Optimal charge scheduling of electric vehicles in solar energy integrated power systems considering the uncertainties

Author(s): Sadati, S. Muhammad Bagher; Moshtagh, Jamal; Shafie-Khah, Miadreza; Rastgou, Abdollah; Catalão, João P. S.

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Cooperation-based Operational Scheduling of Electric Vehicle Parking Lots in a Smart Distribution System

Abstract- The role of electric vehicle (EV) parking lots (PLs), as well as optimal sitting, sizing and operation of them, are far more important than before in a smart distribution system (SDS) due to a large number of the EVs and the vehicle-to-grid (V2G) ability. In the smart grid with digital communications technology, etc., features of the parking lot-to-grid (PL2G) and even parking lot-to-parking lot (PL2PL) because of the EVs' discharging power are easily used. So, in this paper, an appropriate model is presented considering uncertainties and the aim of maximizing profit of the PL owners (PLOs) to investigate these features. The model is evaluated in three parts. Firstly, each PLO only purchases power from an SDS operator (SDSO) for charging of the EVs. In the second case, each PLO exchange power with the SDSO (purchasing/selling power to an SDSO), and finally in the 3rd part, each PLO could trade energy with both the SDSO and other PLOs. These parts are tested in an SDS with 3 PLs that the maximum capacity of each PL is 700 EVs. The results show that in the third part, with the cooperation of PLOs, the PLOs gain more profit. Furthermore, in each part, the EVs' specifications (such as arrival/departure time of the EVs and the initial state of energy (SOE)), have the main effect on PLOs' profit.

Keywords: Energy management modeling, electric vehicle parking lots, uncertainties, smart distribution system, stochastic programming.

Nomenclature

Indices

EV	Index for EV number
PL	Index for PL number
S	Index for scenarios
t	Index for time (hour)

Parameters

C^{cd}	Cost of equipment depreciation ($/kWh)
P^{max}	Maximum charging/discharging rate (kWh)
SOE^{arv}	Initial SOE of EVs at the arrival time to the PLs (kWh)
SOE^{dep}	Desired SOE of EVs at the departure time from PLs (kWh)
SOE^{max}	Maximum rate of SOE (kWh)
SOE^{min}	Minimum rate of SOE (kWh)
t^{arv}	Arrival time of EVs to the PLs
t^{dep}	Departure time of EVs from the PLs
π^{PL2EV}	Charging tariff of EVs ($/kWh)
π^{G2PL}	Price of purchasing energy from SDSO by the PLOs ($/kWh)
π^{PL2G}	Price of selling energy to SDSO by the PLOs ($/kWh)
π^{PL}	Price of exchanging energy by the PLOs ($/kWh)
η^{ch}	Charging efficiency (%)
η^{dch}	Discharging efficiency (%)

Variables

$P^{ch\text{-}G2PL}$	Charging power of each PL from SDSO (kW)
$P^{ch\text{-}PL'2PL}$	Charging power of each PL from other PLOs (kW)
$P^{dch\text{-}PL2G}$	Discharging power of each PL to SDSO (kW)
$P^{dch\text{-}PL2PL'}$	Discharging power of each PL to other PLOs (kW)
SOE	EVs' state of energy (kWh)
X^{ch}	Binary variable which shows the charge status of each EV

1. Introduction

1.1. Motivation and aims

With the high penetration of electric vehicles (EVs), the role of parking lots (PLs) has particular importance for the smart distribution system operator (SDSO) and the PL owners (PLOs). Depending on the vehicle-to-grid (V2G) ability of the EVs and discharging power, especially at the on-peak periods and also to arrange a contract to purchase energy from the PLOs, the SDSO achieves several benefits such as loss reduction, decreasing of peak demand and so on. Also, the operation of the SDS becomes more flexible. Moreover, the PLOs must earn an appropriate profit to encourage the establishment of the PLs. Certainly just purchasing energy from the SDSO and selling it to the EV owners (EVOs) bring low profit to the PLOs. Also, this profit increases by arrangement a contract between the PLOs and the EVOs (by offering the appropriate clauses incentives to reduce the cost of EVs' charging power) for the exchanging energy that leads to the selling energy to the SDSO. In this case, the PLOs have both the power consumer and power generator roles. If there is an energy management system (EMS) that can perform charging of EVs (consumer mode) at the off-peak and mid-peak periods and discharging of EVs (generation mode) at the on-peak periods, then the profit of PLOs will probably increase due to the difference in the energy prices at these times. Of course, the main features of the EVs such as the nominal rated of battery capacity, the arrival/departure time to/from PLs, the initial state of energy (SOE) and the desired SOE, etc., also affect the amount of this profit.

This profit increases even more when energy is traded between PLOs, i.e., each PLO interacts with other PLOs at the appropriate energy price in addition to an SDSO. Therefore, proper modeling of PLOs' behavior is essential for optimum decision-making that leading to optimal operation of PLOs and increasing their profit.

Therefore, in this paper the behavior of the PLOs in three different modes, i.e. 1) purchasing energy from the SDSO, 2) purchasing/selling energy from/to the SDSO and 3) purchasing/selling energy from/to the SDSO and other PLOs are investigated. Finally, the sensitivity analysis of some of the important parameters on the profit of the PLOs is examined.

1.2. **Literature review**

With the advent of new technologies such as smart meters, digital communications technology, information systems, etc., the power system, especially at the distribution system level has changed and become a smart grid. The SDSO has also faced with a major challenge in terms of operation and planning. Of course, the performance of SDS has improved from technical and economical point of view by integration of demand response programs (DRPs), renewable-energy sources (RERs), electric vehicles parking lots (EV PLs), energy storage system (ESS), etc.

Today, the using of EVs in the transportation section has been accelerating more and more, and most of their manufacturers have improved the EVs' performance in terms of speed, distance traveled, batteries' lifetime, etc. This high penetration of EVs has led to the establishment of EV PLs in urban areas. In recent years, studies about EV PLs have focused on some categories that in the following, some of these papers have reviewed.

In [1], by financial and technical aims, the scheduling model of EVs is presented with the goal of maximizing each EVO's profit by charging/discharging in a proper time. also, the SOE of each EV is maximized. In [2], a controller is suggested for the management of EVs' power charging with the aim of reducing total cost and their impact on the power system. In [3] for EV PL scheduling a new convexified model without considering EVs' uncertainty is proposed by minimizing total cost. In [4], a new scheme is presented for finding the optimized EVs' charging power with maximization of the profit of PLO. In [5], A day-ahead EV PL scheduling based on an aggregative game model with the aims to minimize the charging cost is proposed. In this model, EVs' uncertainty and V2G mode are not considered. A multi charging scheduling system considering the PL's profit and customer satisfaction is suggested in [6]. In [7], for operational scheduling of EV PL in energy and reserve market a bi-level model is presented. The main objective of the upper level is minimizing the operation cost of the distribution system and the lower level is minimizing the cost of PL. In [8], a new model with maximizing the PLO's profit is suggested for the operation of EV PL only in charging mode. Due to price uncertainty, the uncertainties of the profits are considered. The results are shown that the algorithm is robust against high-level uncertainty. In [9], by maximization profit of EVO and PLO, an intelligent charging process due to battery specification and time-of-use (TOU) price. Also, in this model, the battery charging characteristic is analyzed with an adaptive utility-oriented scheduling algorithm. In [10], A new model is offered with maximizing the load factor during the daily operation of an EV PL taking into account the uncertainties of EV and without V2G. Some case studies with different peak load reductions are done to proving the effectiveness of the model. In [11], for providing an optimal schedule of V2G and G2V modes of EVs intelligent energy management with the goal of minimizing the cost energy consumption is designed. Also, to encourage EV owners to participate in V2G mode, their profits are calculated considering battery degradation cost. In [12], the optimized charging scheduling of EV PL that is feed by the solar system and power grid is obtained. The objective function was maximizing the PLO's profit with satisfying EVO. Results are shown the efficiency of the suggested charging scheme. In [13], the operation of EV PL is modeled with the multiple servers and heterogeneous service rates. Also, by minimizing the service dropping rate, a new scheme for charging processes is presented. Results are proved the efficiency of the suggested charging scheduling program. In [14], for economical operational (minimizing cost) of EV PL considering the environmental issues, a multi-objective optimized model is presented. The result is shown that the suitable charge/discharge power schedule of EVs is led to reducing total emission and operation costs. In [15], the EV charging's optimization in the PL with the energy storage system (ESS) and the solar system is formulated by cost minimization objective function. It is determined by results, the improved binary grey wolf optimizer (IBGWO) be a better solver for the suggested model compared with other meta-heuristic methods. In [16], the operation of PV-based EV PL with the aim of maximizing profit PLO considering energy, reserve and regulation market is modeled. By maximizing PLO's profit, a new stochastic model for charging/discharging of EV PL with a hydrogen storage system (HSS) is proposed in [17]. The results are shown that the novel algorithm is efficient from an economic point of view. In [18-19], in bi-level framework operational scheduling of PLO with maximization PLO's profit [18] and minimization PLO's cost [19] is investigated.

Although various models studied the operation of PLs, the cooperation of different PLOs has not been addressed in the literature. To this end, a novel energy management model for operational scheduling of PLs is suggested in this paper with the aim of maximizing PLOs' profit considering uncertainties of PLs including the arrival and departure times of EVs and their initial SOE.

1.3. **Contribution**

The main contribution of this paper is developing an optimal cooperation model for operational scheduling of PLs in an SDS. The proposed model enables cooperation of PLOs in future SDS. To the best of the authors' knowledge, it is the first time that cooperation of different PLs is proposed to model the operational scheduling of these virtual energy storage resources. In addition, a sensitivity analysis is performed to evaluate the important factors that may affect the objective function.

1.4. **Paper organization**

The rest of the paper is formed as follows. Modeling of the EVs is performed in section 2. Problem formulation is explained in Section 3. Numerical results and sensitivity analysis are discussed in Section 4. Finally, conclusions are reported in Section 5.

2. Modeling of the EVs

The EVs can be categorized into three groups of battery-electric vehicles, hybrid-electric vehicles, and fuel cell electric vehicles. All these EVs have a battery as well as the V2G capability. Furthermore, due to the insignificant pollution, EVs are very popular in the transportation section. Therefore, in the near future, these EVs are widely used. With the increasing of the number of EVs, the batteries of them can provide a high-availability storage system for the power system. In this way, the EVs can act as an active element in the system during the parked times. So, the power stored in the batteries, particularly at the on-peak hours sold to the SDSO. The initial SOE, arrival time/departure time of EVs to/from PLs are the main uncertainties of each EV. Some studies are shown that the behavior of the EVs can be modeled with appropriate probability distribution function (PDF) such as a truncated Gaussian distribution [18]. Thus, the modeling of EVs is shown by Eqs. (1) to (3). Other important characteristics of the EVs are the charging/discharging rate and the desired final SOE that in this paper are considered as [19].

$$SOE_{EV}^{ini}=f_{TG}\left(X;\mu_{SOE};\sigma_{SOE}^{2};\left(SOE_{EV}^{ini,\min};SOE_{EV}^{ini,\max}\right)\right) \qquad \forall EV \qquad (1)$$

$$t_{EV}^{arv}=f_{TG}\left(X;\mu_{arv};\sigma_{arv}^{2};\left(t_{EV}^{arv,\min};t_{EV}^{arv,\max}\right)\right) \qquad \forall EV \qquad (2)$$

$$t_{EV}^{dep}=f_{TG}\left(X;\mu_{dep};\sigma_{dep}^{2};\left(\max(t_{EV}^{dep,\min},t_{EV}^{arv});t_{EV}^{dep,\max}\right)\right) \qquad \forall EV \qquad (3)$$

Due to the high number of the EVs are in the PLs every day, the more energy is needed for charging of the EVs. In addition, because of the V2G capability, the performance of the SDS can be improved; therefore, the EVs are considered a load/source at the off-peak and mid-peak hours/during the on-peak hours. So, a complexity creates in the operation and planning of the SDS. Thus, proper PL's operation will only be possible if there is an EMS that is capable of controlling and managing the process of charging and discharging of the EVs. Fig. 1 illustrates the flowchart of charging or charging/discharging schedule of the EVs [19]. Based on this flowchart, after the entrance of EVs to PL, required data such as initial and desired SOE of the EVs, the battery specifications and departure time are achieved from EVOs. By computing the energy needed for each EV, the EMS determines the time and charging/discharging power of the EVs.

In this paper, each PLO can interact energy with other PLOs and the SDSO in three ways as already stated. Fig 2 shows the interaction of each PLO with other PLOs and SDSO in the third mode. It is noted that in the second mode, there is no connection between the PLOs (without power exchange and information exchange). In the first mode, in addition to the second mode, the exchanging power is also one-way, i.e. from the SDSO to the PLOs.

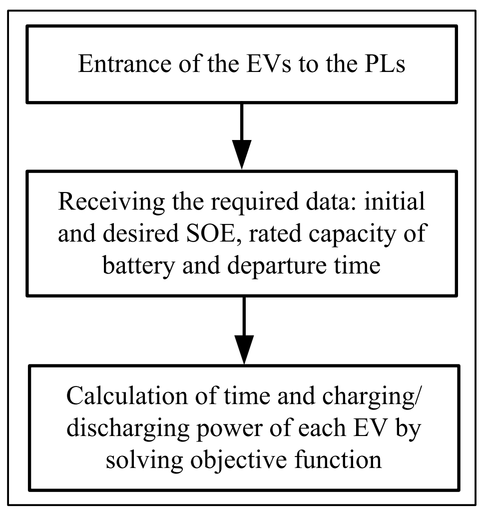

Fig. 1. The Flowchart of each EV's operation [19]

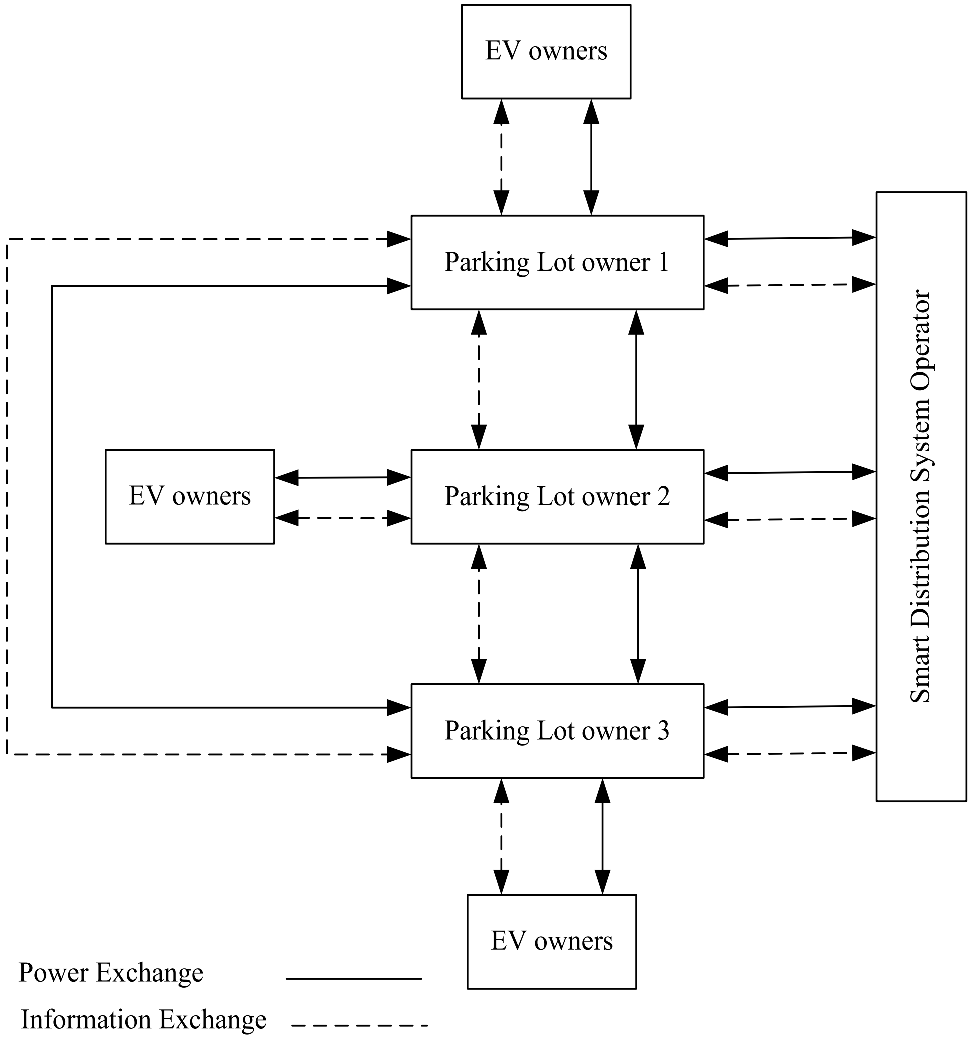

Fig. 2. Interaction of PLOs with each other and an SDSO

3. Problem formulation

The objective function of each PL, i.e. maximization profit of PLOs in the case of EVs are only charged is equal to the difference between the income result from the energy sold to EVs, and the cost of energy purchased from the SDSO. This objective function is described in (4).

$$\text{Profit}_{PL} = \sum_{s=1}^{Ns} \rho_s \sum_{EV=1}^{N_{EV}} \sum_{t=1}^{24} \left(\left(P_{PL,ev,t,s}^{ch-G2PL} \pi_t^{PL2EV} \right) - \left(P_{PL,ev,t,s}^{ch-G2PL} \pi_t^{G2PL} \right) \right) \quad (4)$$

When EVOs are encouraged that participate in EV2PL program (charging/discharging schedule of EVs) that leads to PL2G mode, the PLOs can sell energy to SDSO. So, EVOs receive α% of the profit of energy sold to SDSO, based on a contract that is written between EVOs and PLO. The PLOs receive another (1-α) %. The second factor for encouraging of EVOs to participate in EV2PL program is the battery depreciation's cost. In this case, the EVOs receive a specific amount from the PLOs due to the depreciation of the battery and reducing its lifetime for each discharging period. In this situation, the objective function of each PLO is determined by the power exchanged with the SDSO and is explained in (5).

$$\text{Profit}_{PL} = \sum_{s=1}^{Ns} \rho_s \sum_{EV=1}^{N_{EV}} \sum_{t=1}^{24} \begin{pmatrix} \left(P_{PL,ev,t,s}^{ch-G2PL} \pi_t^{PL2EV} \right) + \left(\alpha P_{PL,ev,t,s}^{dch-PL2G} \pi_t^{PL2G} \right) \\ -\left(P_{PL,ev,t,s}^{ch-G2PL} \pi_t^{G2PL} \right) - \left(P_{PL,ev,t,s}^{dch-PL2G} C^{cd} \right) \end{pmatrix} \tag{5}$$

As already mentioned, in the proposed model, each PLO will be able to interact and energy exchanged with other PLOs in addition to exchanging energy with the SDSO. So, in the following, the interactions between PLOs are modeled. The profit from selling energy to other PLOs is as (6). The profit of each PLO in interactions between other PLOs includes the revenue from the energy sold to the EVOs, as well as the revenue from the energy sold to the other PLOs. This selling energy to other PLOs comes from the previous contract. This contract leads to EV2PL and then PL2PL mode. So, EVOs receive β% of the profit of energy sold to other PLOs. The PLO also receives another (1-β) %. The cost of the energy purchased from the other PLOs and the cost of the battery depreciation are two cost terms for PLOs.

$$\text{Profit}_{PLtoPL'} = \sum_{s=1}^{Ns} \rho_s \sum_{\substack{PL=1 \\ PL \neq PL'}}^{N_{PL}} \sum_{EV=1}^{N_{EV}} \sum_{t=1}^{24} \begin{pmatrix} \left(P_{PL,ev,t,s}^{ch-PL'2PL} \pi_t^{PL2EV} \right) + \left(\beta P_{PL',ev,t,s}^{dch-PL2PL'} \pi_t^{PL} \right) \\ -\left(P_{PL,ev,t,s}^{ch-PL'2PL} \pi_t^{PL} \right) - \left(P_{PL',ev,t,s}^{dch-PL2PL'} C^{cd} \right) \end{pmatrix} \tag{6}$$

So, the total objective function of each PLO by interaction with SDSO and other PLOs is shown in (7).

$$\begin{aligned} \text{Profit}_{PL} &= \sum_{s=1}^{Ns} \rho_s \sum_{EV=1}^{N_{EV}} \sum_{t=1}^{24} \begin{pmatrix} \left(P_{PL,ev,t,s}^{ch-G2PL} \pi_t^{PL2EV} \right) + \left(\alpha P_{PL,ev,t,s}^{dch-PL2G} \pi_t^{PL2G} \right) \\ -\left(P_{PL,ev,t,s}^{ch-G2PL} \pi_t^{G2PL} \right) - \left(P_{PL,ev,t,s}^{dch-PL2G} C^{cd} \right) \end{pmatrix} \\ &+ \sum_{s=1}^{Ns} \rho_s \sum_{\substack{PL=1 \\ PL \neq PL'}}^{N_{PL}} \sum_{EV=1}^{N_{EV}} \sum_{t=1}^{24} \begin{pmatrix} \left(P_{PL,ev,t,s}^{ch-PL'2PL} \pi_t^{PL2EV} \right) + \left(\beta P_{PL',ev,t,s}^{dch-PL2PL'} \pi_t^{PL} \right) \\ -\left(P_{PL,ev,t,s}^{ch-PL'2PL} \pi_t^{PL} \right) - \left(P_{PL',ev,t,s}^{dch-PL2PL'} C^{cd} \right) \end{pmatrix} \end{aligned} \tag{7}$$

Here, the objective function must maximize the daily profit of each PLO. Hence, we will deal with several objective functions, so the simple additive weighting (SAW) method is used for converting it to a single-objective function. In this method, a weighted coefficient is assigned to each objective function. Therefore, the objective function is rewritten as (8).

$$\text{Maximize} \sum_{PL=1}^{N_{PL}} \text{Profit}_{PL} \times \omega_{PL} \tag{8}$$

ω_{PL} is the weighted coefficient that represents the relative importance of the objective functions so that the sum of them is equal to 1. Since none of the PL is preferable to the other, these coefficients allocated to each of the three PLOs will be 0.333.

The constraints for objective function (7) are described in (9) to (21). Of course, with regard to the objective function (4), the parameters or variables related to the discharging power to SDSO and charging/discharging power between PLOs must be ignored. Furthermore, based on objective function (5), one of them, i.e. charging/discharging power between PLOs must be eliminated.

According to (9) and (10), charged power and discharged power as well as charging/discharging efficiency, SOE of the EV in arrival time to PL and remained SOE from the previous hour are the main factor of the EV's SOE. Based on (11), EV's SOE has to remain between the minimum and maximum value.

(12) and (13) show that, for charging of each EV, PLOs purchase power from SDSO, and other PLOs. Also, each PLO sell discharging power of each EV to SDSO and other PLOs. These powers are limited between zero and nominal charging/discharging rated i.e. 10 kWh. The charge and discharge of EVs are not simultaneous.

Based on (14) to (19), hourly charging of each EV can be done either through the SDSO or through another PLOs, or both of them. Furthermore, the energy of each EV can be delivered to the SDSO or other PLOs, or both of them. As already stated, charging of EV through SDSO is carried out at the mid-peak or off-peak periods. Additionally, at the on-peak periods, the discharging power of EVs is also sold to SDSO. However, the power exchanged between PLOs is possible every period. Charging/discharging powers during each period are limited between zero and nominal charging/discharging rate. Eq. (20) indicates the discharging power of EVs in each PL is used for charging of EVs in other PLs. Finally, since each EV departs the PLs with the desired SOE, based on (21), the EV's SOE at the departure time has to reach this value.

$$SOE_{\mathrm{PL,ev,t,s}} = SOE_{\mathrm{PL,ev,t-1,s}} - \left(\frac{P^{dch}_{PL,ev,t,s}}{\eta^{dch}}\right) + \left(P^{ch}_{PL,ev,t,s}\right)\eta^{ch} \; : \forall PL, ev, t \succ t^{arv}, \mathrm{s} \tag{9}$$

$$SOE_{\mathrm{PL,ev,t,s}} = SOE^{\mathrm{arv}}_{\mathrm{PL,ev,t^{arv},s}} - \left(\frac{P^{dch}_{PL,ev,t,s}}{\eta^{dch}}\right) + \left(P^{ch}_{PL,ev,t,s}\right)\eta^{ch} \; : \forall PL, ev, t^{arv}, \mathrm{s} \tag{10}$$

$$SOE^{\min}_{PL,ev,t,s} \le SOE_{PL,ev,t,s} \le SOE^{\max}_{PL,ev,t,s} \; : \forall PL, ev, t, \mathrm{s} \tag{11}$$

$$0 \le P^{ch}_{PL,ev,t,s} = P^{ch-G2PL}_{PL,ev,t,s} + P^{ch-PL'2PL}_{PL,ev,t,s} \le X_{PL,ev,t,s} \times P^{\max} \; : \forall PL \ne PL', ev, t, \mathrm{s} \tag{12}$$

$$0 \le P^{dch}_{PL,ev,t,s} = P^{dch-PL2PL'}_{PL',ev,t,s} + P^{dch-PL2G}_{PL,ev,t,s} \le \left(1 - X_{PL,ev,t,s}\right) \times P^{\max} \; : \forall PL \ne PL', ev, t, \mathrm{s} \tag{13}$$

$$0 \le P^{ch-G2PL}_{PL,ev,t,s} \le P^{\max} \; : \forall PL, ev, t^{mid/off-peak}, \mathrm{s} \tag{14}$$

$$P^{ch-G2PL}_{PL,ev,t,s} = 0 \; : \forall PL, ev, t^{on-peak}, \mathrm{s} \tag{15}$$

$$0 \le P^{dch-PL2G}_{PL,ev,t,s} \le P^{\max} \; : \forall PL, ev, t^{on-peak}, \mathrm{s} \tag{16}$$

$$P^{dch-PL2G}_{PL,ev,t,s} = 0 \; : \forall PL, ev, t^{mid/off-peak}, \mathrm{s} \tag{17}$$

$$0 \le P^{ch-PL'2PL}_{PL,ev,t,s} \le P^{\max} \; : \forall PL \ne PL', ev, t, \mathrm{s} \tag{18}$$

$$0 \le P^{dch-PL2PL'}_{PL',ev,t,s} \le P^{\max} \; : \forall PL \ne PL', ev, t, \mathrm{s} \tag{19}$$

$$\sum_{ev} P^{dch-PL2PL'}_{PL',ev,t,s} = \sum_{ev} P^{ch-PL'2PL}_{PL,ev,t,s} \; : \forall PL \ne PL', t, \mathrm{s} \tag{20}$$

$$SOE_{PL,ev,t,s} = SOE^{\mathrm{dep}}_{\mathrm{PL,ev,t^{dep}}} \; : \forall PL, ev, t^{dep}, \mathrm{s} \tag{21}$$

4. Numerical results

For evaluation of the proposed model, three PLs are considered. The maximum capacity of each PL is 700 EVs. Moreover, the arrival/departure times of EVs to/from PLs and the initial SOE of each EV are considered as the uncertain parameters of PLs. For modeling of these uncertainties, the normal probability distribution function that is limited to the maximum and minimum values i.e. truncated Gaussian distribution function is used. Furthermore, the necessary data for modeling are shown in Table 1 [19]. Based on Table 1, the arrival/departure times of EVs in these three PLs in scenario 1 are illustrated in Figs. (3) and (4). In addition, Fig (5) shows the initial SOE of five typical EVs in scenario 1. The charge and discharge efficiency of EVs is 90% and 95%, respectively [19]. The charging/discharging rate is considered 10 kWh [19]. Forasmuch as the EVOs' satisfaction in the departure time from the PLs is very important, the desired SOE that the EVOs want at the arrival time to the PLs must be met. So, the desired SOE of each EV with considering the battery capacity of EVs, i.e. 32 kWh is 28.8 kWh (i.e. $0.9C_{batt}$) at the departure time. Each EV also charges or discharges up to 40 kWh, e.g. four times charging or discharging with maximum charging and discharging rates (10 kWh). The minimum and maximum values of SOE are $0.15C_{batt}$ and $0.9C_{batt}$, respectively. Moreover, α and β values are considered 0.5.

The charging of EVs through the SDSO occurs at the off-peak and mid-peak periods, i.e. (01:00-06:00, 20:00-24:00) and (07:00-11:00, 18:00-19:00) [20]. The discharging time of EVs for supplying the SDSO is done at the on-peak periods, i.e. 12:00-17:00. The charging tariffs for PLOs are 65 $/MWh, 94 $/MWh. Furthermore, the discharging tariff is 134 $/MWh. In the mode of energy exchanges between PLOs, the energy price is considered 94 $/MWh. It is assumed that the energy price to EVOs is 15% higher than these amounts. Also, the battery depreciation's cost is 20 $/MWh. The time interval is one hour.

Table 1. The modified probability distribution of EVs [19]

	Mean	Standard Deviation	Min			Max		
			PL 1	PL 2	PL 3	PL 1	PL 2	PL 3
Initial SOE(%)	50	25	30	35	45	60	55	65
Arrival Time (h)	8	3	6	7	6	9	10	11
Departure Time (h)	16	3	18	19	18	22	23	21

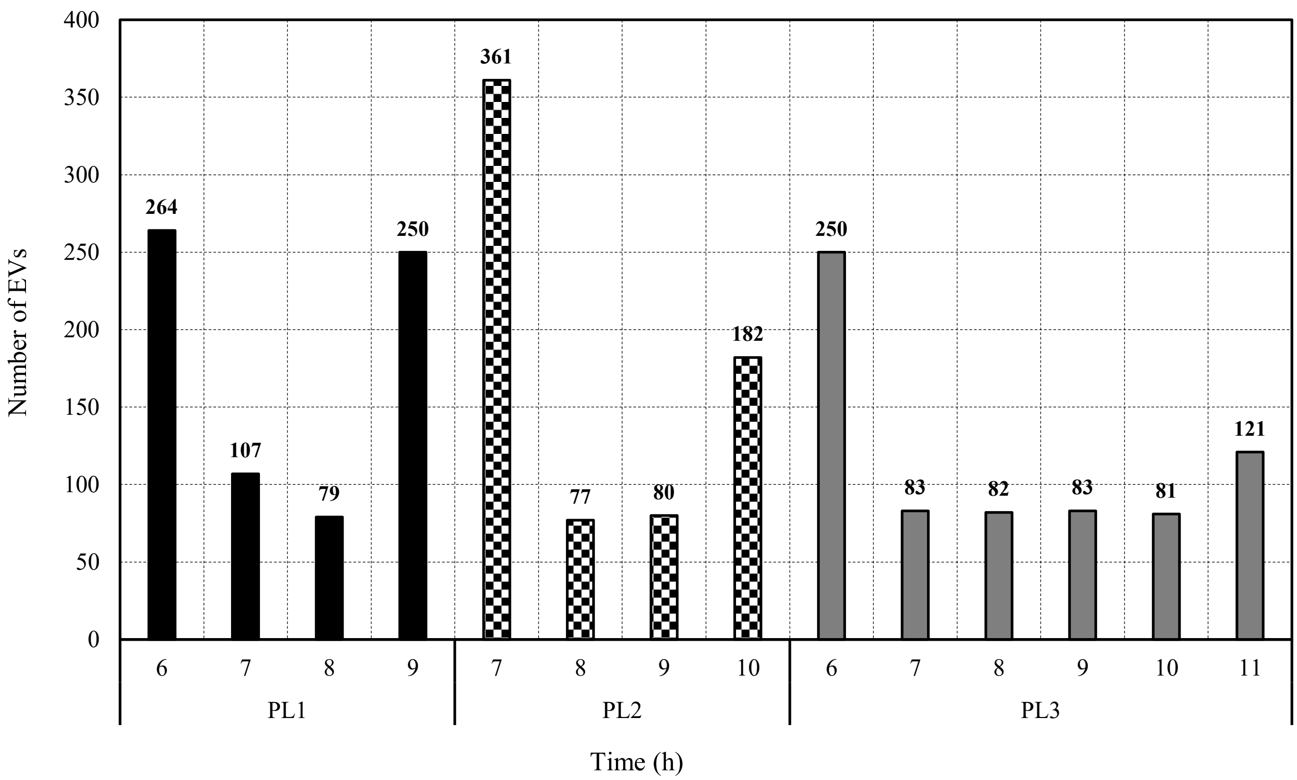

Fig. 3. The EVs' number at the arrival time to PLs

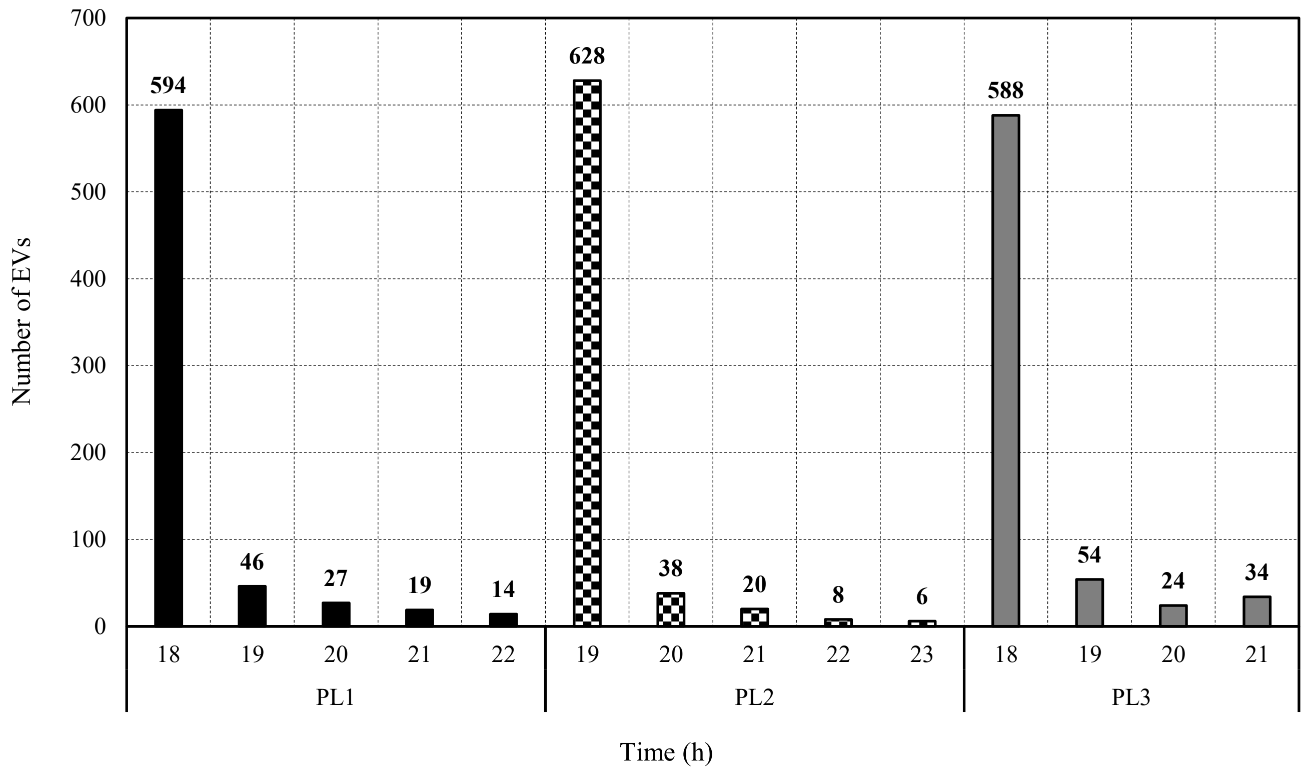

Fig. 4. The EVs' number at the departure time from PLs

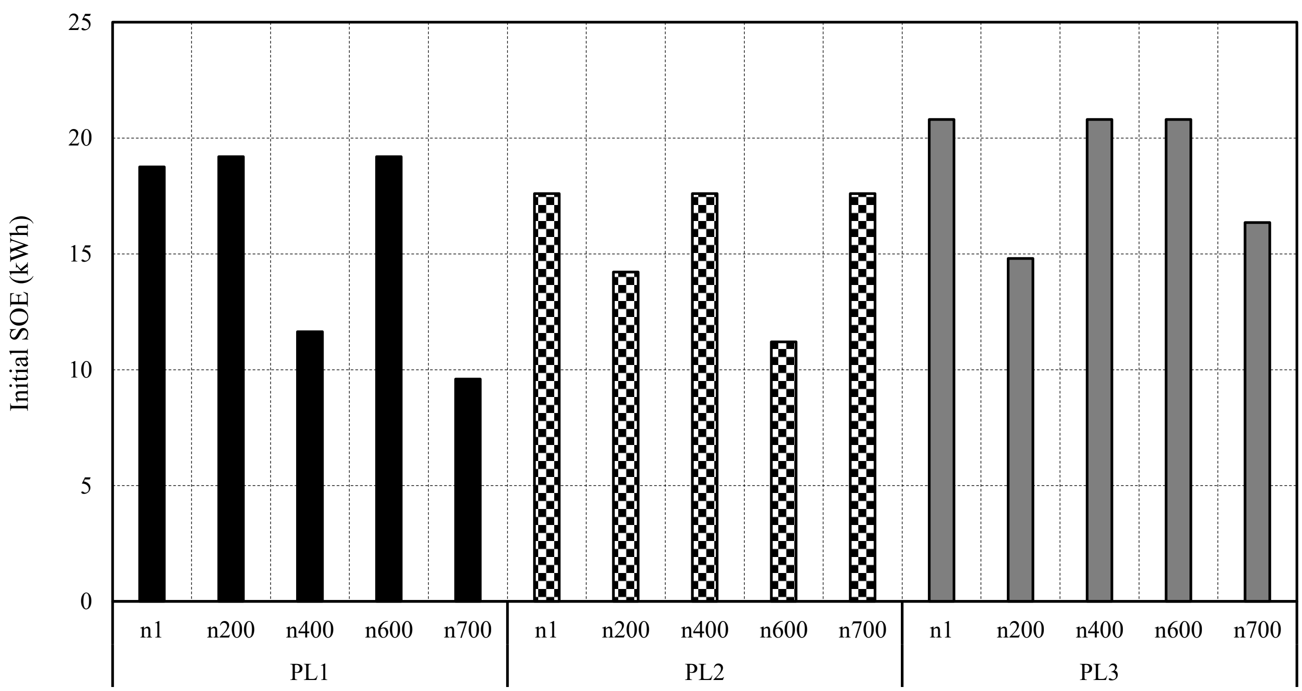

Fig. 5. The initial SOE of 5 typical EVs in PLs

In the following, the proposed formulation is investigated. For accurate exploring, three different modes are considered for each PLO. In each mode, the profit of PLOs as well as charging or discharging power and so forth. are evaluated. These modes are:

1. Controlled charging of EVs without the cooperation of PLOs
2. Charging/discharging schedule of EVs without the cooperation of PLOs
3. Charging/discharging schedule of EVs with the cooperation of PLOs

Since this problem has different uncertainties, stochastic programming is used for solving the objective function. The proposed model is a Mixed-Integer Linear Programming (MILP) problem. So, the simulations are done through the CPLEX solver in GAMS software.

4.1. Controlled charging of EVs without the cooperation of PLOs

In this case, PLOs receive energy for charging of EVs from the SDSO. The objective function, in this case, is according to Eqs. (4) and (8). Table (2) shows the profit of PLOs. This amount of profit is exactly related to the initial SOE and arrival/departure time of EVs to/from PL. In fact, if the initial SOE of EVs at the arrival times is high (e.g. PL 3), the lower energy needs for reaching the desired SOE at departure time, so less profit is obtained. Furthermore, Fig. (6) shows the EVs' charging power. The total amount of this power for PL 1, PL 2 and PL 3 is 10.658 MW, 10.858 MW, and 9.104 MW, respectively. The charging schedule is correctly done. That means EVs are charged at the off-peak or mid-peak periods. Of course, since the energy price at the off-peak periods, i.e. 6:00 and 20:00-24:00 is lower than the mid-peak periods, the EVs at these times are not charged. Inasmuch as purchasing energy at these times is led to less profit.

According to Fig. (4), the arrival time of EVs to PL 2 is 7:00. Also, at the early hours, i.e. 7:00 and 8:00, there are 361 and 438 EVs in PL 2. So the power purchased at these times is the highest. The arrival time of EVs to PL 1 and PL 3 is 6:00. At this time 264 and 250 EV arrives at PL 1 and PL 3, respectively. However, EVs are not charged at this time due to low energy prices. Therefore, these EVs are charged at other times. In PL 1, with arriving 250 EVs at 9:00, the PL's capacity is filled and so at this time a high amount of power is purchased. Also in PL 3, up to 9:00, there are 500 EVs, and at this time more power is purchased.

The departure time from PL 1 and PL 3 is 18:00 so that 594 and 588 EVs leave the PLs at this time. According to the satisfaction of the EVOs at the departure time, too much power is purchased at this time. At PL 2, the departure time is 19:00, and 628 EVs leave PL. So more purchasing power occurs at this time.

Table 2. Profit of PLOs in mode 1 ($)

Number of PL	PL 1	PL 2	PL 3
Revenue from energy sold to EVOs	1152.220	1173.770	984.157
Cost of energy purchased from SDSO	1001.931	1020.670	855.789
Profit	150.289	153.100	128.368

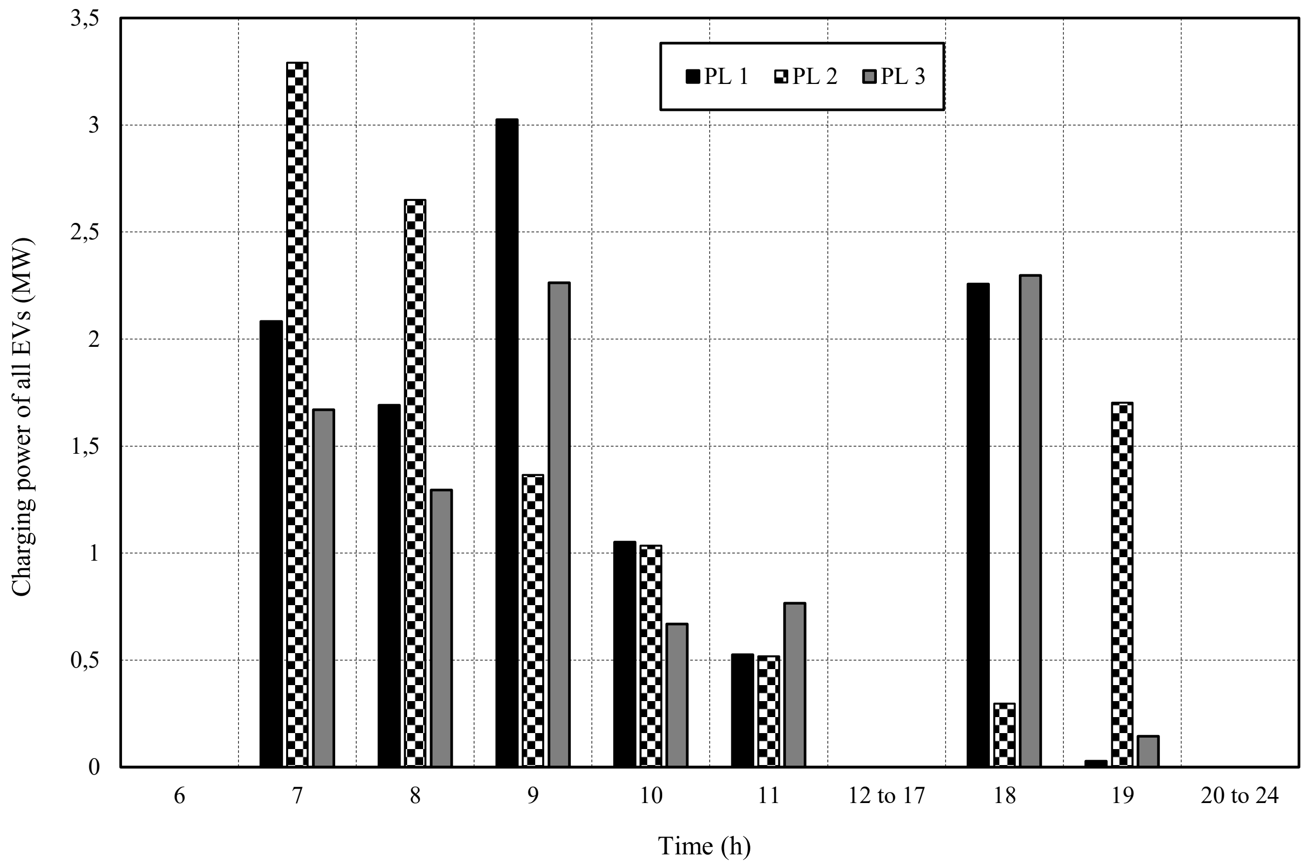

Fig. 6. Charging power of all EVs in PLs (mode 1)

4.2. **Charging/discharging schedule of EVs without the cooperation of PLOs**

These days EVs due to V2G ability have the main role in the operation and planning of SDS. So, returning discharging energy to the grid leads to reducing cost, minimization of network losses, improving voltage profile and providing ancillary services such as regulation and operating reserve, and so on. Therefore, in this section, mode 2 is considered, i.e. charging/discharging schedule of EVs. This mode shows that not only has good effects on SDS but also the PLOs achieve more profit. First of all, Table (3) shows the profit of PLOs. Based on this table and comparison with Table (2), PLOs get more profit between four to six times. In the following, causing the rising profit of PLOs is investigated.

Table 3. Profit of PLOs in mode 2 ($)

No. of PL	PL 1	PL 2	PL 3
Revenue from energy sold to EVOs	2041.447	2707.082	1846.437
0.5 × Revenue from energy sold to SDSO	475.857	817.249	463.163
Cost of energy purchased from SDSO	1775.172	2353.985	1605.597
Cost of battery depreciation	142.046	243.955	138.257
Profit	600.086	926.392	565.745

Figs. (7) and (8) show the EVs' charging/discharging power. The total amount of charging power for PL 1, PL 2 and PL 3 is 18.965 MW, 25.124 MW, and 17.189 MW, respectively. Also, power discharged of all EVs for these PLOs is 7.102 MW, 12.197 MW, and 6.912 MW, respectively. According to these Figs, in this mode, firstly, EVs are charged. Then, all EVs are participated in the V2G program and are discharged at the on-peak periods. Finally, at the departure time and according to the satisfaction of the EVOs, EVs charge again. As motioned in the previous section, a large percentage of PL capacity is filled up to 9:00. (Of course, in the PL 1, 100% capacity will be filled). Therefore, high power at the first mid-peak periods is purchased from SDSO. On the other hand, the departure time of EVs from the PL 2 is at 19:00, and from the PL 1&3 is at 18:00. This means that if EVs are participated in V2G program, in the PL 2 at 18:00 and 19:00, all EVs could fully charge, and this case could occur in the PL 1&3 at 18:00. So all EVs in PL 2 and PL 1&3 could discharge at least two times and once, respectively. Thus, the PLO 2 could sell more power to the SDSO. The purchasing power of PLO 2 from the SDSO at 18:00 and 19:00 is exactly 7 MW (700 EVs are charged with full charging rate, i.e. 10 kWh), and this power in PL 1&3 at 18:00 is also 7 MW (i.e. two times and once discharging of each EV). Moreover, in the remaining second mid-peak periods, due to the low number of EVs, less power is purchased from the SDSO.

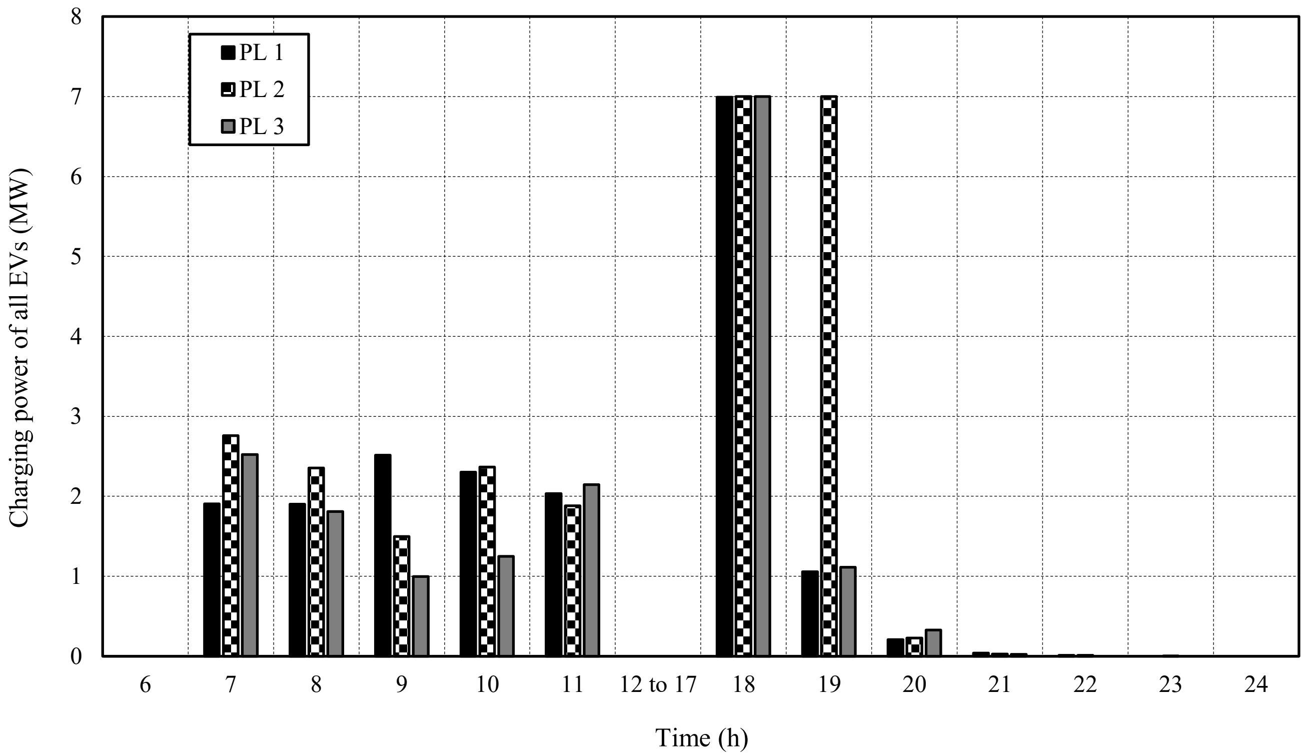

Fig. 7. Charging power of all EVs in PLs (mode 2)

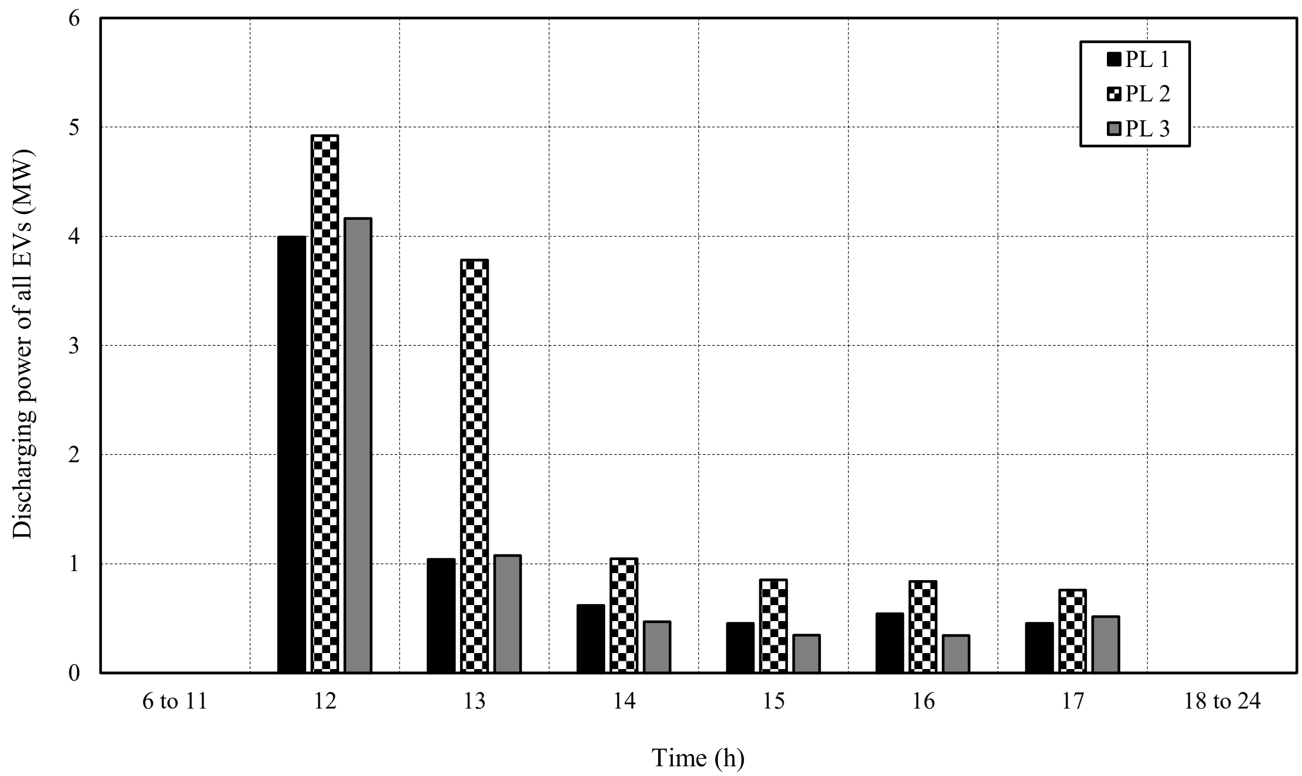

Fig. 8. Discharging power of all EVs in PLs (mode 2)

4.3. Charging/discharging schedule of EVs with the cooperation of PLOs

In this section, in addition to interacting PLOs with the SDSO, the interaction between PLOs is intended to increase the PLOs' profit. In fact, in this case, the PLOs are trading energy together. It can be seen that the characteristics of PLs such as the arrival/departure time of EVs to/from PL and initial SOE of EVs are very effective in increasing this profit. Firstly, Tables (4) to (6) show the profit of PLOs.

Table 4. Profit of the first PLO in mode 3 ($)

No. of PL	PL 1
Revenue from energy sold to EVOs by SDSO	2000.401
Revenue from energy sold to EVOs by PL 2	238.912
Revenue from energy sold to EVOs by PLO 3	682.893
0.5 × Revenue from energy sold to SDSO	453.208
0.5 × Revenue from energy sold to PLO 2	202.727
0.5 × Revenue from energy sold to PLO 3	140.481
Cost of energy purchased from SDSO	1739.480
Cost of energy purchased from PLO 2	207.750
Cost of energy purchased from PLO 3	593.820
Cost of battery depreciation due to energy sold to SDSO	135.286
Cost of battery depreciation due to energy sold to PLO 2	86.267
Cost of battery depreciation due to energy sold to PLO 3	59.779
Profit	896.242

Table 5. Profit of the second PLO in mode 3 ($)

No. of PL	PL 2
Revenue from energy sold to EVOs by SDSO energy	2386.950
Revenue from energy sold to EVOs by PLO 1	466.274
Revenue from energy sold to EVOs by PLO 3	123.650
0.5 × Revenue from energy sold to SDSO	699.278
0.5 × Revenue from energy sold to PLO 1	103.875
0.5 × Revenue from energy sold to PLO 3	79.173
Cost of energy purchased from SDSO	2075.610
Cost of energy purchased from PLO 1	405.456
Cost of energy purchased from PLO 3	107.522
Cost of battery depreciation due to energy sold to SDSO	208.740
Cost of battery depreciation due to energy sold to PLO 1	44.202
Cost of battery depreciation due to energy sold to PLO 3	33.691
Profit	983.982

Table 6. Profit of the third PLO in mode 3 ($)

No. of PL	PL 3
Revenue from energy sold to EVOs by SDSO energy	2393.397
Revenue from energy sold to EVOs by PLO 1	323.107
Revenue from energy sold to EVOs by PLO 2	182.100
0.5 × Revenue from energy sold to SDSO	520.971
0.5 × Revenue from energy sold to PLO 1	296.910
0.5 × Revenue from energy sold to PLO 2	53.760
Cost of energy purchased from SDSO	2081.215
Cost of energy purchased from PLO 1	280.963
Cost of energy purchased from PLO 2	158.347
Cost of battery depreciation due to energy sold to SDSO	155.514
Cost of battery depreciation due to energy sold to PLO 1	126.345
Cost of battery depreciation due to energy sold to PLO 2	22.877
Profit	944.985

Tables (7) and (8) show the trading charging/discharging power of a PLO with SDSO and other PLOs. based on these Tables; the discharging power of a PL is used for charging of EVs in other PLs, e.g. discharging power of PL 2 to PL 1 is equal to the charging power of PL 1 from PL 2, etc.

Table 7. charging power of PLOs in mode 3 (MW)

NO. of PL	From SDSO	From PLO 1	From PLO 2	From PLO 3
PLO 1	18.583	-	2.210	6.317
PLO 2	22.163	4.313	-	1.143
PLO 3	22.251	2.988	1.684	-

Table 8. discharging power of PLOs in mode 3 (MW)

NO. of PL	To SDSO	To PLO 1	To PLO 2	To PLO 3
PLO 1	6.764	-	4.313	2.988
PLO 2	10.436	2.210	-	1.684
PLO 3	7.775	6.317	1.143	-

Figs. (9) to (11) show the EVs' charging power. The total amount of charging power for PLO 1, PLO 2 and PLO 3 is 27.111 MW, 27.620 MW, and 26.924 MW, respectively. Also, Figs. (12) to (14) show the entire discharging power of all EVs. The amount of this power is 14.066 MW, 14.331 MW and 15.236 MW for three PLOs, respectively.

Based on these Figs, due to the arrival time of EVs to PLs 1&3 is 06:00, so at this hour, energy exchanged begins between the two PLs but in PL 2 the trading energy with PLs 1&3 commence at 07:00. This energy exchanged between PLOs continues until 10:00. At 11:00, there is no exchange between PLOs, and PLOs purchase more energy from SDSO for charging of EVs because at 12:00 (on-peak hours), selling energy to the SDSO begins. The energy exchanged between PLOs is also continued at the on-peak periods. Of course, since the price of energy sold to SDSO at these times is higher than the price of energy exchanged between PLO, the exchanging power between the PLOs at this time is low. Also as stated, in PL 2, EVs could charge at 18:00 and 19:00, so this PLO prefers to exchange more power with SDSO. In fact, due to the characteristics of the PL 2 (especially the appropriate time for recharging of EVs after participating in the V2G program), there is less willingness to exchange energy with other PLO (also see Tables (7) and (8)). For this reason, in this mode, increasing profit of PLO 2 is the lowest. The charging power of EVs after 18:00 is the same as mode 2.

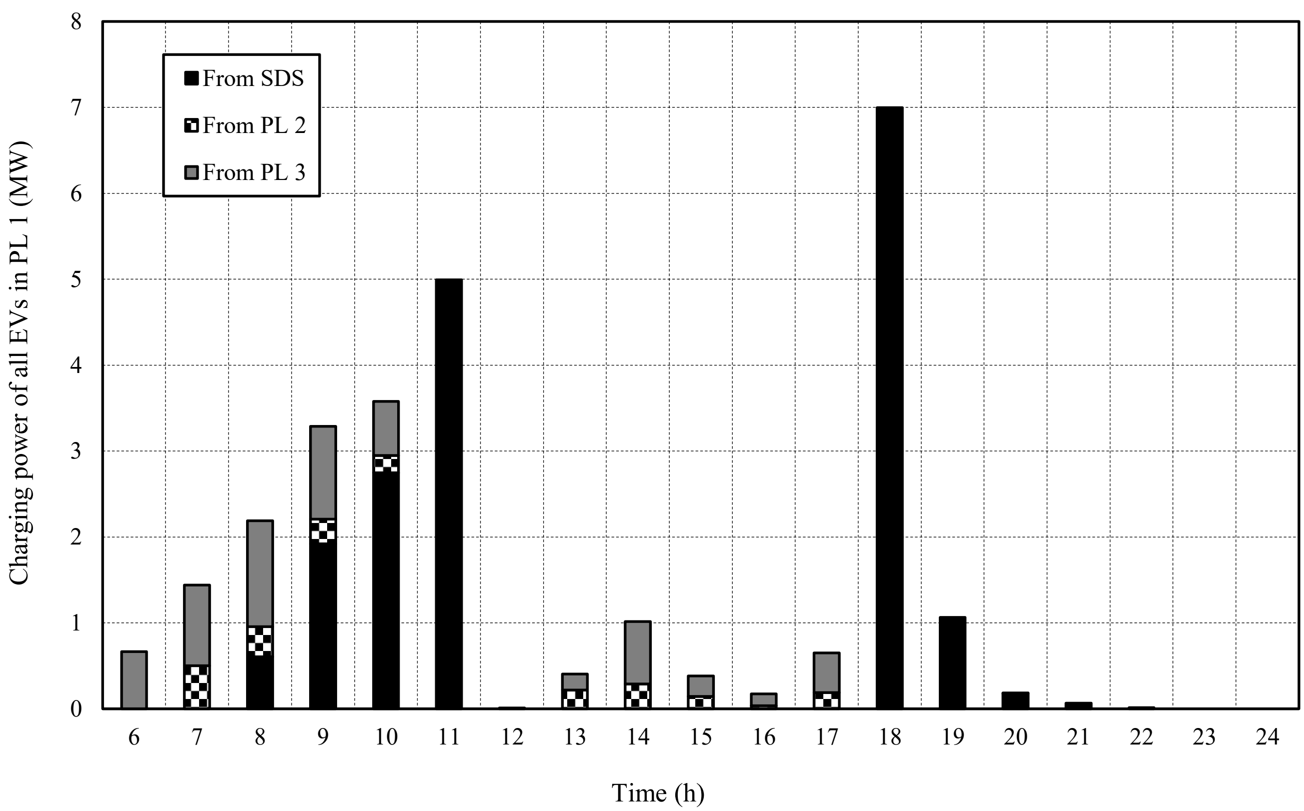

Fig. 9. Charging power of all EVs in PL 1 from SDSO and PL 2&3

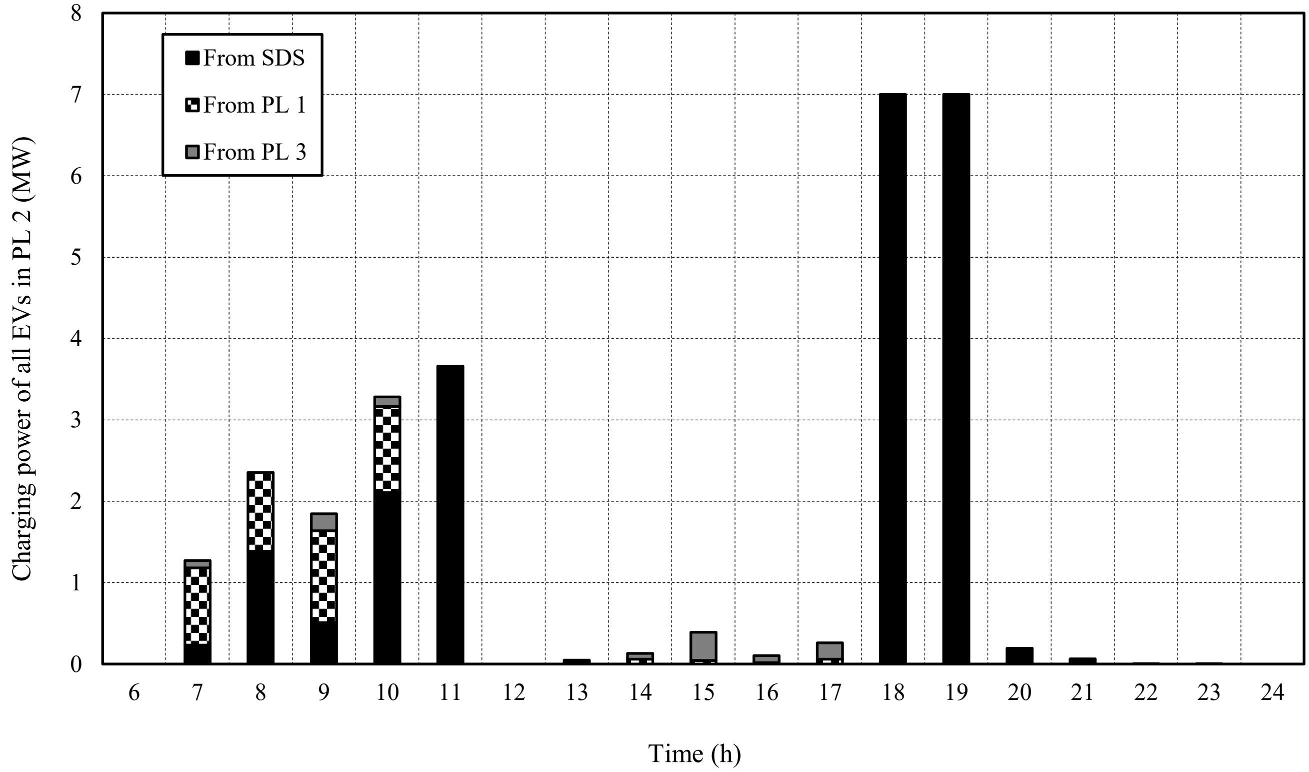

Fig. 10. Charging power of all EVs in PL 2 from SDSO and PL 1&3

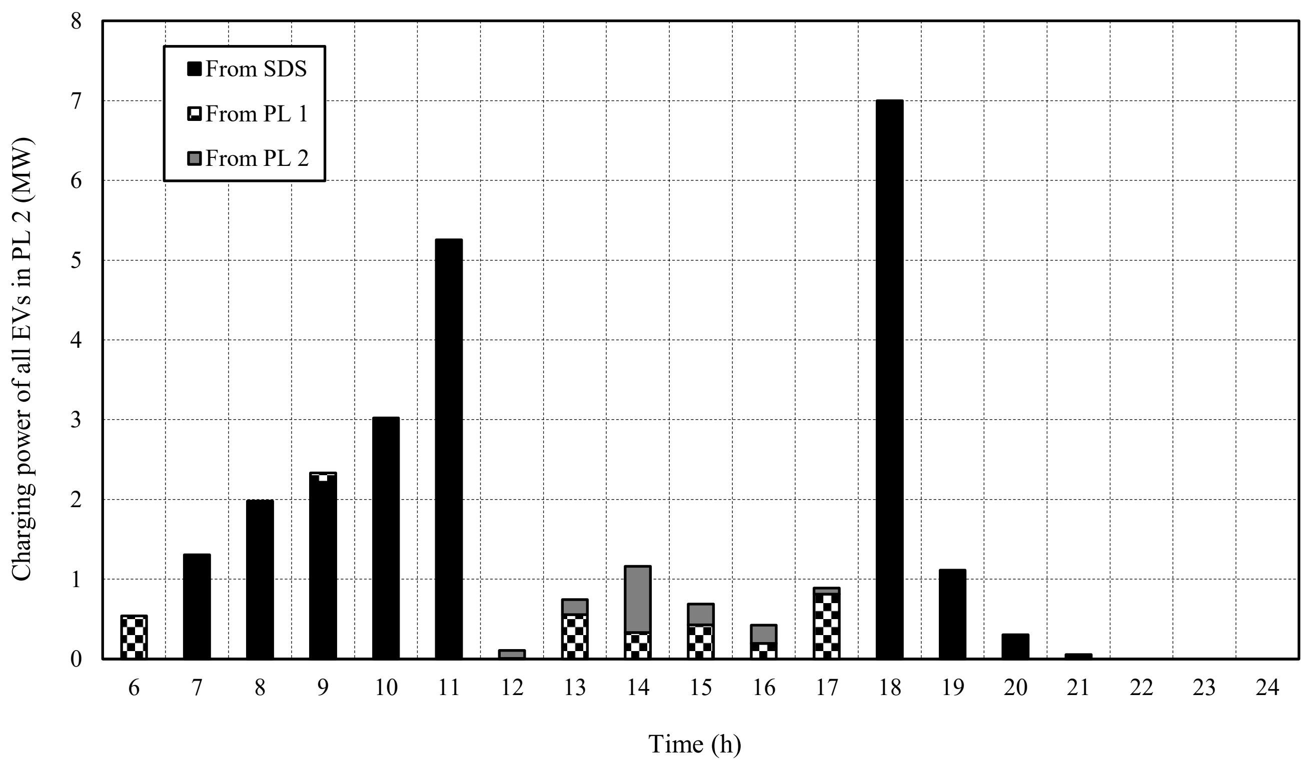

Fig. 11. Charging power of all EVs in PL 3 from SDSO and PL 1&2

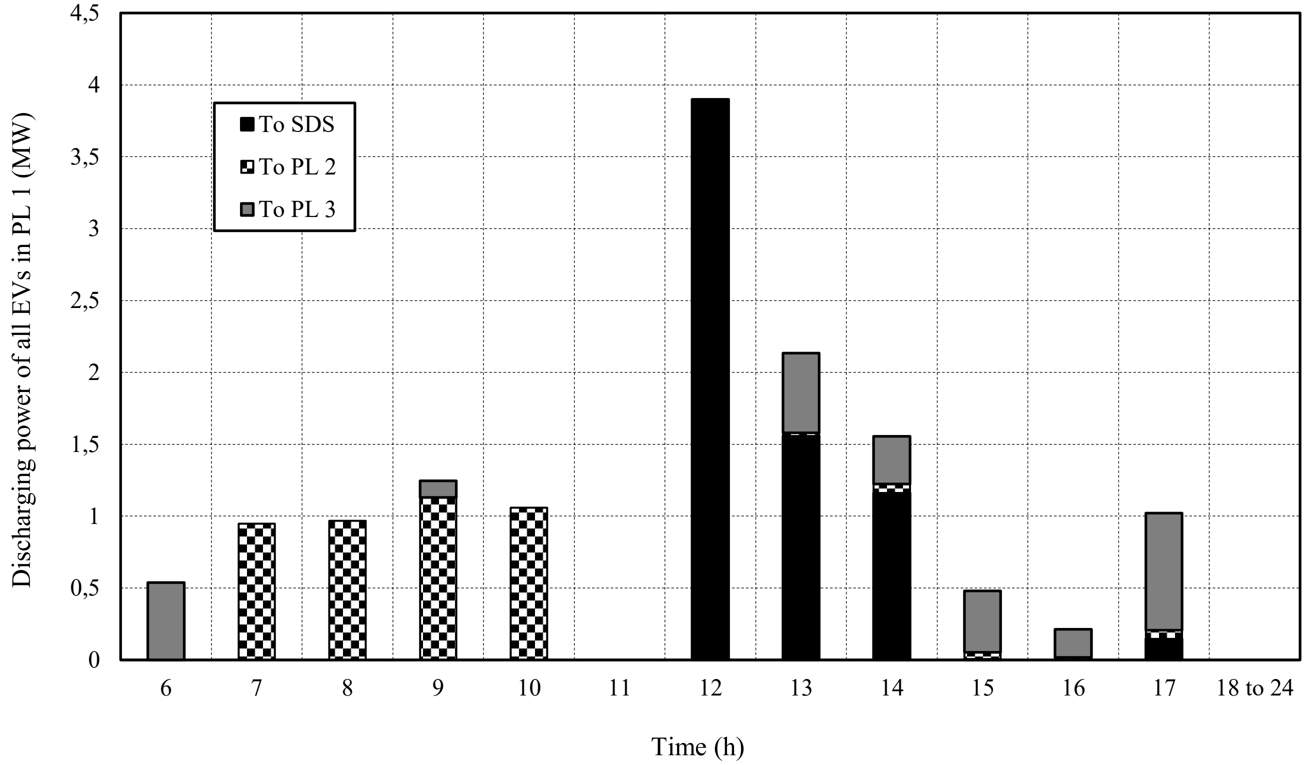

Fig. 12. Discharging power of all EVs in PL 1 to SDSO and PL 2&3

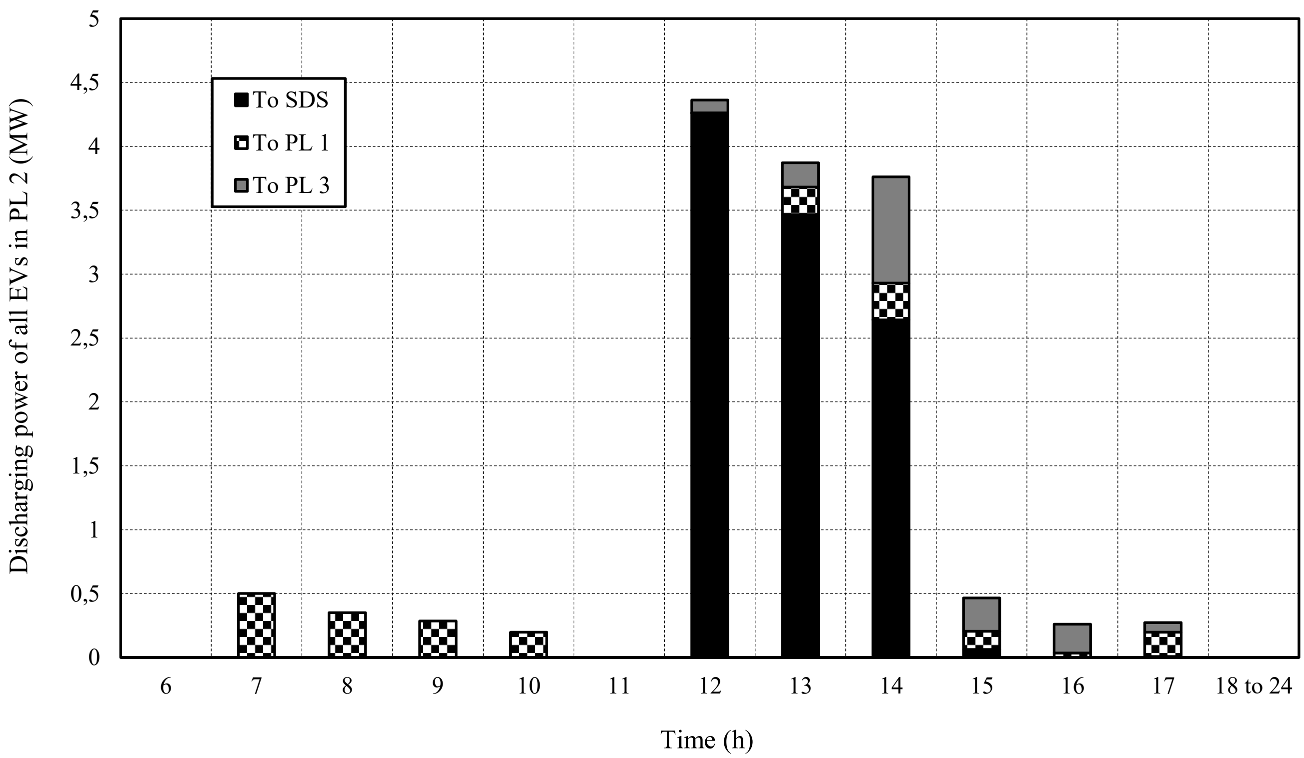

Fig. 13. Discharging power of all EVs in PL 2 to SDSO and PL 1&3

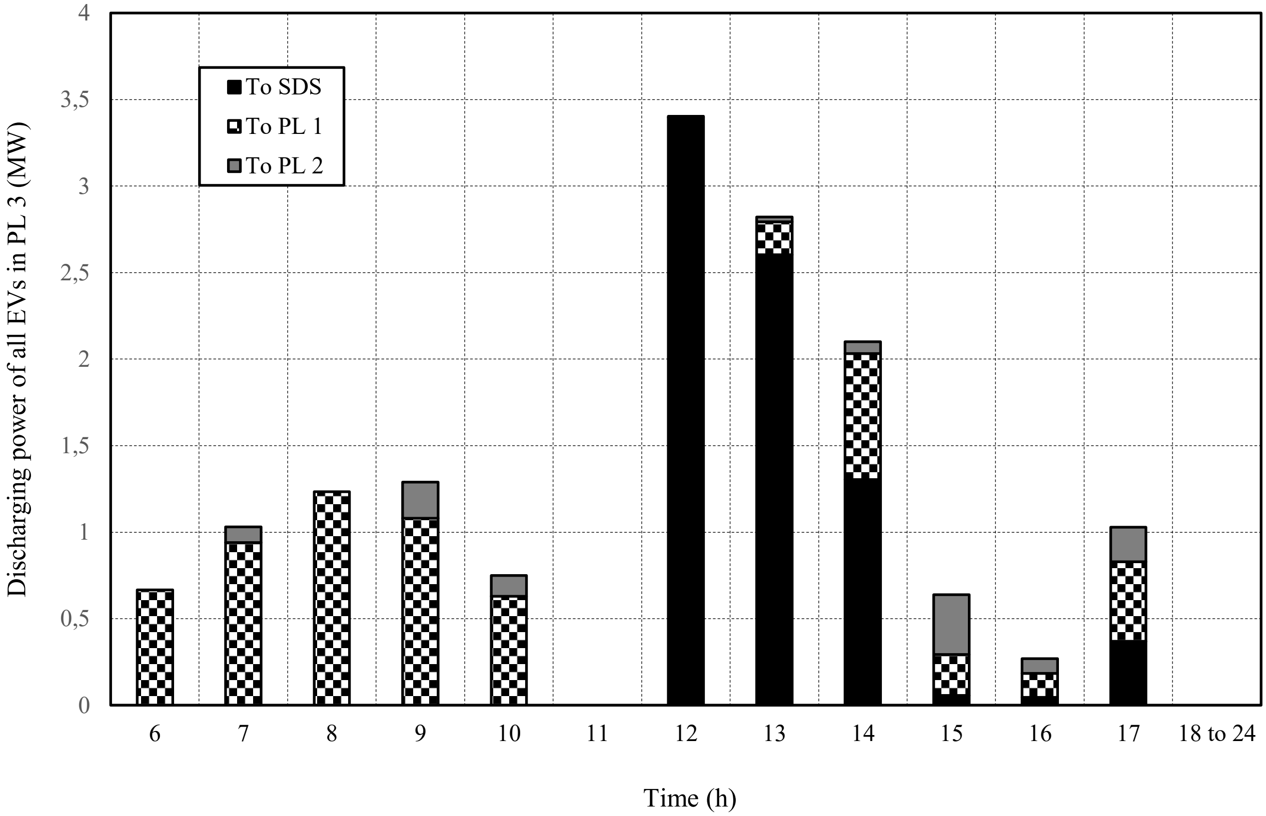

Fig. 14. Discharging power of all EVs in PL 3 to SDSO and PL 1&2

The sensitivity analysis is also done to further examine the affecting factors on PLOs' profit. Based on Fig. 15, since the third mode brings the most benefit to PLOs, sensitivity analysis is performed on this mode.

First, with changing the energy price between PLO (between the price of the mid-peak and the off-peak periods), these profits are evaluated. Fig. (16) shows the results of these changes. According to this Fig., as the price increases, the profit also increases. At low prices, the profit of PLO 1&3 is higher than the mode 2, but in the PL 2, the increasing profit (because of unwillingness to trading energy with other PLOs) is negligible and about 1 $.

The next important factor is the maximum charging/discharging power of each EV. Fig. (17) shows the results of this changing. By reducing/increasing the amount of charging/discharging power, PLOs are less/more participated in the PL2PL and PL2G programs. So, PLOs sell less/more energy to the SDSO and other PLOs; therefore, their profits reduce/increase.

The power purchased from the SDSO by the PLOs for charging of EVs is also one of the main factors. Fig. (18) shows the results of this changing. Definitely, by reducing this amount, less power is available to the charging of EVs, so PLOs less participate in PL2PL and PL2G programs, thus the PLOs achieve less profit. With increasing this power, PLOs' profit also increases.

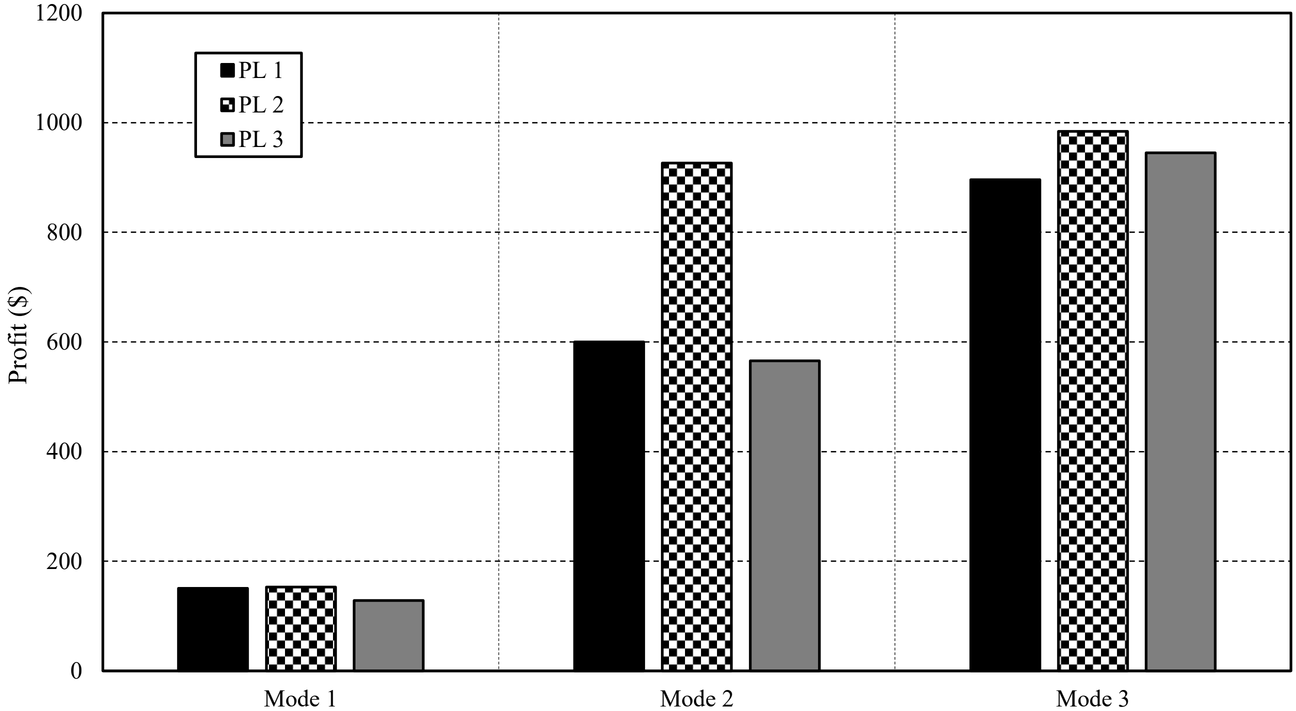

Fig. 15. Comparison of PLOs' profit in three modes

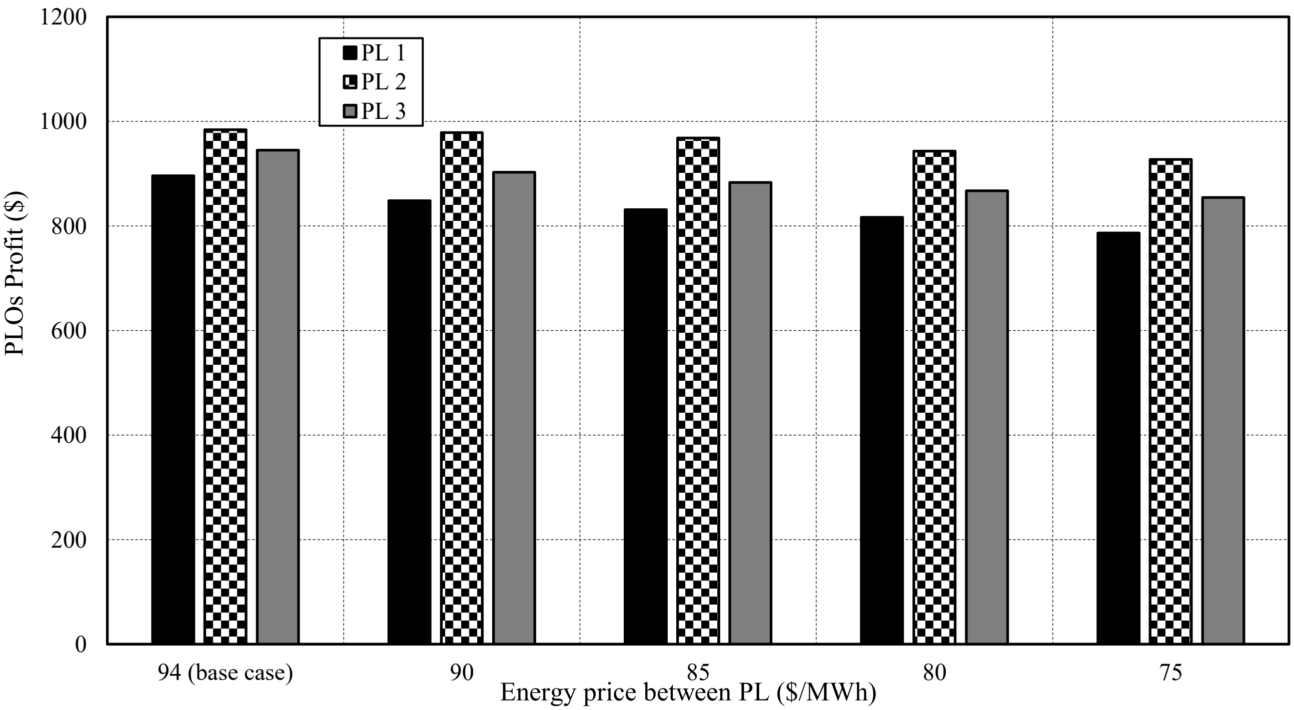

Fig.16. Effect of energy price between PLO on PLOs' profit

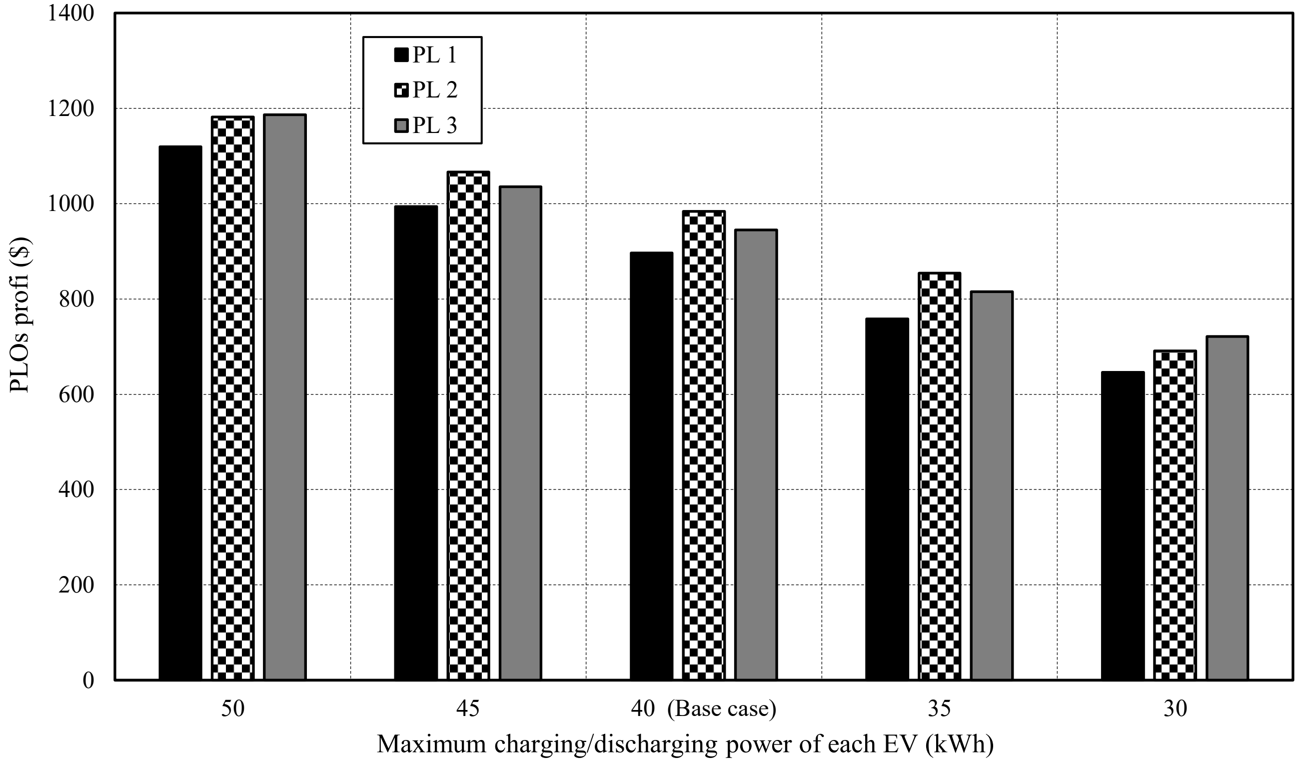

Fig 17. Effect of maximum charging/discharging power of each EV on PLOs' profit

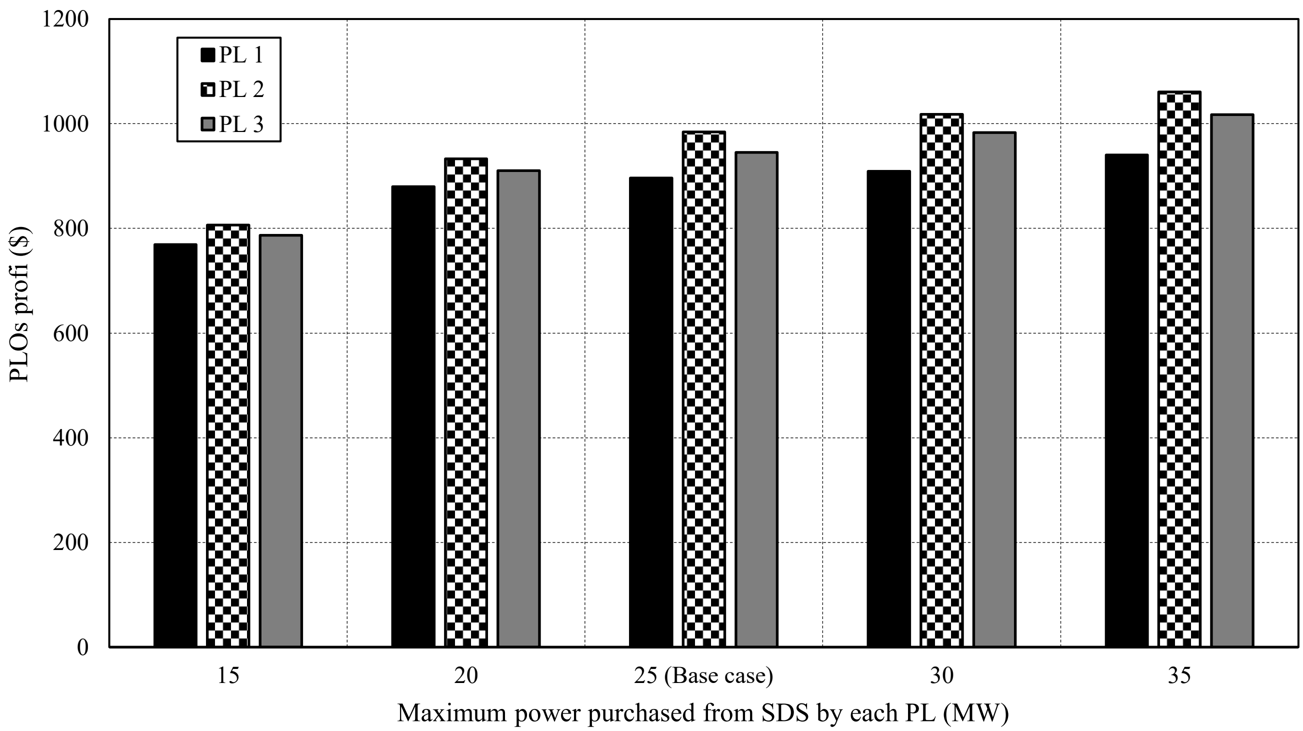

Fig 18. Effect of maximum power purchased from SDSO on PLOs' profit

5. Conclusion

In this paper, firstly, the uncertainty of each EV was modeled. Then, in three modes, i.e. mode 1) controlled charging of EVs without the cooperation of the parking lots, mode 2) charging/discharging schedule of EVs without the cooperation of parking lot s and mode 3) charging/discharging schedule of EVs with the cooperation of PLOs, the PLOs' behavior was modeled for optimal operation and increasing the profit. The results were demonstrated that in mode 3, the PLO could obtain more profit. Of course, the main feature of EVs, such as the stay duration in the parking lots as well as the initial state of energy, had an important effect on the increasing the profit compared to the mode 1 and mode 2, so that the second PLO due to these properties was less participated to PL2PL program and gained fewer profits. The sensitivity analysis also was done by changing the price of energy between PLOs, the amount of EVs' charging/discharging power as well as the amount of energy purchased from the SDSO. These factors were shown that directly impact on the increase of the PLOs' profit.

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