Optimal Planning of PEV Charging Station With Single Output Multiple Cables Charging Spots

Hongcai Zhang, *Student Member, IEEE*, Zechun Hu, *Member, IEEE*,
Zhiwei Xu, *Student Member, IEEE*, and Yonghua Song, *Fellow, IEEE*

***Abstract*—Coordinated charging can alter the profile of plug-in electric vehicle charging load and reduce the required amount of charging spots by encouraging customers to use charging spots at off-peak hours. Therefore, real-time coordinated charging should be considered at the planning stage. To enhance charging station's utilization and save corresponding investment costs by incorporating coordinated charging, a new charging spot model, namely single output multiple cables charging spot (SOMC spot), is designed in this paper. A two-stage stochastic programming model is developed for planning a public parking lot charging station equipped with SOMC spots. The first stage of the programming model is planning of SOMC spots and its objective is to obtain an optimal configuration of the charging station to minimize the station's equivalent annual costs, including investment and operation costs. The second stage of the programming model involves a probabilistic simulation procedure, in which coordinated charging is simulated, so that the influence of coordinated charging on the planning is considered. A case study of a residential parking lot charging station verifies the effectiveness of the proposed planning model. And the proposed coordinated charging for SOMC spots shows great potential in saving equivalent annual costs for providing charging services.**

***Index Terms*—Plug-in electric vehicle, charging facility planning, single output multiple cables charging spot, coordinated charging.**

NOMENCLATURE

Definitions/Abbreviations

PEV	Plug-in electric vehicle
SOSC	Single output single cable charging
MOMC	Multiple outputs multiple cables charging
SOMC	Single output multiple cables charging
HIES	Hybrid Integer Evolution Strategy
SoC	State of charge of PEV/battery

Indices/Sets

ω/Ω	Index/set of scenarios
n	Index of charging spots
c	Index of charging cables at a spot
t	Index of time intervals in a day
i/I	Index/set of PEVs
I_n	Set of PEVs connected to charging spot n

Parameters

π_ω	Probability of occurrence of scenario ω
Δt	Duration of each sub-hourly interval, 15 minutes
r	Discount rate
m	Service life of the charging spot, in year
$cost^{\mathrm{s}}$	Investment cost per charging spot ($)
$cost^{\mathrm{c}}$	Investment cost per charging cable of a spot ($)
T_t^{e}	Time-of-Use electricity tariff during t ($/kWh)
T^{pe}	Penalty for unsatisfied charging demands ($/kWh)
B_i	Battery size of PEV i (kWh)
E_i	Energy consumption per kilometer of PEV i (kWh/km)
P^{ra}	Rated charging power of a charging spot (kW)
$P^{\max}$	Upper limit of the charging power of a station (kW)
η	Charging efficiency
$t_i^{\mathrm{a/(d)}}$	Arrival/(expected departure) time of PEV i
$SoC_i^{\mathrm{a/(d)}}$	Arrival/(required departure) SoC of PEV i
SoC_i^{p}	The present SoC of PEV i at real-time
$S_{i,t}^{\mathrm{park}}$	Parking status of PEV i during t, $S_{i,t}^{\mathrm{park}} = 1$, if i is parking in the charging station; $S_{i,t}^{\mathrm{park}} = 0$, otherwise
d_i	Daily drive range of PEV i (km)

Variables

N	Number of charging spots in the targeted charging station
C	Number of charging cables of each charging spot
$P_i(t)$	Charging power of PEV i during time interval t (kW)
E_i^{loss}	Unsatisfied charging power of PEV i (kWh)
$S_{n,i,t}^{\mathrm{charge}}$	Charging status of PEV i with spot n during t, $S_{n,i,t}^{\mathrm{charge}} = 1$, if it is getting charged via spot n; $S_{n,i,t}^{\mathrm{charge}} = 0$, otherwise.

I. INTRODUCTION

As a cleaner method of transportation with less emission and energy consumption, PEVs have drawn much attention around the world [1]. Although governments, automobile companies, energy corporations, etc. have taken great

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The authors are with the Department of Electrical Engineering, Tsinghua University, Beijing 100084, China (e-mail: zechhu@tsinghua.edu.cn).

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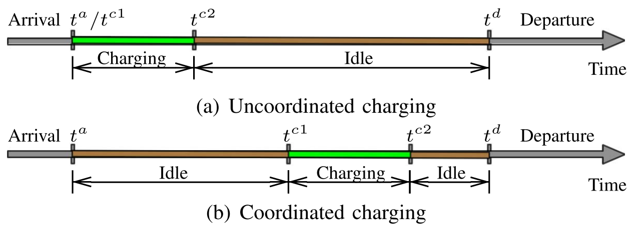

Fig. 1. A PEV's parking and charging processes in a public parking lot.

efforts to promote PEVs, there remains a large gap between current and expected PEV development since 2008 across the world [2], [3]. The inconvenience of recharging is one of the major hurdles for PEVs. Therefore, properly planned and economical infrastructure for PEV charging will bolster their market acceptance.

PEV charging can be divided into two types:

1) Destination charging. PEV charging at its destination, including home, workplace, etc.;
2) Urgent charging. Charging the PEV while still on the road once its *SoC* decreases to a certain threshold.

Destination charging needs are largely satisfied by parking lot charging stations/spots with low or normal power chargers, whereas urgent charging needs must be satisfied by fast charging stations. In recent years, parking lot and fast-charging stations or spots have experienced heavy investment [4], [5]. However, this is far from enough for the rapidly growing PEV fleet. Furthermore, improper planning has resulted in inconvenient recharging options for PEVs and under-utilization of high cost charging facilities, with consequential disappointing profitability for charging stations [5], [6].

Driven by the urgent need to satisfy growing PEV charging demands and promote development of the PEV industry, planning for PEV charging facilities has become an important research focus. Appropriate planning methods can enhance the utilization of charging facilities and reduce corresponding investment costs. Integration of renewable resources [15] or network constraints [11], [13], [14] in the planning can also help reduce operation costs, e.g., power losses.

Generally, charging station operators (particularly parking lot stations) adopt coordinated charging strategies to reduce operation costs under time-of-use or real-time electricity tariff conditions [20]–[26]. Two typical destination parking and charging processes (uncoordinated and coordinated) for PEVs are shown in Fig. 1, in which the intended parking time ($t^d - t^a$) is longer than the required charging time ($t^{c2} - t^{c1}$). Note that we only consider unidirectional grid-to-vehicle scenario in this paper, so that during the periods that the PEV is not charged (t^{c2} to t^d in Fig. 1, or t^a to t^{c1} and t^{c2} to t^d in Fig. 1), the charging spot stays idle. In vehicle-to-grid scenario, a PEV can also discharge to the grid with its battery energy during the idle period of its stay in Fig. 1.

Since coordinated charging alters the PEV charging load profile, it can also influence charging station planning. Besides, the required number of charging spots can be reduced if the charging spot occupied by one PEV can be shared during its idle time when the first PEV is fully recharged or postpones its charging duration. Therefore, if the coordinated charging could also consider scheduling of the connecting and charging relationships between PEVs and spots, the charging stations may realize their full charging potential and investment costs will be significantly reduced.

There are a few published papers that have investigated the potential of incorporating coordinated charging to enhance the utilization of charging facilities. In [18], the authors found public charging stations will be underutilized significantly without adequate coordinated charging strategies (a spot's service ability may be wasted during its idle time shown in Fig. 1). In [19], the authors introduced a *SoC* threshold-based admission control policy to prevent PEVs with high *SoC* to use the charging facilities and therefore reduce the idle time of charging facilities. One disadvantage of this approach is that refusing to provide services for some PEVs deliberately may decrease customer satisfaction. Besides, providing services for PEVs with low *SoC* but much longer parking time than the required charging time will still waste the charging ability inevitably.

Based on the above analysis, coordinated charging may significantly influence the PEV charging facility planning. However, to the best of our knowledge, there is no published literature on PEV charging facility planning that has taken coordinated charging into consideration.

In [7], the PEV charging facilities were planned based on the number of petrol stations and parking spaces. In [8]–[12], the optimal siting and sizing problem of PEV charging stations was studied and various planning strategies were proposed, in which the PEV charging loads were all assumed to be constant and proportional to PEV penetration. In [13], a multi-objective PEV charging station planning model considering traffic constraints was proposed. Reference [14] studied the coordinated planning for the integrated power distribution network and PEV charging systems. References [13] and [14] both assumed PEV charging demands to be proportional to the traffic flow which was modeled as poisson distribution. Reference [15] discussed the technical design criteria for fast-charging infrastructure. In [16], the planning of highway DC fast-charging stations was investigated. In [17], an integrated planning framework for various types of charging facilities was developed and the substitution effect between them was analyzed. References [15]–[17] all utilized uncoordinated charging loads obtained by mobility behavior simulation models based on statistical transport data.

We study the PEV charging station planning problem considering coordinated charging. And we seek to incorporate coordinated charging to enhance the utilization of charging facilities and therefore save investment and operation costs at the planning stage. Compared with published papers on similar topics, the major contributions are summarized as follows.

1) We propose SOMC spots, a novel type of PEV charging spot which can take the advantage of coordinated charging to enhance utilization and reduce investment costs. Compared with [19], utilizing SOMC spots can guarantee higher customer satisfaction that even PEVs with high *SoC* can get served. To the best of our knowledge,

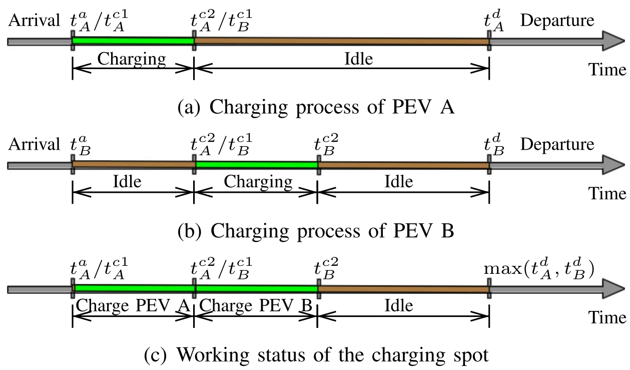

Fig. 2. A schematic diagram of two PEVs sharing one charging spot.

there are no published works that have proposed SOMC spots;

2) We construct a two-stage stochastic programming model to optimize the configuration of SOMC spots in a public parking lot charging station incorporating coordinated charging. Unlike the works introduced in [7]–[17], a probabilistic cost simulation procedure, in which coordinated charging is simulated, is involved at the second stage. So that the influence of coordinated charging is considered;
3) The unique characteristics of the SOMC spot require a new coordinated charging strategy. We propose a two-step heuristic strategy for SOMC stations that not only schedules the charging process of each PEV but also determines which charging spot each PEV should be recharged from. The coordinated charging strategy also serves as the second stage simulation algorithm for the planning model.

The SOMC spot is introduced in Section II. In Section III, the planning model for an SOMC station is formulated, and the coordinated charging strategy is introduced. Section IV shows case studies to verify the effectiveness of the proposed planning methodology, and Section V concludes.

II. Comparison of Three Kinds of Charging Spots

In this section, the traditional types of charging spots, i.e., the SOSC spot and the MOMC spot, are reviewed and the new type of charging spot, i.e., the SOMC spot, is proposed, which can take the advantage of coordinated charging to enhance utilization by enabling several PEVs to share a single charging spot for destination charging demands. A schematic diagram of two PEVs sharing one spot is shown in Fig. 2. Without proper management, the charging spot occupied by PEV A will stay idle after PEV A has got fully recharged after t_A^{c2} and it will not be released until PEV A departs at time t_A^d. While if the charging spot can be switched to serve PEV B after time t_A^{c2}, the spot can then provide charging service again. By this way, the two PEVs can share a single spot and the utilization level of the spot can be improved.

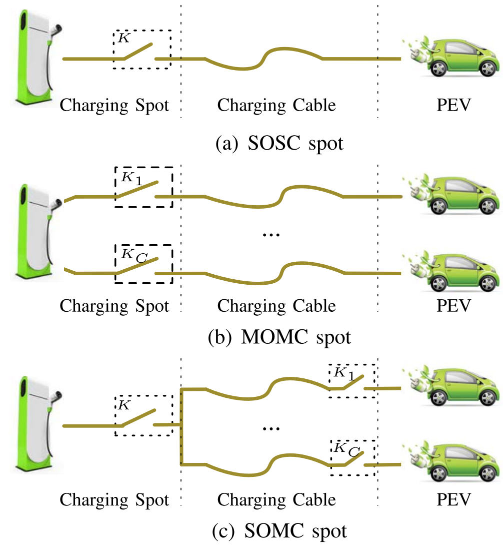

Fig. 3. Types of PEV charging spots.

A. *SOSC Spot and MOMC Spot*

The SOSC spot is the most commonly used type of charging spot, with a single cable, and can connect and charge a single PEV at any time (see Fig. 3(a)) [28].

An MOMC spot (see Fig. 3(a)) has multiple cables which can charge several PEVs simultaneously [29]. Since the rated charging power of an MOMC spot is the sum of those of all its cables, it can be viewed as a combination of several SOSC spots. In [30], an improved version of the MOMC spot is designed whose current for each cable is variable and can be adjusted under the control of a station operator. Therefore, it can be used to manage PEV charging for various purposes, such as to avoid overload problems during peak load time intervals in distribution systems.

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In real-time operation, manual intervention is required if one SOSC spot (or one cable of an MOMC spot) occupied by one PEV needs to be switched to another PEV during its idle time (See Fig. 2), which is inconvenient and often impractical for the charging spots deployed in a public parking lot.

Therefore, coordinated charging in a traditional charging station equipped with SOSC or MOMC spots will be unable to significantly reduce the investment for charging facilities.

B. *SOMC Spot*

The proposed SOMC spot also has multiple cables, potentially connected to several PEVs at any time (see Fig. 3(c)). However, an SOMC spot charges only one PEV connected to it at any time, the other charging cables remaining idle.

The SOMC spot is equipped with a load switch (K), to cut off the charging current, and each cable is equipped with one disconnector (K_c, $0 \leq c \leq C$), to isolate the corresponding charger coupler. Only one disconnector can be on at any time, and the load switch always turns off before changing the status of any disconnector, and on again after the change.[1]

[1]To charge one PEV via cable c, load switch K is turned OFF, disconnector K_c is turned ON (and any other disconnector switches are turned OFF), and K is then turned ON.

TABLE I
CHARACTERISTICS OF DIFFERENT KINDS OF CHARGING SPOTS

Type	Output Number	Cable Number	Rated Power	Utilization Level	Cost Per Cable
SOSC	1	1	P^{ra}	low	high
MOMC	C	C	CP^{ra}	low	high
SOMC	1	C	P^{ra}	high	low

Unlike MOMC spot, an SOMC spot can be regarded as an SOSC spot equipped with several cables. The cost for an SOMC spot with C charging cables is much lower than that for an MOMC spot with the same number of charging cables or C SOSC spots. The reasons are as follows:

1) Generally, the higher the rated power, the higher the cost of a given spot. The rated charging power of an SOMC spot is equal to that of an SOSC spot. So that the costs for the main body of an SOMC spot is approximately equal to that of an SOSC spot and much lower than that of an MOMC spot;
2) Only one high-cost load switch is incorporated (K in Fig. 3(c)), whereas the disconnectors in an SOMC spot (K_1-K_C in Fig. 3(c)) are comparatively cheaper, since they need never switch under load. So adding one extra charging cable to an SOMC spot is much cheaper than installing a new SOSC spot.

Once a PEV is connected to an SOMC spot, its charging process is controlled automatically following coordinated charging strategies. When one PEV becomes fully recharged or its charging is postponed, the SOMC spot can automatically charge another PEV via another cable, without manual intervention. Therefore, the utilization of SOMC spots is enhanced and corresponding investment costs significantly reduced.

Table I summarizes the main characteristics of the three types of charging spots, where the rated charging power of one PEV is P^{ra} and the cable numbers of an MOMC and SOMC spot are both C.

Since the structure of an SOMC spot is simple and its modification from an SOSC spot is not much, it can be easily implemented.

SOMC spots would be particularly suitable for destination charging demands, e.g., home charging in multi-family dwellings, where the intended parking time is usually much longer than the required charging time, so several PEVs can share one charging spot. In countries such as China, many residents live in condominiums and do not have personal parking garages, so that they mainly park their vehicles in residential public parking lots at night. The proposed SOMC spot will be an economic choice for them.

III. PLANNING METHODOLOGY FOR SOMC STATION

A. Two-Stage Stochastic Programming Model for the Planning

The planning objective for an SOMC station is to minimize the equivalent annual costs for providing charging services, including the equivalent annual investment costs and the expected annual operation costs. The planning variables include the number of charging spots (N) and the number of charging cables (C) of each spot.[2]

Since future PEV charging demands are uncertain during planning, a set of finite potential future scenarios of charging demands (Ω) should be forecasted.

The planning problem of an SOMC station incorporating coordinated charging can be formulated as the two-stage stochastic programming problem:

$$f = \min_{x}\left\{\underbrace{C^{\mathrm{I}}(x)}_{\text{stage one}} + \underbrace{\mathbb{E}_p[Q(x,\omega)]}_{\text{stage two}}\right\}$$
$$= \min_{x}\left\{C^{\mathrm{I}}(x) + \sum_{\omega\in\Omega}(\pi_\omega \cdot Q(x,\omega))\right\} \quad (1)$$

where:

$$C^{\mathrm{I}}(x) = \frac{r(1+r)^m}{(1+r)^m-1}\left(cost^{\mathrm{s}} \cdot N + cost^{\mathrm{c}} \cdot C \cdot N\right) \quad (2)$$

$$Q(x,\omega) = \min_{y}\left\{365\sum_{t\in T}\sum_{i\in I}\left(P_{\omega,i}(t)\cdot \Delta t \cdot T^{\mathrm{e}}(t)\right) + 365\sum_{i\in I}\left(E^{\mathrm{loss}}_{\omega,i}\cdot T^{\mathrm{pe}}\right)\right\}. \quad (3)$$

1) Stage One: Stage one is planning, with decision variables $x = \{N, C\}$. Its objective (1) is to obtain optimal x to minimize the equivalent annual costs for providing charging services. The first term in objective (1) is the equivalent annual investment costs, which can be calculated by equation (2). In (2), r is the discount rate, m is the service life of the charging spot, and $\frac{r(1+r)^m}{(1+r)^m-1}$ is the capital recovery factor of the investment costs which converts the present investment costs into a stream of equal annual payments over m years. $cost^{\mathrm{s}}$ and $cost^{\mathrm{c}}$ are the costs for the main body of an SOMC spot and a charging cable respectively, in \$. The second term in objective (1) is the expected annual operation costs, in which π_ω is the occurrence probability of scenario ω.

2) Stage Two: Stage two is the probabilistic operation cost simulation procedure, in which the station's coordinated charging is simulated (see Fig. 4). The decision variables include the charging power of each PEV during each time interval t ($P_{\omega,i}(t)$), and the corresponding charging status ($S^{\mathrm{charge}}_{\omega,n,i,t}$) in each scenario, i.e., $y = \{P_{\omega,i}(t), S^{\mathrm{charge}}_{\omega,n,i,t}, \forall\omega, n, i, t\}$. $S^{\mathrm{charge}}_{\omega,n,i,t} = 1$, if it is getting charged via spot n during t in scenario ω; $S^{\mathrm{charge}}_{\omega,n,i,t} = 0$, otherwise. Once variables (x) of stage one are available, the objective of stage two is to schedule the charging process of each PEV to minimize the annual operation costs for each scenario ($Q(x,\omega)$), which can be calculated by (3). The first term in (3) is the annual purchased electricity cost, in which $P_{\omega,i}(t)$ is the charging power of PEV i during time interval t, in kW, and $T^{\mathrm{e}}(t)$ is the corresponding electricity tariff, in \$/kWh. The second term in (3) is the penalty for unsatisfied charging demands, in which $E^{\mathrm{loss}}_{\omega,i}$ is the unfulfilled energy of PEV i, in kWh, and T^{pe} is the corresponding per-unit penalty cost, in \$/kWh. On one hand,

[2]We assume that the number of charging cables of each spot is the same for the convenience of mass production.

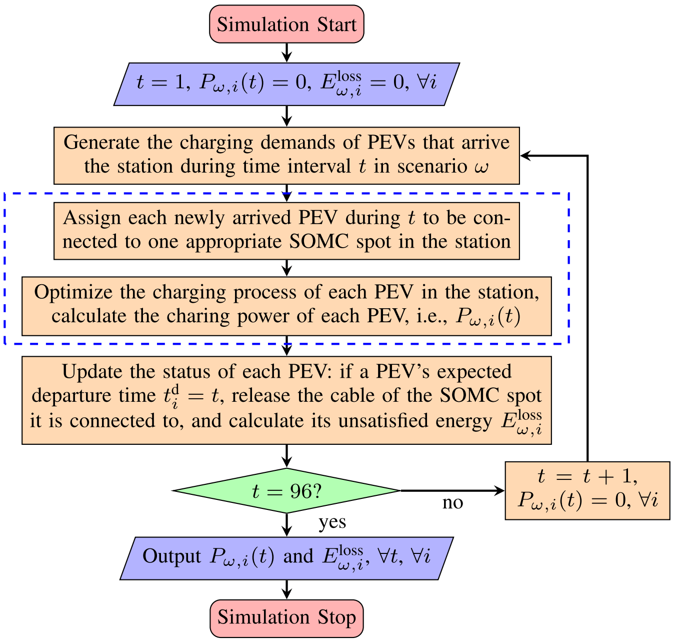

Fig. 4. Probabilistic coordinated charging simulation for scenario ω.

since several PEVs will be connected to a same SOMC spot, charging conflicts between them may arise which will lead to parts of the charging demands being unsatisfied. On the other hand, it is wasteful to install too many charging spots in order to satisfy sporadic peak charging demands from the perspective of a station investor. Thus, at the planning stage, the station operator is allowed to deliberately dissatisfy parts of the charging demands as a trade-off for economizing the investment of charging spots.

The probabilistic operation cost simulation for a scenario ω is presented in Fig. 4. Since the PEV charging demands can be influenced by various stochastic factors, such as weather, personal travel arrangements, etc., forecasting intraday charging demands for a charging station is quite difficult. Therefore, the objective ($Q(x, \omega)$) calculated by (3) should be obtained based on a rolling optimization simulation procedure for each scenario ω, during which the future charging demands are unknown. The simulation time interval, Δt, is 15 minutes in Fig. 4, so that each day has 96 intervals for each scenario. The strategies to assign PEVs to SOMC spots and optimize charging process of each PEV will be introduced in the following section.

The total charging power of the station should not violate its upper limit, i.e., $P^{\max}$, such as the transformer capacity etc.:

$$P^{\text{ra}} \cdot N \leq P^{\max}. \tag{4}$$

where, P^{ra} is the rated charging power of each SOMC spot.

B. Coordinated Charging Strategy

Since several PEVs will be connected to a same SOMC spot in an SOMC station, charging demand conflicts between them may arise without proper management. The unique characteristic of the SOMC spot requires a coordinated charging strategy differing from traditional ones [20]–[26]:

1) The coordinated charging strategy should schedule connecting and charging relationships between PEVs and spots rather than only determining the charging time and power of PEVs;
2) Some charging demands at peak hours may be deliberately unfulfilled as a trade-off for economizing the investment of charging spots.

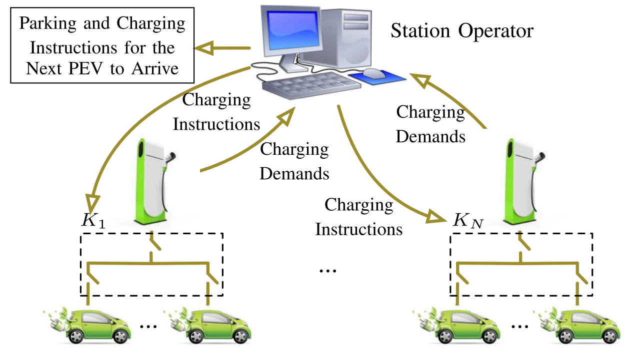

Fig. 5. Framework of the coordinated charging.

We only consider coordinated charging for a single station, which is assumed to be optimized by a station operator (see Fig. 5). Through a communication system, the station operator collects the real-time charging status of every PEV and spot in the station and provides charging instructions to the PEVs and spots. We propose a two-step heuristic coordinated charging strategy.

1) Determine Which Spot Each Incoming PEV Should Connect to at the First Step: The operator provides instructions for the next PEV to arrive (rather than for PEVs that have already arrived) that specify which spot it should connect to on the principle of minimizing the possibility of charging conflict using a heuristic strategy:

Step 1.a: Select SOMC spots with the least number of cables currently occupied by PEVs;

Step 1.b: Sort the SOMC spots obtained in *Step* 1.a by the total remaining charging requirement for the PEVs connected to them;

Step 1.c: Instruct the next PEV to arrive to connect to the SOMC spot from *Step* 1.b with the smallest remaining charging requirement.

Whenever a new PEV arrives, the instructions should be updated, and they should also be updated regularly, e.g., every 15 minutes, to update the status of the existing in-use charging spots and PEVs.

The first step heuristic strategy is similar with the priority-based strategies proposed in previous works, such as the charging completeness-based strategy in [26] and the laxity-based strategy in [27]. However, Xu *et al.* [26] and Subramanian *et al.* [27] concentrate on determining the order of PEVs (or distributed resources) to consume energy. While in our work, the heuristic strategy is used to determine the order of charging spots that each upcoming PEV should be connected to.

2) Schedule the PEV Charging Process at the Second Step: When a PEV is connected, the customer should upload the PEV's charging demand data, including SoC_i^{d}, and t_i^{d}, to the SOMC spot.[3] Each SOMC spot then independently schedules the charging processes of PEVs connected to it, or following instructions from the station operator.

Let τ^{H} denote the maximum future parking duration of all PEVs in the station during time interval t. The coordinated charging strategy for a spot during t can be formulated as the mixed integer linear programming problem:

$$\min F_n(t) = \sum_{\tau=1}^{\tau^{\mathrm{H}}} \sum_{i \in I_n} \big(P_i(t+\tau) \cdot \Delta t \cdot T^{\mathrm{e}}(t+\tau)\big) + \sum_{i \in I_n} \left(E_i^{\mathrm{loss}} \cdot T^{\mathrm{pe}}\right) \tag{5}$$

Subject to:

$$0 \leq P_i(t+\tau) \leq S_{n,i,t+\tau}^{\mathrm{charge}} \cdot P^{\mathrm{ra}}, \forall i \in I_n, \tau \tag{6}$$

$$\sum_{\tau=1}^{\tau^{\mathrm{H}}} P_i(t+\tau)\eta\Delta t + E_i^{\mathrm{loss}} = B_i(SoC_i^{\mathrm{d}} - SoC_i^{\mathrm{p}}), \forall i \in I_n \tag{7}$$

$$E_i^{\mathrm{loss}} \geq 0, \forall i \in I_n \tag{8}$$

$$\sum_{i \in I_n} S_{n,i,t+\tau}^{\mathrm{charge}} \leq 1, \forall \tau \tag{9}$$

$$\begin{cases} S_{i,t+\tau}^{\mathrm{park}} = 1, t+\tau < t_i^{\mathrm{d}} \\ S_{i,t+\tau}^{\mathrm{park}} = 0, t+\tau \geq t_i^{\mathrm{d}} \end{cases}, \forall i \in I_n \tag{10}$$

$$S_{n,i,t+\tau}^{\mathrm{charge}} \leq S_{i,t+\tau}^{\mathrm{park}}, \forall i \in I_n, \tau. \tag{11}$$

In the objective function (5), the first term is the purchased electricity costs and the second is the penalty for unsatisfied charging demands, including the penalty for a poor user experience and opportunity costs for unfulfilled charging services, which we assume to be proportional to the total unsatisfied energy (E_i^{loss}).[4] Equation (6) defines the charging power limit of each PEV. $S_{n,i,t+\tau}^{\mathrm{charge}}$ is the charging status of PEV i with spot n during $t+\tau$, $S_{n,i,t+\tau}^{\mathrm{charge}} = 1$, if it is getting charged via spot n; $S_{n,i,t+\tau}^{\mathrm{charge}} = 0$, otherwise. Equations (7)–(8) define the charging demands constraints.[5] Equation (9) guarantees that one charging spot charges only one PEV at any time, which corresponds to the unique characteristic of the SOMC spot. Equations (10)–(11) ensure that the PEVs can only get recharged during the time they are parked in the station. $S_{i,t+\tau}^{\mathrm{park}}$ is the parking status of PEV i during $t+\tau$, $S_{i,t+\tau}^{\mathrm{park}} = 1$, if it is parked in the station and can therefore get recharged; $S_{i,t+\tau}^{\mathrm{park}} = 0$, otherwise.

The station's operation costs ($F(t)$) is the sum of all the spots' operation costs ($F_n(t)$).[6]

C. Hybrid Integer Evolution Strategy

Since (1)–(4) defines a stochastic mixed integer nonlinear problem and stage two includes heuristic rolling optimization, it is computationally intractable. Since the decision variables (x) of stage one are integers, we propose HIES, which is derived from hybrid mixed integer evolution strategy (HMIES), to solve it. HMIES is a robust and flexible optimization technique for mixed integer nonlinear problems that has been used in many fields, such as chemical batch scheduling, and energy system planning [31]–[35]. Unlike HMIES which has mixed integer stage one variables, in HIES, the stage one variables are all integers.

In HIES, integer evolution is the master algorithm employed that performs the search on the stage one variables (x), whereas the decoupled stage two sub-problems (3) for a given x are solved by the probabilistic coordinated charging simulation shown in Fig. 4. The objective value in (1) is interpreted as the fitness of the evolution strategy.

We employ the $(\mu, \kappa, \lambda) - \textit{selection}$ strategy [33], [34], which chooses the best μ individuals from the union of μ parents and λ offspring, except those parent individuals which exceed the maximum age, κ. The flow diagram of the solution method for the planning model (1)–(4) based on $(\mu, \kappa, \lambda) - \textit{selection}$ strategy is shown in Table II.

The recombination operation at step 07 in Table II enables the offspring to inherit the best parents' properties. In this paper, the arithmetic mean of both parental variables are used as the offspring's variables [33].

The mutation operation at step 08 enables the offspring to obtain new properties to ensure a global search for the feasible region. In this paper, we employ the integer mutation procedure first proposed by [32] and also used by [33] and [34]. This procedure uses multi-dimensional geometric distributions, in contrast to the normal distributions of continuous variables, to generate variances. Due to space limitation, details of the mutation operation are omitted. Interested readers may need to refer to [32]–[34] for detailed information.

The constraint on the maximum age (κ) at step 12 enables the HIES to escape from a local optimum.

In the HIES algorithm, $\mu + \lambda \times g^{\max}$ individuals are solved totally.

IV. Case Studies

A. Case Overview and Parameter Settings

We use a case study of a residential parking lot providing charging services for 100 PEVs to verify the effectiveness of the proposed methodology. The Nissan Leaf PEV was chosen to represent the PEV population, with battery capacity 24 kWh

[3] The data can be uploaded via an interactive screen window at the spot.

[4] The income of the charging station and how it charges customers for its services are beyond the scope of this paper.

[5] We assume that PEV owners will not change their charging demands here. In practice, PEV owners may occasionally need to use their PEVs before the expected departure time. In case of emergency, a few fast-charging SOSC spots need to be installed in reserve. The integrated planning of SOMC spots and SOSC spots will be our future focus.

[6] Occasionally, the station operator may need to limit the total charging power at the station, which requires coordination between different spots. However, this would also waste the service capability of the station, which should be avoided at the planning stage. Hence, this possibility is ignored here.

TABLE II
SOLUTION METHOD FOR THE PLANNING OF AN SOMC STATION BASED ON $(\mu, \kappa, \lambda) - selection$

Algorithm: (μ, κ, λ) - Evolution strategy

Set generation number $g = 0$.
Initialize μ individuals (N_p, C_p), $p = 1...\mu$, randomly in the feasible space to form the first-generation parent population $P(g)$, and set the age of all the initial parent individuals to be 1.
Evaluate the μ initial individuals applying objective function (1), i.e., get f_p^{Parent}, $p = 1...\mu$.
While termination criteria, i.e., $g > g^{\max}$, not fulfilled, **do**
  Set offspring population $O(g) = \emptyset$.
  For $q = 1 : \lambda$, **do**
    Recombine two parent individuals randomly chosen from $P(g)$ to obtain offspring individual (N_q, C_q) and set its age to be 0.
    Mutate offspring individual (N_q, C_q).
    Evaluate offspring individual (N_q, C_q) applying objective function (1), i.e., get $f_q^{\text{Offspring}}$.
    Update offspring population $O(g) = O(g) \bigcup \{(N_q, C_q)\}$.
  End for
  Select μ best individuals from $P(g) \bigcup O(g)$, according to f_p^{Parent} and $f_q^{\text{Offspring}}$, $\forall p, \forall q$, whose ages are lower than the maximum lifespan κ to form the next-generation parent population $P(g+1)$.
  Increase the age of each individual in $P(g+1)$ by 1.
  Update generation number $g = g + 1$.
End while
Output the best individual, i.e., the individual with the lowest f_p^{Parent}, in population $P(g)$ as the solution.

and energy consumption 0.14 kWh/km.[7] The rated charging power (P^{ra}) was 6.6 kW [36] and the charging efficiency (η) was assumed to be 92% [26].

The investment cost of each charging spot including a load switch (c^{s}) and a zigbee device (for communication) was assumed to be \$4000 [36]. The service life of each charging spot (m) was 10 years and the discount rate (r) was 6% [37]. We assumed that adding one more cable required 3 m extra material, according to the parking lot planning rule in China [40]. The corresponding material cost was 6 \$/m and the labor cost was 100 \$/m (trenching & boring etc.)[8] [36]. The cost for a disconnector was assumed to be \$26, which is equal to that of a contactor, model DP30C2P-2, produced by ABB [38]. Thus, adding one extra cable to a charging spot costs approximately \$344, i.e., $c^{\text{c}} = \$344$.

A station utilizing coordinated charging requires computer control, this cost was assumed to be \$500. For an SOMC station, an LCD screen is also required to give instructions to incoming PEVs, with cost assumed to be \$300.

Industrial time-of-use electricity tariffs in Beijing [39] were used as station purchase prices (T^e), as shown in Table III. The penalty for unsatisfied charging demands (T^{pe}) was assumed to be five times the maximum time-of-use electricity tariff, i.e., 0.69 \$/kWh.

TABLE III
TIME-OF-USE TARIFFS FOR CHARGING STATIONS

	TOU tariff (\$/kWh)	Time
Peak	0.138	(8:00–12:00], (17:00–21:00]
Shoulder	0.109	(12:00–17:00], (21:00–24:00]
Off-peak	0.058	(0:00–8:00]

B. Charging Scenario Preparation

Since the penetration of PEVs is still very low, recorded PEV charging load data is quite limited. We used the NHTS data [41] to generate charging demand scenarios for the charging station, which was introduced in our previous work [42].[9]

The arrival time of a PEV determines its potential charging start time (t^a in Fig. 1). The temporal probability distribution of PEV arrival ($P^{\text{A}}(t)$, $t = 1, 2, \ldots, 96$), given their history of home arrival, was derived from the NHTS data to generate the charging start time [42].

The parking duration of a PEV determines its potential charging duration (from t^a to t^d in Fig. 1). Since a PEV's parking duration is strongly related to its arrival time, we used a probability matrix $\mathbf{H} = [h_{t_1,t_2}]$ $(t_1, t_2 = 1, 2, \ldots, 96)$ derived from the NHTS data to describe the temporal distribution of PEV parking duration. h_{t_1,t_2} represents the percentage of PEVs with arrival time $(t_1 - 1, t_1]$ and parking duration $((t_2 - 1)\Delta t, t_2 \Delta t]$ [42].

The arrival SoC of each PEV, i, was generated from the probability distribution of daily drive range (d_i), which was assumed to conform to a log-normal distribution (P^d), i.e., $\log(d_i) \sim N(3.7, 0.9^2)$ [41]. Assuming that all private PEVs are recharged after their last trip and arrive at the residential parking lot each day, the corresponding arrival SoC of the ith PEV is

$$SoC_i^a = 1 - (d_i \times E_i)/B_i. \tag{12}$$

The set $\{t_i^{\text{a}}, t_i^{\text{d}}, SoC_i^a, SoC_i^d\}$ contains all the charging demand information of the ith PEV. In this case, t_i^{a} is sampled based on $P^{\text{A}}(t)$, t_i^{d} is sampled based on t_i^{a} and $\mathbf{H}$, and SoC_i^a is sampled based on P^d and equation (12). For simplicity, SoC_i^d is assumed to be 100%. We assume that there are 28 representative scenarios, i.e., seven consecutive days in every season, in one year with equal probabilities of occurrence. Each scenario is sampled by Monte Carlo simulation according to $P^{\text{A}}(t)$, $\mathbf{H}$ and P^d.[10]

C. Planning Results

The planning for an SOMC station utilizing coordinated charging was solved and an SOSC station utilizing uncoordinated or coordinated charging was used for comparison, as summarized in Table IV. We used CPLEX [43] to solve the problem on a laptop with a 4 cores Intel Core i7 processor and 8 GB memory. The total solution time is about 3 hours.

For an SOSC station, only the electricity costs can be reduced, whereas for an SOMC station, the investment costs can also be significantly reduced by utilizing coordinated

[7] For practical planning, planners should consider the mix of PEV types at the targeted station.

[8] Parts of the cables are suggested to be placed underground for safety.

[9] In practice, real charging demand data shall be used.

[10] In practice, the charging demand scenarios should be obtained by forecasting using clustered historical charging demand data.

TABLE IV
PLANNING RESULTS

Spot Type	Operation Strategy	Spot Number (N)	Cable Number(C)	Unfulfilled Energy (%)	Equivalent Annual Costs (k$)				Daily Cost Per PEV($)
					Investment	Electricity	Penalty	Total	
SOSC	Uncoordinated	100	1	0	59.02	42.19	0	101.21	2.77
SOSC	Coordinated	100	1	0	59.09	16.72	0	75.81	2.08
SOMC	Coordinated	12	9	0.13	11.68	19.77	0.25	31.70	0.87

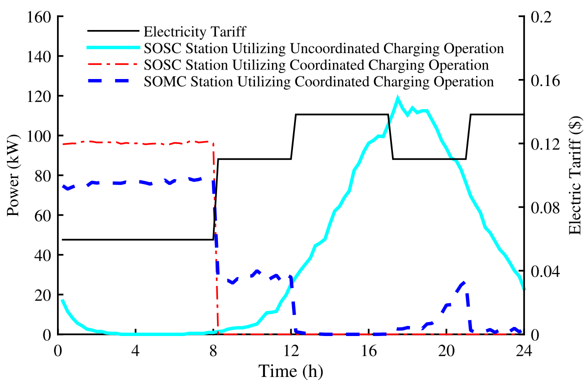

Fig. 6. Charging profiles of PEVs.

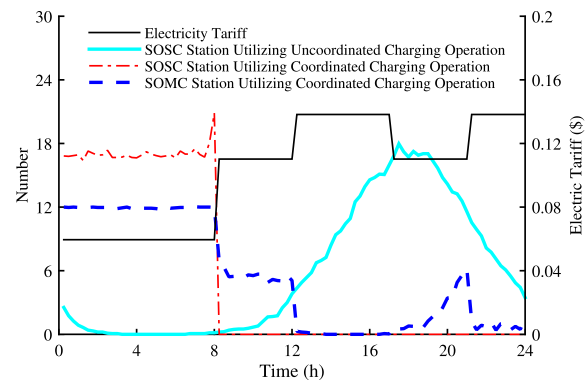

Fig. 8. Number of PEVs getting recharged.

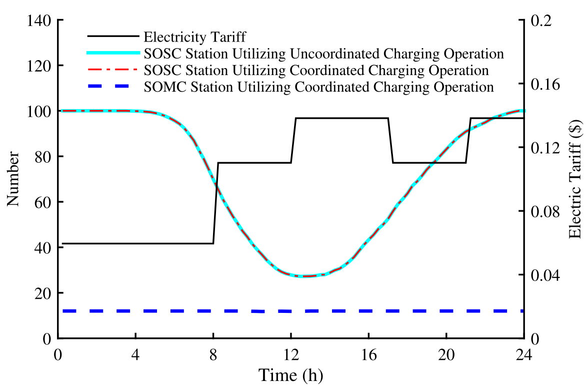

Fig. 7. Number of charging spots connected by at least one PEV.

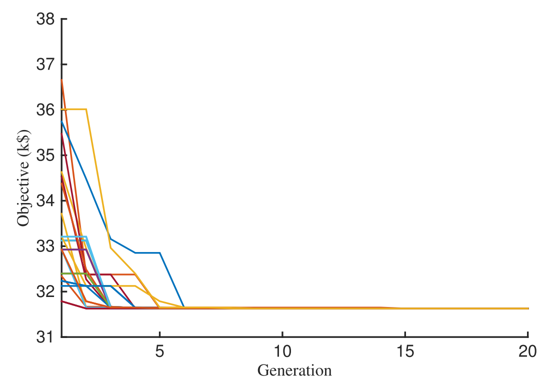

Fig. 9. Convergence curves of HIES.

charging at the expense of slightly increased operation costs (the electricity and penalty costs). Though more than 9 PEVs may connect to a same SOMC spot in the charging station, the percentage of the unsatisfied charging demands in an SOMC station is only 0.13%. Furthermore, charging services for an SOSC spot for one PEV costs more than $2 per day, whereas an SOMC costs less than $0.9 per day.

The average charging profiles of all the scenarios generated by the probabilistic cost simulation of (3) are shown in Fig. 6. Coordinated charging shifts the PEV charging power to low tariff periods for both SOSC and SOMC stations. However, the charging power of the SOMC station during high tariff period is higher than for SOSC, due to limited charging service capability, which leads to increased electricity costs (see Table IV).

The average number of charging spots connected with at least one PEV during each time interval are shown in Fig. 7. SOMC spots are almost always occupied by at least one PEV, whereas an SOSC station will have many charging spots idle during off-peak hours.

Fig. 8 shows the average number of PEVs being recharged during each time interval. For an SOSC station, although 100 charging spots are deployed, less than 20 PEVs charge simultaneously whether utilizing coordinated charging or not. Thus, the majority of the charging spots have no charging power most of the time whether they are connected to PEVs or not. However, during low tariff periods all the charging spots in the SOMC station are fully utilized, and during other periods the utilization level of SOMC spots is also higher.

Utilizing SOMC spots, incorporating coordinated charging at the planning stage, can significantly enhance the utilization level of charging spots and reduce the equivalent annual costs for providing charging services.

D. Convergence Analysis

To guarantee optimality of the planning results, the stability of HIES should be ensured. The convergence curves for objective (1) of 30 independent experiments are illustrated in Fig. 9. The HIES algorithms of all the experiments assumed

TABLE V
INFLUENCE OF RATED CHARGING POWER ON THE PLANNING RESULTS

P^{ra} (kW)	N	C	Equivalent Annual Costs (k$)			
			Investment	Electricity	Penalty	Total
3.3	25	4	8.74	20.16	1.20	30.10
6.6	12	9	11.68	19.77	0.25	31.70

$\mu = 4$ parents, $\lambda = 12$ offsprings, $\kappa = 3$ maximum generation lifespan, and $g^{\max} = 20$ maximum generations.

The results show all the experiments converged to a same objective value in 20 generations, which proves the convergence of HIES to be stable for the proposed two-stage stochastic programming problem.

E. Sensitivity Analysis

The rated charging power (P^{ra}) has significant influence on the operation and planning of an SOMC station. Planning results utilizing different P^{ra}, i.e., 3.3 kW and 6.6 kW, are compared in Table V.

The investment cost per 3.3 kW spot was assumed to be $1200 [36]. The material cost and labor cost for adding cables were estimated to be 5 $/m and 100 $/m respectively [36]. The cost for a suitable disconnector was assumed to be $20. Thus, adding one extra cable to a charging spot costs approximately $335, i.e., $c^{\mathrm{c}} = \$335$.

Table V shows that when P^{ra} decreases, the required charging spots increase and the corresponding number of cables per spot decrease. This is because, for the same parking duration ($t^{\mathrm{a}}, t^{\mathrm{d}}$], an SOMC spot can fulfill more PEV charging demands with higher P^{ra}. However, since a 3.3 kW SOMC spot is significantly cheaper than a 6.6 kW SOMC spot, the corresponding equivalent annual costs is lower.

V. CONCLUSION

In this paper, we first proposed a new type of PEV charging spot, i.e., SOMC spot. Then a two-stage stochastic optimization formulation was built to plan the public charging station using the SOMC spots. Coordinated charging of SOMC spots was taken into account at the planning stage. Simulation results show that using the proposed PEV charging station planning methodology, the required investment for the charging facilities and subsequently equivalent annual costs for providing charging services can be significantly reduced.

These findings provide a promising option to reduce usage costs of PEVs, improve profitability for providing charging services, and benefit development of the PEV industry.

In practice, a few fast-charging SOSC spots can be installed in reserve to make up for the unsatisfied charging demands by SOMC spots. The integrated planning of SOMC spots and SOSC spots will be our future focus. Besides, studies on methods to decrease the unsatisfied charging demands during real-time operation will also be our future work.

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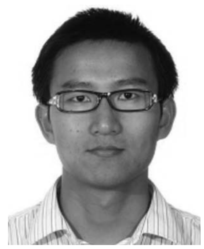
Hongcai Zhang (S'14) received the B.S. degree in electrical engineering from Tsinghua University, Beijing, China, in 2010, where he is currently pursuing the Ph.D. degree in electrical engineering.

His current research interests include electric vehicles, demand response, and power systems modeling and operations.



Zechun Hu (M'09) received the B.S. and Ph.D. degrees in electrical engineering from Xi'an Jiao Tong University, Xi'an, China, in 2000 and 2006, respectively.

He worked at Shanghai Jiao Tong University after graduation and also worked as a Research Officer at the University of Bath from 2009 to 2010. He joined the Department of Electrical Engineering, Tsinghua University, in 2010, where he is currently an Associate Professor. His major research interests include optimal planning and operation of power systems, electric vehicles, and energy storage systems.

Zhiwei Xu (S'09) received the B.S. degree (with distinction) in electrical engineering from Tsinghua University, Beijing, China, in 2011, where he is currently pursuing the Ph.D. degree in electrical engineering.

He is currently a Research Assistant with the Smart Grid Operation and Optimization Laboratory, Tsinghua University. His current research interests include electric vehicles, demand response, and power systems modeling and operations.

Yonghua Song (M'90–SM'94–F'08) received the B.E. degree from the Chengdu University of Science and Technology, Chengdu, China, in 1984, and the Ph.D. degree from the China Electric Power Research Institute, Beijing, China, in 1989, both in electrical engineering.

From 1989 to 1991, he was a Postdoctoral Fellow at Tsinghua University, Beijing. He then held various positions at Bristol University, Bristol, U.K.; Bath University, Bath, U.K.; and John Moores University, Liverpool, U.K., from 1991 to 1996. In 1997, he was a Professor of Power Systems at Brunel University, where he has been a Pro-Vice Chancellor for Graduate Studies since 2004. In 2007, he was a Pro-Vice Chancellor and a Professor of Electrical Engineering at the University of Liverpool, Liverpool. He was a Professor in the Department of Electrical Engineering, Tsinghua University, where he was the Assistant President and the Deputy Director of the Laboratory of Low-Carbon Energy in 2009. His current research interests include smart grid, electricity economics, and operation and control of power systems.

Prof. Song was a recipient of the D.Sc. Award from Brunel University, in 2002, for his original achievements in power system research. He was elected as the Vice-President of the Chinese Society for Electrical Engineering (CSEE) and appointed as the Chairman of the International Affairs Committee of the CSEE in 2009. In 2004, he was elected as a Fellow of the Royal Academy of Engineering, U.K.