{i,\omega,t}^{out,EX} + \sum_j N_{i,j,\omega,t}^{out,zone} \forall i, \omega, t, \tag{10}$$

$$N_{i,\omega,t}^{in,net,zone} = TN_{i,\omega,t}^{in,zone} - TN_{i,\omega,t}^{out,zone} \forall i, \omega, t, \tag{11}$$

$$N_{i,\omega,t}^{zone} = N_{i,0}^{PL} + \sum_{h|h \leq t} N_{i,\omega,h}^{in,net,zone} \forall i, \omega, t, \tag{12}$$

$$NEV_{n,\omega,t} = d_{n,t} N_{i,\omega,t}^{zone}, \forall i, \omega, t, n \in \Omega_i. \tag{13}$$

PLs are usually located in places that most people like to visit, such as workplaces and shopping malls, and hence drivers seek to find parking space for their vehicle. PEVs demand for parking space will be satisfied if they can find an EVPL within their maximum walking distance ($D_{\max}$). Thus, an available EVPL in a node

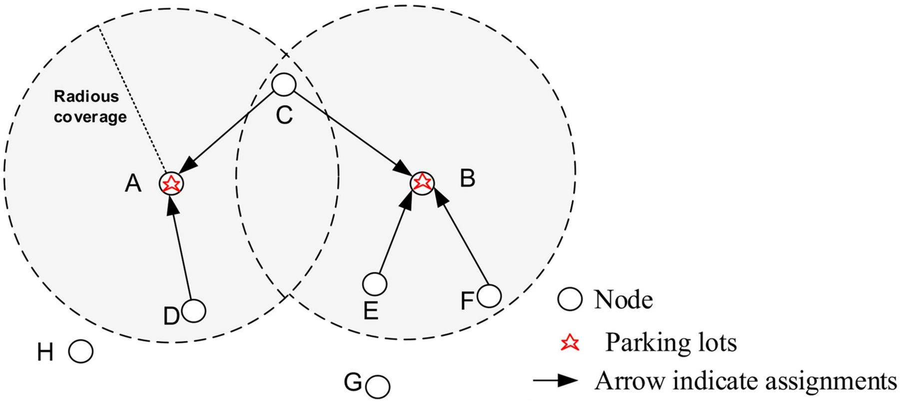


Figure 5. Illustrative example of vehicles' access to PLs in an area.

can also serve the PEVs that are visiting adjacent nodes with the distance less than $D_{\max}$. Figure 5 displays an example including an 8-node transportation network including two PLs installed at nodes A and B.

A part of the capacity (charging spots) of the PLs at nodes A and B will be occupied by the PEVs visiting these nodes, and their vacant capacity can be filled with PEVs from other nodes within $D_{\max}$. Node C is within the coverage area of both PLs. Thus, vehicles entering node C can refer to nodes A or B. Vehicles entering node D have to go to node A and vehicles entering node E and F must go to node B. Any PL will not cover the parking demand of the vehicles of nodes G and H since they are out of the walking distance of both PLs. In this way, the installed PLs can meet the parking demand of nodes A, B, C, D, E, and F. This is while if a PL is installed in nodes E or F instead of node B, in addition to the previous nodes it can also meet the parking needs of the vehicles referring to node G. This means that the serviceability of PLs in this area will be higher in comparison with the first case. Hence, the location of PLs can affect the access of vehicles to the parking spaces. If the PLs are not installed in the right places, a significant number of PEVs may not be able to find parking spot for charging. Here, we introduce a mathematical model for optimal allocation of PEVs to the existing PLs of each area, regarding their location and capacity.

According to Eq. (14), we define the binary parameter $cover_{m,n}$, which is 1 if nodes m and n are within their maximum walking distance. Based on Eq. (15), if node m is out of coverage area of node n, its PEVs cannot refer to the PL of node n. Eq. (16) implies that the total number of vehicles that can refer to node n cannot exceed its parking spaces. The maximum number of PEVs of every node that can refer to other nodes are expressed by Eq. (17). Eq. (18) guarantees that the charging points at the EVPL of each node are firstly occupied by its own PEVs, and the excess capacity can be filled by the PEVs from other nodes. Total number of vehicles that can be parked in the PLs of each zone in every hour is calculated by Eq. (19).

$$cover_{n,m} = 1, \quad \text{if} \quad distance_{n,m} \leq D_{\max},$$

$$\forall (m,n) \in \Omega_i, i \neq 1, \tag{14}$$

$$NEV^{ref}_{m,n,\omega,t} \leq NEV_{m,\omega,t} cover_{m,n},$$

$$\forall (m,n) \in \Omega_i, i \neq 1, \tag{15}$$

$$\sum_m NEV^{ref}_{m,n,\omega,t} \leq nsPLA_n, \forall (m,n) \in \Omega_i, i \neq 1, \tag{16}$$

$$\sum_n NEV^{ref}_{m,n,\omega,t} \leq NEV_{m,\omega,t}, \forall (m,n) \in \Omega_i, i \neq 1, \tag{17}$$

$$\sum_{n \neq m} NEV^{ref}_{m,n,\omega,t} \leq \max(0, NEV_{m,\omega,t} - nsPL_m),$$

$$\forall (m,n) \in \Omega_i, i \neq 1, \tag{18}$$

$$n^{PL}_{i,\omega,t} = \sum_n \sum_m NEV^{ref}_{m,n,\omega,t}, \quad \forall (m,n) \in \Omega_i, i \neq 1. \tag{19}$$

The objective function of the middle layer (F_{mid}) is shown by Eq. (20), which is subjected to the constraints expressed by Eqs. (14)–(19). It is a Linear Programming (LP) model which maximizes the expected coverage of PEVs demand for parking space in all zones. F_{mid} can be used to evaluate the solutions for location and size of EVPLs from the viewpoint of urban planner which aims to provide the maximum usage of parking spaces by the PEVs.

$$\text{maximize} \{F_{mid} = \text{total\_coverage} =$$

$$\sum_\omega \rho_\omega \left\{ \sum_{i=2}^{Nz} \sum_{t=1}^{T} n^{PL}_{i,\omega,t} \right\}. \tag{20}$$

After optimizing F_{mid}, Eq. (21) determines the ratio of the hourly satisfied parking demand at each zone to the total number of PEVs referring to the traffic nodes in that zone.

$$PC_{i,\omega,t}^{zone}=\frac{n_{i,\omega,t}^{PL}}{\sum_{n} NEV_{n,\omega,t}} \quad \forall n \in \Omega_i \quad i=2,3,4, \tag{21}$$

Eq. (22) calculates the number of vacant charging spots in the EVPLs of each area. According to Eq. (23) not until the parking capacity of an area is filled, the number of vehicles entering its EVPLs is equal to multiplication of the percentage of vehicles served by PLs in the area and vehicles entering the area; otherwise it is equal to the remaining vacant charging spots at that time. According to Eq. (24), the number of vehicles that exit from EVPLs is assumed proportional to the percentage of vehicles parked in the EVPLs. The number of PEVs leaving the zone from the outside of the EVPLs is obtained from Eq. (25). These parameters will be used to calculate the optimal interaction of the EVPLs with the network and PEV owners in the inner layer.

$$n_{i,\omega,t}^{vac,PL}=NPL_i^{zone}-n_{i,\omega,t}^{PL}, \qquad i=2,3,4, \tag{22}$$

$$n_{i,\omega,t}^{ar,PL}=\min\left\{n_{i,\omega,t-1}^{vac,PL}+n_{i,\omega,t}^{dep,PL}, TN_{i,\omega,t}^{in,zone} PC_{i,\omega,t}^{zone}\right\}, \tag{23}$$

$$N_{i,\omega,t}^{dep,PL}=TN_{i,\omega,t}^{out,zone} PC_{i,\omega,t}^{zone}, \tag{24}$$

$$N_{i,\omega,t}^{dep,nonPL}=TN_{i,\omega,t}^{out,zone}-N_{i,\omega,t}^{dep,PL}. \tag{25}$$

3.3. Mathematical formulation of the inner layer (F_{in})

3.3.1. Objective function

Assuming the same hourly curves for all days (including load profile, electricity market prices, and traffic patterns), the annual operating profit of EVPLs is obtained from Eq. (26) through multiplying the number of days in a year (N_d) by the expected daily profit. However, this assumption can be easily extended by considering several daily patterns over a year.

$$\text{Maximize } F_{in}=N_d\sum_{\omega}\rho_\omega\left(\left(\sum_i Revenue_{i,\omega}^{PL}\right)-c_\omega^{loss}\right), \quad i=2,3,4, \tag{26}$$

$$Revenue_{i,\omega}^{PL}=\sum_t Revenue_{i,\omega,t}^{EMI}+Revenue_{i,\omega,t}^{RMI}+Revenue_{i,\omega,t}^{POI}, \tag{27}$$

$$Revenue_{i,\omega,t}^{EMI}=(P_{i,\omega,t}^{PL,out}-P_{i,\omega,t}^{PL,in})\pi_t^E, \tag{28}$$

$$Revenue_{i,\omega,t}^{RMI}=re_{i,\omega,t}^{PL,out}\pi_t^R+re_{i,\omega,t}^{PL}\rho_{i,t}^{del}(1-FOR_i^{PL})\pi_t^E-re_{i,\omega,t}^{PL}\rho_{i,t}^{del}FOR_i^{PL}{\pi_t}^{con}, \tag{29}$$

$$Revenue_{i,\omega,t}^{POI}=n_{i,\omega,t}^{PL}\pi^{Tariff}+P_{i,\omega,t}^{PL,in}{\pi_t}^{G2V}-(P_{i,\omega,t}^{PL,out}+re_{i,\omega,t}^{PL}\rho_{i,t}^{del}(1-FOR_i^{PL}))(\pi_t^{V2G}+Cd), \tag{30}$$

$$c_\omega^{loss}=\sum_t \pi_t^E(loss_{\omega,t}-loss_t^0), \tag{31}$$

$$loss_{\omega,t}=\sum_l R_{b,b'}i_{b,b',\omega,t}^2. \tag{32}$$

The components of the objective function are defined by Eqs. (27)-(31), where $Revenue_{i.\omega.t}^{EMI}$ is the revenue from the energy exchange of EVPLs with the network, $Revenue_{i.\omega.t}^{EMI}$ is the income from the sale and call of reserve in the case of possible events. In this section, penalties are applied for failure to deliver a committed reserve. FOR_i^{PL} indicates failure probability of EVPL to deliver power to the upstream network. $Revenue_{i.\omega.t}^{POI}$ indicates revenue from parking tariffs and selling energy to the owners of PEVs plus the cost including the purchase of energy from the owners of PEVs, and the cost of degradation of the battery which is calculated based on the power taken from the batteries and sold to the network.

In this paper, we assumed that the cost of incremental network losses due to the presence of EVPLs, will be the responsibility of the EVPL owners. This cost is equal to the losses in the presence of PEVs minus the system losses without the presence of PEVs multiplied by the hourly energy prices as shown in Eqs. (31) and (32) is used to calculate energy loss. For calculating the energy loss, linearized AC load flow equations are employed for the radial distribution network.

3.3.2. PL equations and constraints

Figure 6 reveals the power exchange of the EVPLs of an area with the PEVs and the electrical network [21]. According to this figure, the SOC of PEVs entering the area is equal to the sum of the SOCs of PEVs arriving from other areas. Also, the power exchange between the EVPLs and the network will change the SOC of their PEVs.

According to Eq. (33), a PEV that moves from zone i at time t reaches zone j at the next hour, while its energy consumption is neglected. Eqs. (34) and (35) show that the SOC of incoming/outgoing PEVs to/from the area cannot exceed the total capacity of their batteries. As shown by Eq. (36), the SOC of EVPL at each hour depends on its SOC at the previous

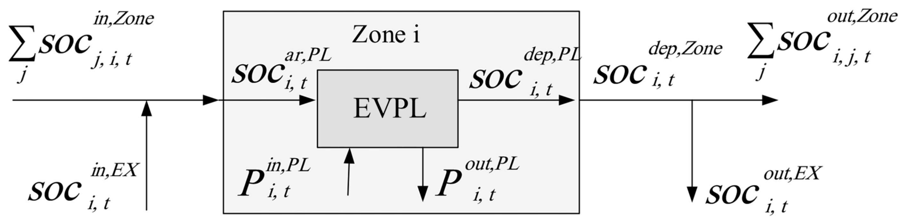


Figure 6. Power exchanges between EVPL, PEVs, and network [21].

hour, the power exchanged with the network, the charging and discharging efficiency, and the charge level of arrived/departed PEVs. In Eq. (37), we assumed that the SOC of the arriving PEVs is proportional to the ratio of the number of PEVs that can park in the EVPLs to the number of PEVs arriving the area. Based on Eq. (38), the SOC of the PEVs departing the EVPLs is proportional to the ratio of the number of PEVs departing the EVPLs to the number of PEVs that exist in the zone. Eq. (39) implies that the SOC of PEVs leaving each area is equal to the sum of the SOC of PEVs departing the EVPLs and of those that were parked outside of EVPLs. Assuming that PEVs cannot be charged outside the EVPLs, their SOC diminishes compared to the initial value (ψ). Eq. (40) limits the SOC of EVPL to the battery capacity of the parked PEVs. According to Eq. (41), the SOC of the departed PEVs should be between the minimum and maximum SOC desired by the PEV owners.

$$soc^{in,zone}_{i,j,\omega,t+1} = soc^{out,zone}_{i,j,\omega,t}, \tag{33}$$

$$soc^{in,zone}_{i,j,\omega,t} \leq C^{in,zone}_{i,j,\omega,t}, \tag{34}$$

$$soc^{out,zone}_{i,j,\omega,t} \leq C^{out,zone}_{i,j,\omega,t}, \tag{35}$$

$$soc^{PL}_{i,\omega,t} = SOC^{PL,0}_{i,\omega,t}\Big|_{t=1} + soc^{PL}_{i,\omega,t-1}\Big|_{t>1} + P^{PL,in}_{i,\omega,t}\eta_c - P^{PL,out}_{i,\omega,t}\frac{1}{\eta_d} + soc^{ar,PL}_{i,\omega,t} - soc^{dep,PL}_{i,\omega,t}, \tag{36}$$

$$soc^{ar,PL}_{i,\omega,t} = \frac{n^{ar,PL}_{i,w,t}}{TN^{in,Zone}_{i,\omega,t}} soc^{in,Zone}_{i,\omega,t}, \tag{37}$$

$$soc^{dep,PL}_{i,\omega,t} = \frac{n^{dep.PL}_{i,\omega,t}}{n^{PL}_{i,\omega,t}} soc^{PL}_{i,\omega,t}, \tag{38}$$

$$soc^{dep,PL}_{i,\omega,t} + N^{dep,nonPL}_{i,\omega,t}(\psi - \Delta\psi/C_{ave-EV}) = \sum_j soc^{out,zone}_{i,j,\omega,t}, \tag{39}$$

$$soc^{EV,\min}_{i} n^{PL}_{i,\omega,t} C_{ave-EV} \leq soc^{PL}_{i,\omega,t} \leq soc^{EV,\max}_{i} n^{PL}_{i,\omega,t} C_{ave-EV}, \tag{40}$$

$$\min soc^{dep,PL}_{i,\omega,t} n^{dep,PL}_{i,\omega,t} c_{ave\_EV} \leq soc^{dep,PL}_{i,\omega,t} \leq \max soc^{dep.PL}_{i,\omega,t} n^{dep,PL}_{i,\omega,t} c_{ave\_EV}. \tag{41}$$

In Eq. (42), the number of PEVs and their charging rate limits the power input to the EVPL. As revealed by Eq. (43), the output power of EVPL is limited by the number of PEVs and their discharge rate, as well as the minimum SOC requirement of the PEV owners at the time of departure. According to Eq. (44), the total scheduled output power and reserve should be less than the maximum discharge rate of the EVPL and the SOC that can be utilized. Eq. (45) states that the output power and reserve of the residential zone are zero since we assume that no EVPL is installed in this area.

$$P^{PL,in}_{i,\omega,t} \leq \Gamma^{PL}_i \cdot n^{PL}_{i,\omega,t}, \tag{42}$$

$$P^{PL,out}_{i,\omega,t} \leq \min\{\Gamma^{PL}_i n^{PL}_{i,\omega,t}; soc^{PL}_{i,\omega,t}\phi^{PL}_i\}, \tag{43}$$

$$P^{PL,out}_{i,\omega,t} + r^{PL,out}_{i,\omega,t} \leq \min\{\Gamma^{PL}_i n^{PL}_{i,\omega,t}, soc^{PL}_{i,\omega,t}\kappa^{PL}_i\}, \tag{44}$$

$$\{p^{PL,out}_{i,\omega,t}, re^{PL,out}_{i,\omega,t}\} = 0, \quad i = 1. \tag{45}$$

3.3.3. Distribution network constraints

The charging/discharging power of EVPLs should be modeled as electrical loads for the distribution network. According to Eqs. (46) and (47), the share of each node from the power exchange of EVPLs with the network is calculated, which is proportional to the number of PEVs at EVPLs. In the residential area, no EVPLs were assumed to be installed. Thus, their charging demand is proportionally added to the buses of this area.

$$p^{PLA,in}_{n,\omega,t} = p^{PL,in}_{i,\omega,t} \cdot \frac{\sum_m NEV^{ref}_{m,n,\omega,t}}{n^{PL}_{i,\omega,t}} \quad \forall n \in \Omega_i, i \neq 1, \tag{46}$$

$$p^{PLA,out}_{n,\omega,t} = p^{PL,out}_{i,\omega,t} \cdot \frac{\sum_m NEV^{ref}_{m,n,\omega,t}}{n^{PL}_{i,\omega,t}} \quad \forall n \in \Omega_i, i \neq 1. \tag{47}$$

Eqs. (48) and (49) express the constraints for active and reactive power balance in each node. Eqs. (50)

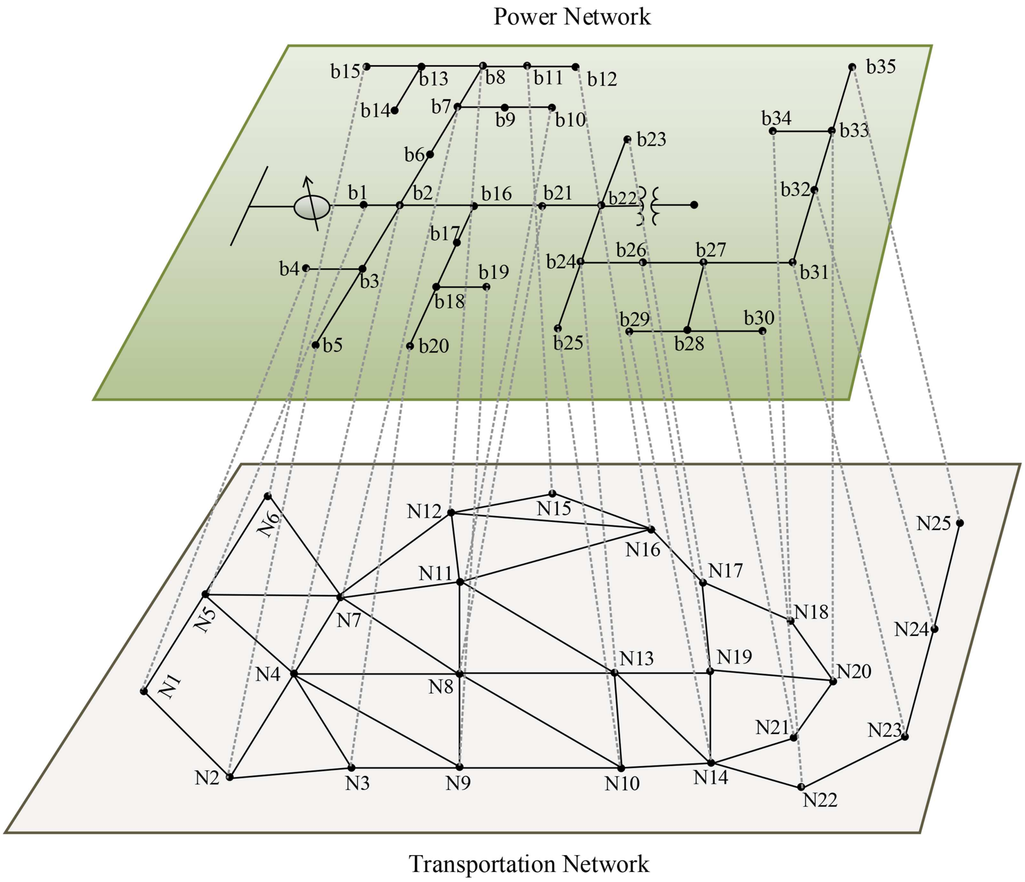


Figure 7. The graphical topology of the coupled 37-bus radial network and the 25-node transportation system.

and (51) showing the voltage drop and the square of current over the line between two consecutive buses are nonlinear. However, they can be linearized by the method described in reference [6]. Hence, the formulation of the inner layer is an MILP model. Eqs. (52) and (53) represent the limits for the voltage of buses and current flows over the lines.

$$p_{b,\omega,t}^{grid}\Big|_{b=1} + \sum_{n|c(b,n)=1} \left(p_{n,\omega,t}^{PLA,in} - p_{n,\omega,t}^{PLA,out}\right)$$

$$-\sum_{b'} (p_{b,b',\omega,t}^{line} + R_{b,b'} i_{b,b',\omega,t}^2) = p_{b,t}^D \qquad \forall b,t, \qquad (48)$$

$$q_{b,\omega,t}^{grid} - \sum_{b'} (q_{b,b',\omega,t}^{line} + X_{b,b'} i_{b,b',\omega,t}^2) = q_{b,t}^D \quad \forall b,t, \quad (49)$$

$$v_{b,\omega,t}^2 - 2\left(R_{b,b'} p_{b,b',\omega,t}^{line} + X_{b,b'} q_{b,b',\omega,t}^{line}\right)$$

$$-Z_{b,b'}^2 i_{b,b',\omega,t}^2 = v_{b',\omega,t}^2 \qquad \forall b,t, \qquad (50)$$

$$i_{b,b',\omega,t}^2 = \frac{\left(p_{b,b',\omega,t}^{line}\right)^2 + \left(q_{b,b',\omega,t}^{line}\right)^2}{v_{b',\omega,t}^2} \qquad \forall b,t, \qquad (51)$$

$$v_b^{\min} \le v_{b,t,\omega} \le v_b^{\max} \qquad \forall b,t, \qquad (52)$$

$$I_{b,b'}^{\min} \le i_{b,b',t,\omega} \le I_{b,b'}^{\max} \qquad \forall b,t. \qquad (53)$$

4. Numerical result

The proposed model was implemented in the IEEE 37-bus radial network coupled with a 25-node traffic network demonstrated by Figure 7 [26]. The peak load of the distribution network is 2.5 MW. The weight of transportation network nodes and their distance (in p.u.) are shown in Figure 8, where the base value for the distances is assumed to be 100 m. The weight of each node indicates what percentage of PEVs in each area refers to that node. Only one type of charger with a charge rate of 11 kW is assumed for all EVPLs, while PEVs in zone 1 use home chargers with 3 kW charging rate. Figure 9 illustrates the hourly energy and reserve prices [6] plus daily load profile [27]. In this paper, the prices of V2G and grid-to-vehicle are considered constant while the price π_t^{con} is assumed to be 20% higher than the energy price. Table 2 reports the value of other parameters used in the simulations [7]. In practice, the land cost depends on the location of PL.

Table 2. Data of EVPLs.

Parameter	Value	Parameter	Value
$D_{\max}$	500 m [19]	c^{eq}	2000 \$/Charger [30]
C_d	0.075 \$/kWh [25]	c^{fix}	18000 \$ [30]
A	25 m^2 [29]	c_n^{land}	407 \$/m^2 [31]
c^M	30 \$/Charger [30]	–	–

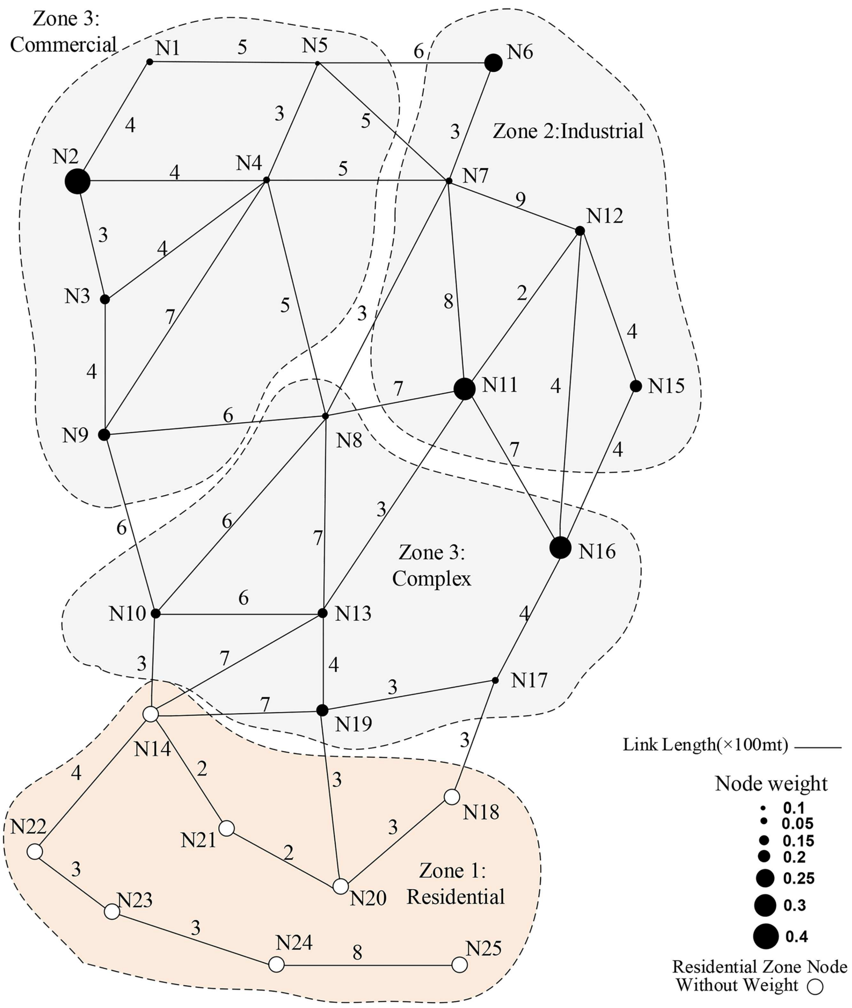


Figure 8. The structure of the 25-node transport network [26].

To model this feature, the land price at each location is assumed to be greater than the base value introduced in Table 2 by $5d_n$, where d_n is the weight of node n [28]. The SOC of PEVs departing the residential area is assumed to be 50% of their battery capacity with the maximum walking distance ($\mathrm{D_{max}}$) being 500 m.

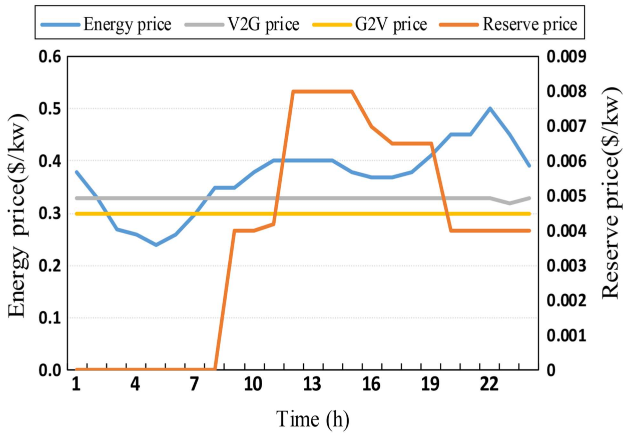
Figure 10 depicts the departure patterns of PEVs from different areas. For considering the uncertainty of travel patterns, initially 10000 scenarios are generated according to Eq. (1) with $\sigma_{i.j.t} = 0.15$, which are then reduced to 10 scenarios by using the forward selection method. Figure 10 demonstrates the final scenarios with the average scenarios indicated by the bold curves.

The proposed model is investigated in the following cases:

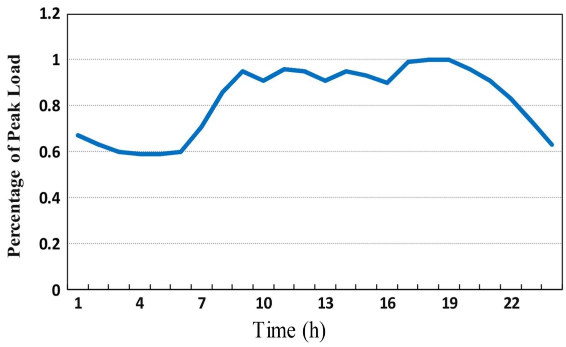
Case 1: Allocation of EVPLs assuming that the EVPLs are equipped with the V2G technology;

Case 2: Allocation of EVPLs assuming that the EVPLs are not equipped with the V2G technology;

Case 3: Coverage-constrained allocation of EVPLs equipped with the V2G technology.



(a): The hourly prices of energy and reserve



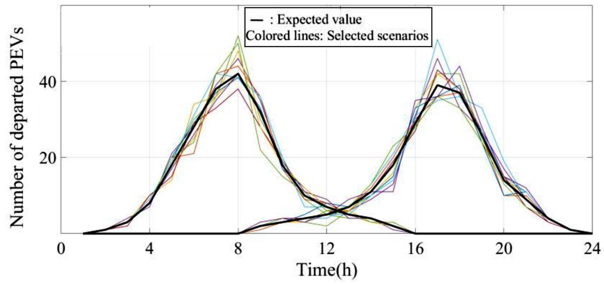
(b): hourly load

Figure 9. Market prices and load curve (a) The hourly prices of energy and reserve and (b) Hourly load.

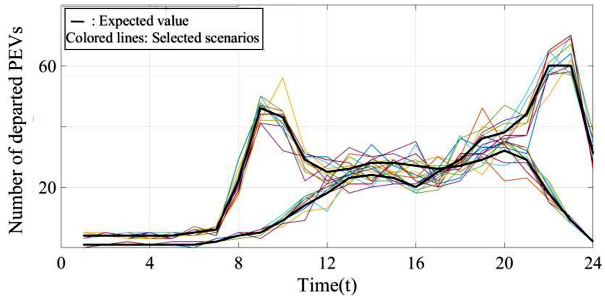
Note that in Cases 1 and 2, we assume the installation of maximum two EVPLs in each zone.

4.1. Case 1

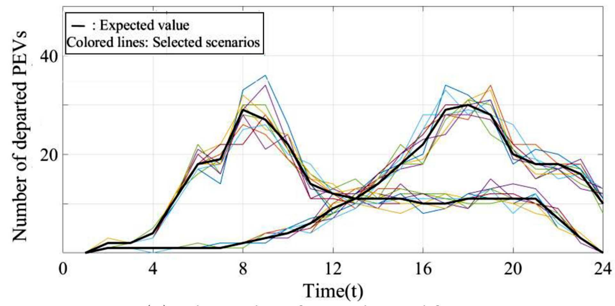
By solving the optimization problem, the number of charging spots is obtained as 125, 135, and 106 for zones 2 to 4, respectively. The optimal location and capacity of EVPLs as well as the allocation of PEVs to the EVPLs of each area during the hour for example 17 are shown in Figure 11. In zone 3 (the commercial zone) at hour 17, 66 PEVs present at node N2. Since there is no PL at this node, 54 PEVs can refer to N1 and 12 PEVs can refer to N3. On the other hand, the capacity of the EVPL installed in N1 is 70 cars, which is filled by 16 cars of its own plus 54 cars from N2. The parking capacity of EVPL in N3 is 65 cars, which is filled by 25 cars of its own, 16 of which will be occupied by the cars belonging to N4, 12 cars from N2, and 12 cars of N9. However, there are 8 cars in node N5 and 21 cars in node N9 that remain without parking space equipped with charger since there is no EVPL within their walking distance. Hence, the parking demand of 135 vehicles of the total of 164 vehicles presented in the nodes of the commercial area (i.e., 82.3% of the vehicles in this area) is covered by the EVPLs of nodes N1 and N3. At the same time, the percentage of vehicles for which parking space provided in zones 2 and 4 is 89.1% and 75.2%, respectively.



(a): The number of PEVs departed from zone 1 to 2 and 2 to 1



(b): The number of PEVs departed from zone 1 to 3 and 3 to 1



(c): The number of PEVs departed from zone 1 to 4 and 4 to 1

Figure 10. The number of PEVs entering and leaving different zones [21] (a) The number of PEVs departed from zone 1 to 2 and 2 to 1; (b) The number of PEVs departed from zone 1 to 3 and 3 to 1; (c) The number of PEVs departed from zone 1 to 4 and 4 to 1.

According to the solution of the problem and the nodes specified for the installation of EVPLs, the number of PEVs in each zone for which parking spot is provided is shown in Figure 12. With the selected nodes, the minimum availability of EVPLs for PEVs in zone 2 at times 12 and 13 is 58.4%, zone 3 at time 17 is 82.3%, and zone 4 at time 13 is 71.1%.

The results of energy and reserve exchanges of EVPLs are shown in Figures 13 and 14. Table 3 presents different components associated with the profit of EVPLs. The negative income caused by energy market interactions demonstrates that EVPLs purchase energy from the network and sell it to PEVs

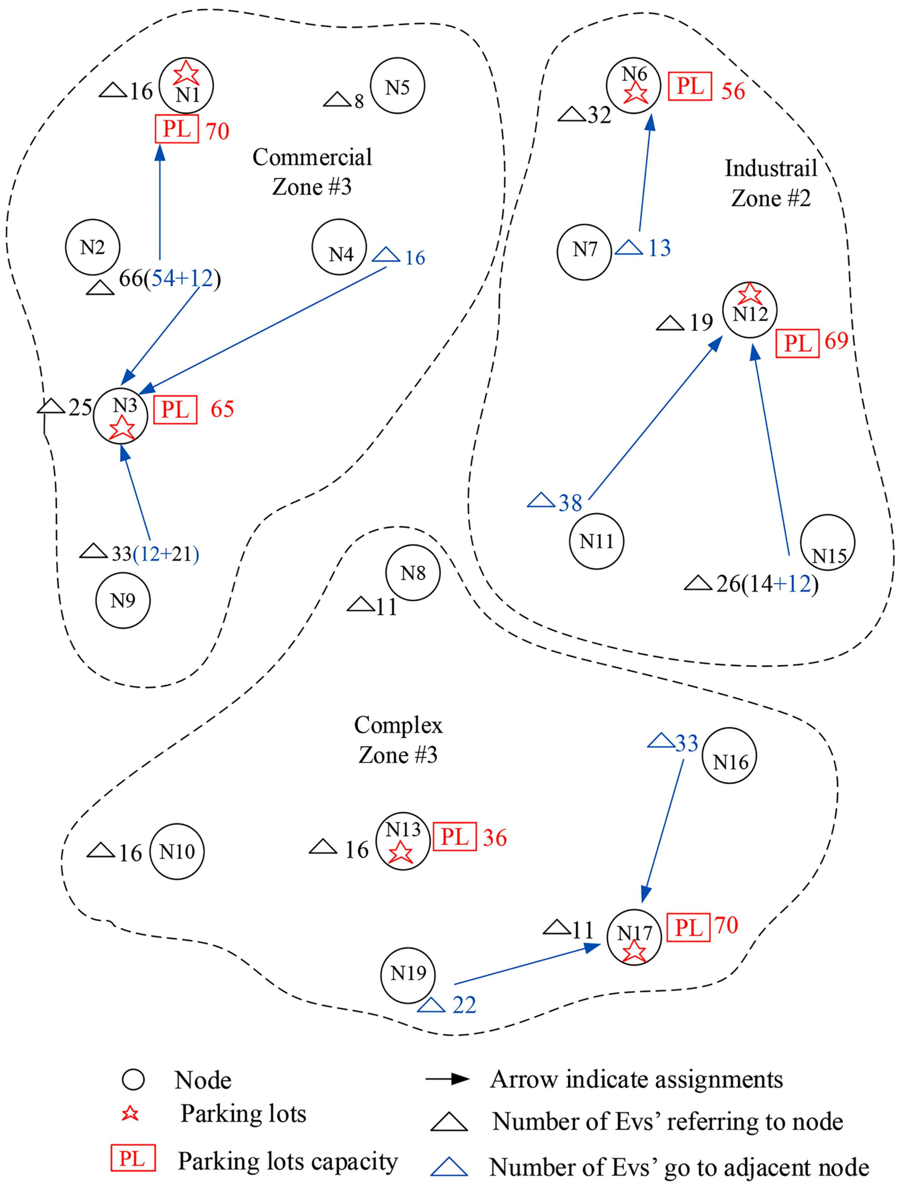


Figure 11. Location and capacity of EVPLs and allocation of PEVs to the EVPLs in Case 1.

Table 3. Different components of the objective function (k$) in Case 1

	Zone		
	2	**3**	**4**
Income from energy exchanges with network	–208.3	–85.3	–63.4
Income from reserve market exchanges	287.5	321.1	215.9
Income from energy exchanges between EVPLs and PEV owners	178.7	65.3	51.1
Income from parking tariffs	1392.8	1591.4	1047.5
Installation cost (fixed and variable)	530.1	492.9	382.1
PL capacity	125	135	106
Total loss cost		6.2	
Total installation cost		1405.1	
Total revenue		4794.3	
Profit of EVPLs		3383	

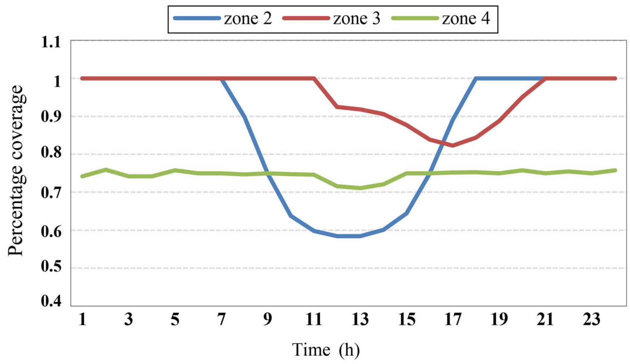


Figure 12. The covered PEVs' parking need in each zone (in p.u.) in Case 1.

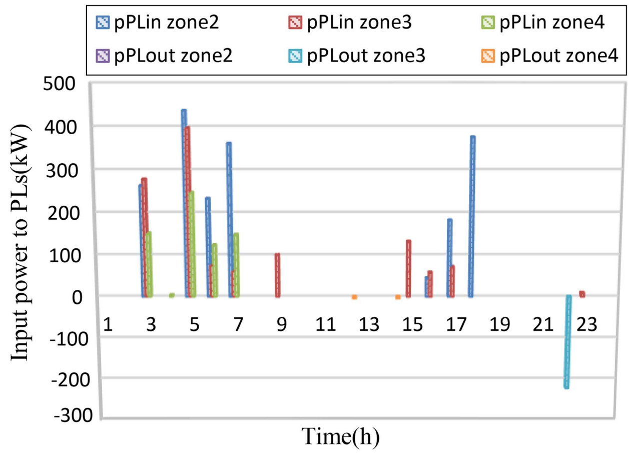


Figure 13. Energy exchanges related to zones 2, 3, and 4 in Case 1.

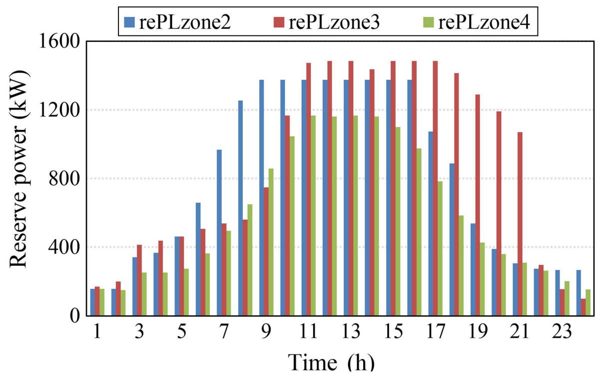


Figure 14. Reserve provision related to zones 2, 3, and 4 in Case 1.

in most hours. It is also observed that the most benefit is obtained through the participation in the reserve market. Meanwhile, according to the number of vehicles available per hour, EVPL owners gain significant revenue from parking tariff.

In Figures 15 and 16, We compared the results for three different values of $D_{\max}$ including 300, 400, and 500 m. According to Figure 15, when $D_{\max}$ declines, EVs drivers prefer to park their car somewhere other

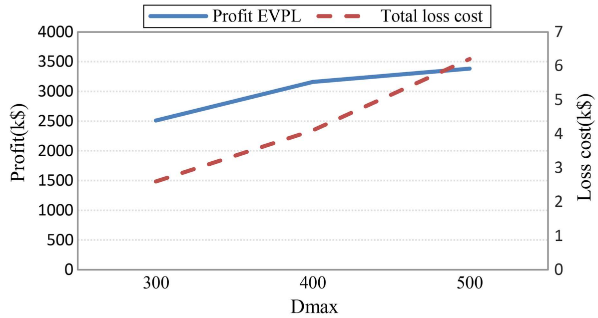


Figure 15. Profit and loss cost changes with different $D_{\max}$ in Case 1.

Table 4. Comparison of EVPLs' profit with and without considering V2G technology (k$) in Case 2.

	With V2G	Without V2G
Revenue of EVPLs	4794.3	3951.2
Total installation cost	1405.1	1435
Total loss cost	6.2	2.6
Profit EVPLs	3383	2513.6

than the EVPLs. Thus, the number of EVs referring to EVPLs diminishes and EVPLs are allocated with less capacity, causing less profit for their owners. The location and capacity of EVPLs resulting with different $D_{\max}$ are very different which are shown in Figure 16.

4.2. Case 2

If the EVPLs are not equipped with the V2G technology, their output power will be zero, thus they cannot participate in the energy and reserve markets as an energy provider. The power exchanges of the EVPLs in this case are shown in Figure 17, which shows a significant reduction in power exchanges. The revenue and cost of EVPLs in two modes, with and without V2G technology, are compared in Table 4, and The location and capacity of EVPLs in this case are illustrated in Figure 18.

4.3. Case 3

In this case, a minimum of 90% coverage of PEV parking demands in each zone is considered. Here, we ignore the constraint on the number of EVPLs of each zone. Figure 19 demonstrates the allocation of EVPLs in this case, whereby the minimum coverage is obtained for zones 2, 3, and 4 as 94.9%, 95.1%, and 94.6%, respectively. Compared to Cases 1 and 2, the number of EVPLs and charging spots in the transportation network have increased. Figure 20 reveals the number of PEVs (in p.u.) in each zone for which a parking spot is provided.

Table 5 reports different components associated with the profit of EVPLs. It can be seen that more profit is obtained in this case through installing more

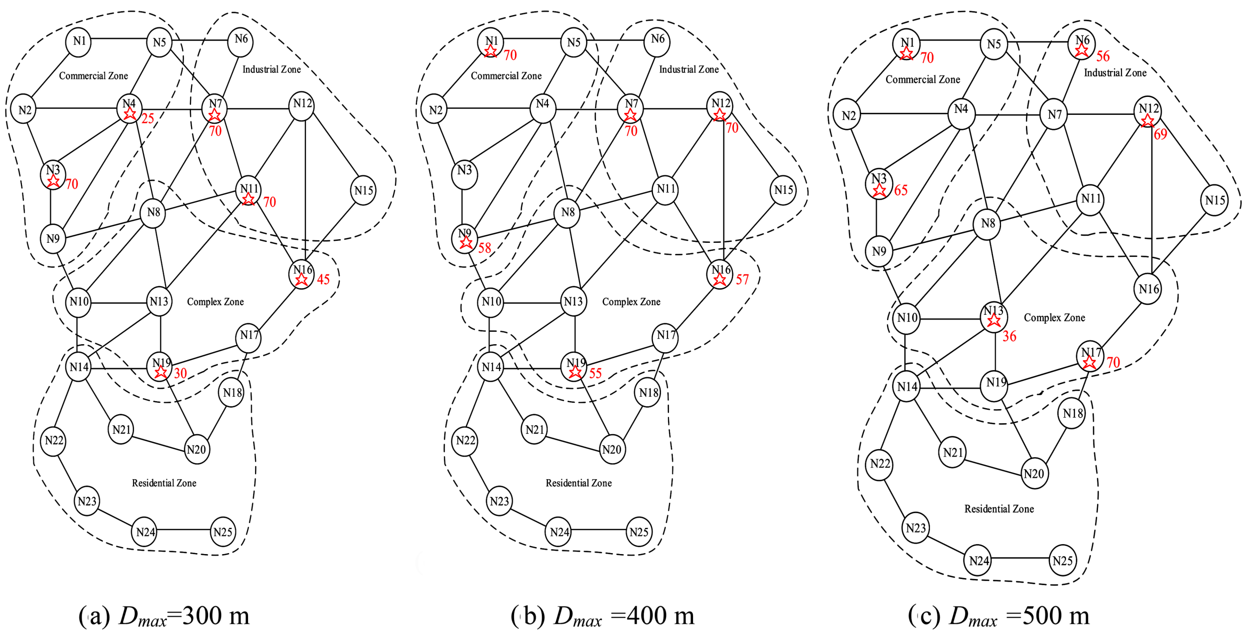


Figure 16. EVPLs allocation with different $D_{\max}$ in Case 1.

Table 5. Different components of the objective function (k$) in Case 3.

	Zone		
	2	**3**	**4**
Income from energy exchanges with network	–189.5	–93.1	–85.9
Income from reserve market exchanges	392.4	348.7	289.3
Income from energy exchanges between PLs and PEVs' owners	154	69.4	69.5
Income from parking tariffs	1803.8	1695.7	1392.1
Installation cost (fixed and variable)	826.6	584.4	567.1
PL capacity	203	156	155
Total loss cost		5.1	
Total installation cost		1978.1	
Total revenue		5846.4	
Profit of PLs		3863.2	

charging spots which boost the revenue of EVPLs from parking tariff as well as reserve provision.

5. Conclusion

Planning of Electric Vehicle Parking Lots (EVPLs) should be performed taking into account the interests and limitations of both distribution and traffic networks. The results show the efficiency of the proposed model in determining the optimal location and capacity of EVPLs as well as managing their charging/discharging to maximize the profits of EVPL owners. At the same time, proper allocation of Plug-in Electric Vehicles (PEVs) to the EVPLs results in maximum coverage of PEV parking needs. According to the results, the main part of the EVPL revenue comes from parking tariffs and reserve sale in the electricity market. In addition, with proper charging management, network loss during peak hours will not increase much, which is an improvement in the distribution network performance.

Comparison of the case studies indicate the following results:

- Imposing constraint for the minimum amount of parking demand coverage increases the number of PLs;
- Without Vehicle-to-Grid (V2G) technology, the sale of energy and reserve to the network diminishes which reduces the profit of EVPL;

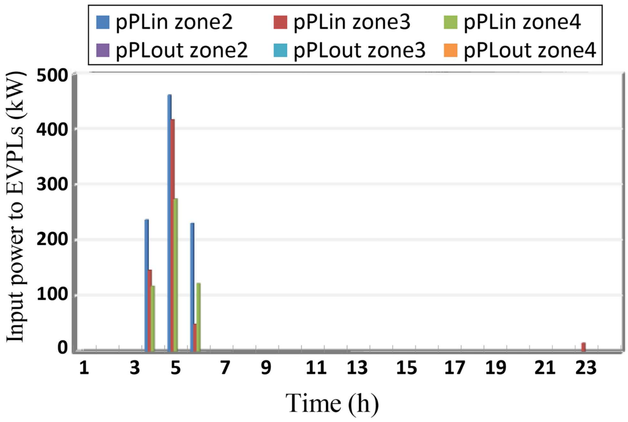


Figure 17. Energy exchanges of PLs in each zone without considering V2G in Case 2.

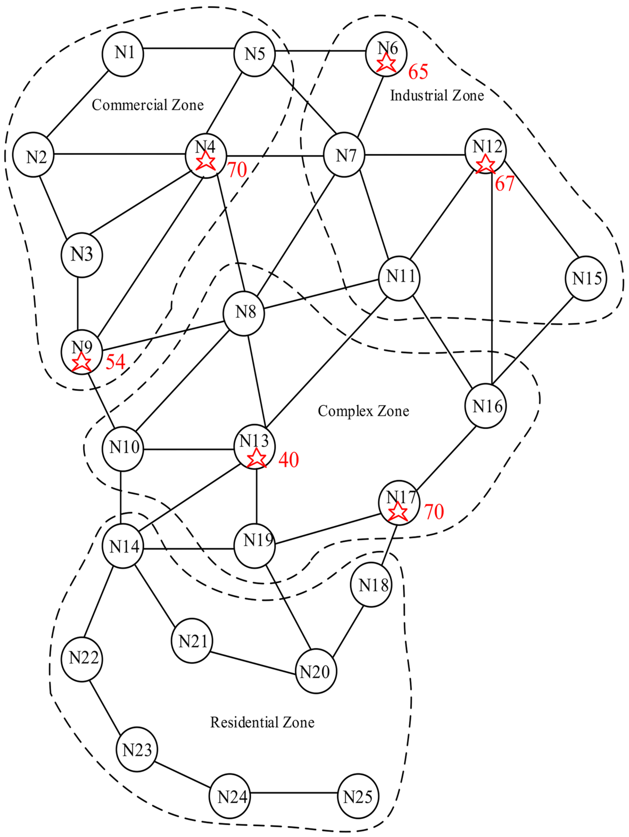


Figure 18. EVPLs allocation without V2G technology in Case 2.

- As the maximum walking distance decreases, the number of PEVs visiting the EVPLs decreases which results in lower revenue and profit of EVPLs.

Acknowledgment

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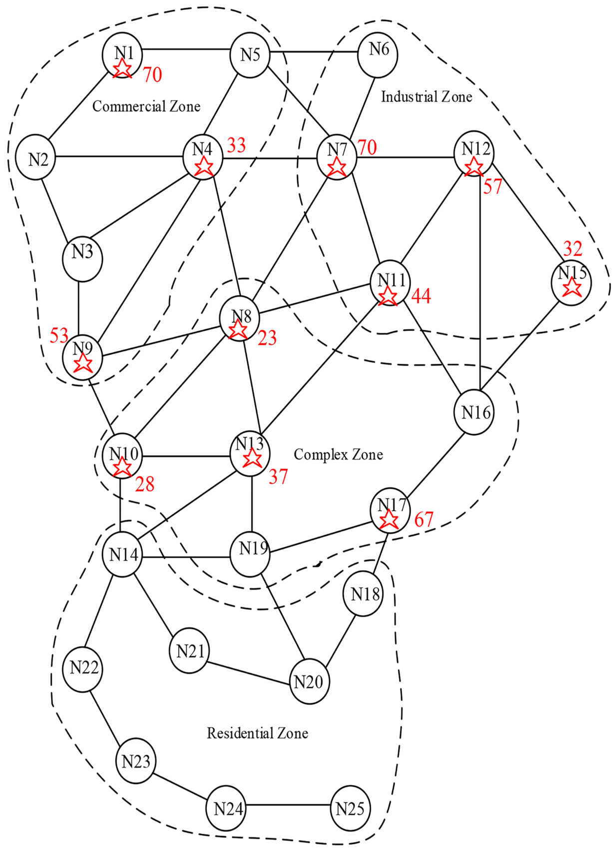

Figure 19. Location and capacity of EVPLs in Case 3.

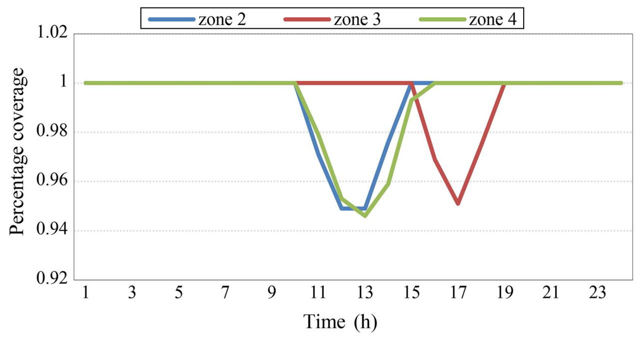

Figure 20. PEVs parking need coverage in each area (in p.u.) in Case 3.

List of symbols and abbreviations

Acronyms

EVPL	Electric Vehicles Parking Lot
GA	Genetic Algorithm
MILP	Mixed Integer Linear Programming
PL	Parking Lot
PEV	Plug-in Electric Vehicle
SOC	State Of Charge
V2G	Vehicle to Grid

Indices and sets

b	Index of buses

i, j	Index of zones
n	Index of transport network nodes
t	Index of hours
ω	Index of scenarios
Ω_i	Set of all nodes in zone i
Ω_s	Set of all selected scenarios

Parameters

A	Space required to install a charging spot (m^2)
C_{av-EV}	Average capacity of PEV battery (kW)
C_d	Cost of battery depreciation ($/kWh)
c^{eq}, c^M	Cost of purchasing and maintenance of each charger ($)
$C_{i.j.t}^{in.zone}$	Battery capacity of the PEVs entering zone j from zone i (kWh)
$C_{i.j.t}^{out.zone}$	Battery capacity of PEVs leaving zone i towards zone j (kWh)
$C_{i.t}^{PL}$	Battery capacity of the PEVs available in the EVPLs of zone i (kWh)
$cover_{n.m}$	Binary variable which is 1 when the parking need of vehicles of node n can be served by EVPL in node m, and 0 otherwise
$c(b, n)$	Binary parameter that indicates connection between bus b and node n
$distance_{n.m}$	Distance from node n to node m (m)
$D_{\max}$	Maximum walking distance (m)
$d_{n,t}$	Weight of transportation node at time t (in p.u.)
$\rho_{i.t}^{del}$	Probability of calling of reserve purchased at time t
FOR_i^{PL}	Failure probability of EVPLs of zone i in delivery of the called reserve
$I_{b.b'}^{\min / \max}$	Minimum and maximum allowable current of the line (in p.u.)
$IC^{\max}$	Maximum budget ($)
N_z	Number of zones
$N^{PL,\max}$	Maximum number of allowable EVPL installation
$N_{i.\omega.t}^{in/out.EX}$	Number of PEVs entering/leaving to/from external zone at time t in scenario ω
$N_{i.\omega.t}^{in/out.zone}$	Number of PEVs entering/leaving zone i from/toward zone j at time t in scenario ω
$N_{i.\omega.t}^{zone}$	Number of PEVs that exist in zone i at time t in scenario ω
$NEV_{n,\omega,t}$	Number of PEVs in node n at time t in scenario ω
NPL_i^{zone}	Total capacity of EVPLs in zone i
$nsPL_n$	Number of charging spots of the PL installed in node n
$R/X/Z_{b,b'}$	Resistance, reactance and impedance of the line between buses b and b' (per unit)
$soc_{i.\omega}^{EV.\min / \max}$	Minimum and maximum acceptable Soc of PEVs in zone i at time t in scenario ω
$\min/\max soc_{i.\omega.t}^{dep.PL}$	Minimum and maximum Soc at the departure of PEVs from zone i at time t in scenario ω
$TN_{i.\omega.t}^{in/out.zone}$	Total number of PEVs entering/leaving zone i at time t in scenario ω
$TN_{i.\omega.t}^{in.net.zone}$	Net number of PEVs entering zone i at time t in scenario ω
$v_b^{\min / \max}$	Minimum and maximum allowable voltage of bus b (per unit)
η_c, η_d	Charging and discharging efficiency (%)
Γ_i^{PL}	Charging and discharging rates in EVPLs of zone i (kW)
Φ_i^{PL}	Minimum Soc required for PEVs when departing zone i (kWh)
κ_i^{PL}	Usable Soc of EVPL according to the contract with PEVs (%)

Variables

c^{fix}	Fixed cost required for the construction of an EVPL in zone i ($)
c_n^{land}	Cost of land for installing a charging spot ($/m^2)
c_ω^{loss}	Cost of energy losses in the distribution network ($) in scenario ω
$cost^{PL}$	The investment cost of EVPLs ($)
$loss_t^0$	Distribution network loss at time t without presence of EVPLs in scenario ω (kW)
$loss_{\omega,t}$	Distribution network loss at time t with presence of EVPLs in scenario ω (kW)
$n_{i.\omega.t}^{PL}$	Total PEVs that can be parked in the EVPLs of each zone at every hour in scenario ω
$n_{i.\omega.t}^{ar.PL}.N_{i.\omega.t}^{dep.PL}$	Number of PEVs arriving/departing the EVPLs of zone i in scenario ω
$N_{i.\omega.t}^{dep.nonPL}$	Number of vehicles leaving the area outside the EVPLs of zone i at time t in scenario ω

$NEV^{ref}_{m.n.\omega.t}$ Number of PEVs of node m that refer to EVPL of node n at time t in scenario ω

$PC^{zone}_{i.\omega.t}$ Percentage of PEVs served by EVPLs in zone i at time t in scenario ω

$p^D_{b.t}.q^D_{b.t}$ Active and reactive power demand in bus b at time t (kW,kVAr)

$p/q^{grid}_{b.\omega.t}$ Active and reactive power from the upstream network to bus b at time t in scenario ω (kW,kVAr)

$p/q^{line}_{b.b'.\omega.t}$ The active/reactive power transmitted through the line between bus b and b' at time t in scenario ω (kW,kVAr)

$p/q^{PL.in/out}_{i.\omega.t}$ Input/output power to/from the EVPLs of zone i in scenario ω

$r^{PL.out}_{i.\omega.t}$ Called reserve from EVPLs of zone i at time t in scenario ω (kW)

$p/q^{PLA.in/out}_{n.\omega.t}$ Input/output power to/from node n at time t in scenario ω (kW)

$soc^{ar/dep.PL}_{i.\omega.t}$ *Soc* of the PEVs entering/leaving to/from EVPLs of zone i at time t in scenario ω (kWh)

$soc^{dep.zone}_{i.\omega.t}$ *Soc* of the PEVs departing zone i at time t in scenario ω (kWh)

$soc^{in/out.EX}_{i.\omega.t}$ *Soc* of the PEVs entering/leaving to/from external zone to zone i at time t in scenario ω (kWh)

$soc^{in.zone}_{i.j.\omega.t}$ *Soc* of the PEVs entering into zone j from zone i in scenario ω

$soc^{out.zone}_{i.j.\omega.t}$ *Soc* of the PEVs departing zone i toward zone j at time t in scenario ω (kWh)

$soc^{PL}_{i.\omega.t}$ *Soc* of the PEVs in EVPLs of zone i at time t in scenario ω (kWh)

u^{PL}_n Binary variable that indicates node n has been selected for installing EVPL

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