Joint PEV Charging Station and Distributed PV Generation Planning

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***Abstract*—Integration of plug-in electric vehicles (PEVs) with distributed renewable resources will decrease PEVs' well-to-wheels greenhouse gas emissions, alleviate power congestions and defer power system investments. This paper proposes a two stage stochastic joint planning model of PEV fast-charging stations and distributed photovoltaic (PV) generation on coupled transportation and power networks, considering stochastic characteristics of base load, traffic flow and PV power. We use origin-destination (OD) traffic flow to estimate PEV charging demands and propose a second order cone programming (SOCP) model for PV power generation with reactive power control. A modified capacitated-flow refueling location model (CFRLM) is used to describe the transportation network and explicitly capture time-varying PEV charging demands under driving range constraints. AC power flow with SOCP relaxation is adopted to incorporate power network constraints. The joint planning model is a mixed-integer SOCP model and can be solved by an off-the-shelf solver.**

***Index Terms*—Plug-in electric vehicle, charging station, PV power, planning, transportation, second order cone.**

I. Introduction

INTEGRATION of PEVs with distributed renewable resources can help reduce PEVs' well-to-wheel emissions, alleviate power congestions and defer power system investment. The emissions of PEVs depend on their energy supply mix, PEVs in areas with high penetration of coal-fired plants may emit more than traditional vehicles [1]. For destination PEV charging, coordinated controlling or vehicle-to-grid technologies can be utilized to alleviate PEV charging's negative effect [2], while rapidly growing uncontrollable fast-charging power may cause significant congestions [3]. Building PEV charging infrastructure along with distributed renewable power generation to promote local power supplies will alleviate power congestions, and thereafter, defer power system investments.

The growing PEV population is leading to massive investments in charging infrastructure [4]. This investment boom gives the society an opportunity to integrate PEVs with renewable resources at the planning stage, i.e., joint planning PEV charging stations with distributed renewable resources so that PEVs can consume renewable power locally.

Integration of renewable power with PEV charging stations has been a research hotspot over recent years. Most of the published papers focus on economic benefit evaluation or coordinated control strategies. References [5], [6] showed that coordinated destination PEV charging could significantly improve distributed PV power integration. Reference [7] demonstrated the benefit of integrating PV generation with fast-charging stations. However, only few published papers have studied the joint planning of PEV charging stations and renewable power generation. Reference [8] studied joint planning of on site PV generation and battery-swapping stations. Reference [9] proposed a multi-year multi-objective planning algorithm for PEV parking lots and renewable generation. In [10], a multi-objective model was developed to optimize the sites and sizes of charging stations and distributed renewable generation.

This paper studies joint planning of PEV charging stations and PV power generation. The contributions are threefold:

1) Instead of traditional PV power generation, this paper considers the new PV power generation technology with reactive power control so that they can help enhance distribution system security.
2) The transportation network is explicitly modeled by the modified capacitated-flow refueling location model (CFRLM) to forecast PEV charging demands considering heterogeneous PEV driving range constraints. By contrast, the published literature ignored the mobility constraints of PEVs.
3) The proposed model is a two stage stochastic mixed integer SOCP model, which can be solved by off-the-shelf solvers and the optimality of the solution can be guaranteed. By contrast, the aforementioned literature all utilized heuristic optimization methods.

II. Charging Station and PV Generation Models

A. PEV Charging Station Model

We adopt the service rate model developed in [11] to describe a PEV charging station's service ability and model PEV load as a function of the traffic flow visiting a station.

We assume that there are K types of PEVs, with different driving ranges and charging behaviors; PEVs of type k arrive in a station at location i following a Poisson process with parameter $\lambda_{i,k}$ and requiring T_k units of charging time. We let $y^{\text{ev}}_{i,k}$ denote the number of Poisson arrivals of type k PEVs in a charging station. Therefore, $y^{\text{ev}}_{i,k} \sim Poisson(T_k\lambda_{i,k}), \forall k \in K$. In the station, the PEVs are served on a first-in first-out

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basis and no arriving PEVs have to wait. Based on these assumptions, we model a charging station's service ability based on the following service quality criterion:

Criterion 1 The probability that any PEV can be charged for at least its required amount of units of time, i.e., T_k for a type k PEV, $k \in K$, is α or greater. Mathematically, $\Pr(t^{\mathrm{d}}_{e_k} - t^{\mathrm{a}}_{e_k} \geq T_k) \geq \alpha, \forall e_k, \forall k \in K$, where, $t^{\mathrm{d}}_{e_k}$ is the departure time and $t^{\mathrm{a}}_{e_k}$ is the arrival time of the PEV e_k.

Criterion 1 is equivalent to the following Criterion 2 [11]:

Criterion 2 $\Pr(y^{\mathrm{ev}}_i \leq y^{\mathrm{cs}}_i) \geq \alpha, \quad y^{\mathrm{ev}}_i = \sum_k y^{\mathrm{ev}}_{i,k}, y^{\mathrm{ev}}_{i,k} \sim Poisson(T_k\lambda_{i,k}), \forall k \in K$.

Each independent Poisson distribution $Poisson(T_k\lambda_{i,k})$ can be approximated by a Normal distribution, i.e., $y^{\mathrm{ev}}_{i,k} \sim N(T_k\lambda_{i,k}, T_k\lambda_{i,k})$. Because the sum of different independent Normal distributions is still a Normal distribution, we have Normal distribution $N(\sum_{k\in K} T_k\lambda_{i,k}, \sum_{k\in K} T_k\lambda_{i,k})$ for the event described in Criterion 2. Then, Criterion 2 is:

$$\int_{-\infty}^{y^{\mathrm{cs}}_i} f(y^{\mathrm{ev}}_i)dy^{\mathrm{ev}}_i = \Phi\left(\frac{y^{\mathrm{cs}}_i - \sum_{k\in K} T_k\lambda_{i,k}}{\sqrt{\sum_{k\in K} T_k\lambda_{i,k}}}\right) \geq \alpha, \quad (1)$$

where, $f(\cdot)$ is the probability density function of the normal distribution; $\Phi(\cdot)$ is the cumulative distribution function of the standard normal distribution.

In practice, the traffic flow passing by one location i may be composed by different types of PEVs from different OD pairs, and only part of them need get charged, thus, we have:

$$\lambda_{i,k} = \sum_{q\in Q_i} \lambda_{q,k}\gamma_{q,i,k}, \quad (2)$$

where, $\lambda_{q,k}$ is the traffic flow of path (OD pair) q, $Q_{(i)}$ is the set of paths through node i, $q \in Q_{(i)}$. $\gamma_{q,i,k}$ is a binary variable indicating charge choice of type k PEVs on path q at node i: $\gamma_{q,i,k} = 1$, if PEVs get charged; $\gamma_{q,i,k} = 0$, otherwise.

Thus, by (1) and (2), we have the closed-form service ability model for a station serving K types of PEVs:

$$y^{\mathrm{cs}}_i \geq \sum_{q\in Q_i}\sum_{k\in K} T_k\lambda_{q,k}\gamma_{q,i,k} + \Phi^{-1}(\alpha)\sqrt{\sum_{q\in Q_i}\sum_{k\in K} T_k\lambda_{q,k}\gamma^2_{q,i,k}}. \quad (3)$$

Note $\gamma_{q,i,k} = \gamma^2_{q,i,k}$ and equation (3) is an SOCP constraint.

The corresponding average PEV charging demand is:

$$P^{\mathrm{ev}}_i = p^{\mathrm{sp}} \sum_{q\in Q_i}\sum_{k\in K} T_k\lambda_{q,k}\gamma_{q,i,k}, \quad (4)$$

in which, p^{spot} is the rated power of a charging spot.

B. PV Generation Model

Besides active power generation, PV plants with fast-reacting and VAR-capable inverters can also generate or consume controllable reactive power for distribution system operations. Reference [12] proposes to use semi-definite programming to model PV plants with reactive power control. In this paper, we propose an SOCP model as follows:

$$\sqrt{|p^{\mathrm{pv}}|^2 + |q^{\mathrm{pv}}|^2} \leq \overline{s^{\mathrm{pv}}}, \quad (5)$$

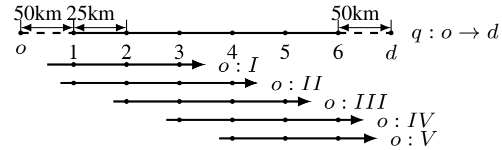

Fig. 1. Driving range logic based on sub-path (100 km driving range).

$$0 \leq p^{\mathrm{pv}} \leq \overline{p^{\mathrm{pv}}}, \quad (6)$$

$$s^{\mathrm{pv}} = p^{\mathrm{pv}} + jq^{\mathrm{pv}}, \quad (7)$$

where, p^{pv} and q^{pv} are respectively the active and reactive power of the PV generation; $\overline{s^{\mathrm{pv}}}$ is its nameplate apparent power; $\overline{p^{\mathrm{pv}}}$ is the upper bound of the active power. Equation (5) is the constraint for both active and reactive power of the PV generation, which is in the form of an second order cone. The active power is constrained by solar radiation in (6). Equation (7) calculates the apparent power. For this PV generation, q^{pv} can be either negative or positive to support voltage control.

III. Transportation Network Model

The modified CFRLM [11] is adopted to model the transportation network and forecast PEV charging demands.

A. PEV Driving Range Logic Based on Sub-paths

Driving range limit is the key characteristic that PEVs have compared to traditional vehicles. Properly modeling this constraint of PEVs on transportation networks ensures the forecasting accuracy of future PEV charging demands.

We explain the driving range logic by Fig. 1. A PEV with a driving range of 100 km arrives at node 1 with $D_a = 50$ km (which means the PEV has already traveled 50 km before arriving at node 1) and needs to depart at node 6 with $D_d = 50$ km (so that it can reach its destination after departure). We add pseudo nodes o and d to denote the original node and the destination node respectively and let $d_{o,1} = 50$ km and $d_{6,d} = 50$ km. Then, the problem becomes that a PEV with its battery fully charged leaves at node o and needs to arrive at node d without running out of energy on the road. The travel trajectory of the PEV, i.e., $\{o, 1, 2, 3, 4, 5, 6, d\}$ is called a path, i.e., q, and a segment of path q is a sub-path. The real nodes on path q, i.e., $\{1, 2, 3, 4, 5, 6\}$ are the candidate locations for charging stations. The **driving range logic** for a PEV on path q is that any sub-path in q with a distance longer than the PEV's driving range, i.e., 100 km, should cover at least one charging station so that the PEV can travel through path q with adequate charging services.

B. Capacitated Flow Refueling Location Model

Based on the driving range logic, the constraints of CFRLM considering time-varying OD traffic flows can be formulated as follows (see Table I for additional notation):

$$\text{Service ability constraint (3)}, \forall i \in \Psi^{\mathrm{tn}}, \forall\omega \in \Omega, \forall t, \quad (8)$$

$$\sum_{i\in\Psi^{\mathrm{tn}}_o} \gamma_{q,i,k} \geq 1, \quad \forall o \in O_{q,k}, \forall q \in Q, \forall k \in K, \quad (9)$$

$$x^{\mathrm{cs}}_i \geq \gamma_{q,i,k}, \qquad \forall q \in Q, i \in \Psi^{\mathrm{tn}}, \forall k \in K, \quad (10)$$

$$\underline{y^{\mathrm{cs}}_i} x^{\mathrm{cs}}_i \leq y^{\mathrm{cs}}_i \leq \overline{y^{\mathrm{cs}}_i} x^{\mathrm{cs}}_i, \qquad \forall i \in \Psi^{\mathrm{tn}}. \quad (11)$$

The objective is omitted here because of space limit. Each station's service ability is constrained by (8). Equation (9) ensures that the PEVs get charged for at least once in each sub-path. Equation (10) constrains that the PEVs can only get charged at the nodes with charging stations. Equation (11) bounds the number of charging spots.

IV. Joint Planning Model

Considering that the base load, traffic flow and PV power are uncertain at the targeted planing horizon, a set of finite potential future scenarios (Ω) should be forecasted. Then a two stage stochastic programming model is adopted to plan PEV fast-charging stations and PV power generation.

The planning model is a mixed-integer SOCP, as follows (see Table I for the notation and decision variables):

$$\min\ \zeta^{\text{ev}} \sum_{i\in\Psi^{\text{tn}}} \left(c_{1,i}x_i^{\text{cs}} + c_{2,i}y_i^{\text{cs}} + c_{3,i}l_i p^{\text{sp}} y_i^{\text{ev}} + c_{4,i}P_i^{\text{sub}}\right) \tag{12a}$$

$$+\,\zeta^{\text{pv}} \sum_{m\in\Psi^{\text{dn}}} \left(c_{5,m}x_m^{\text{pv}} + c_{6,m}\overline{s_m^{\text{pv}}}\right) \tag{12b}$$

$$+\,365\sum_{\omega\in\Omega}\sum_{t}\pi_\omega\left(c_{\text{e}}^{+}p_{0,\omega,t}^{+}\Delta t - c_{\text{e}}^{-}p_{0,\omega,t}^{-}\Delta t\right) \tag{12c}$$

$$+\,365\sum_{\omega\in\Omega}\sum_{t}\sum_{i\in\Psi^{\text{tn}}}\pi_\omega\left(c_{\text{p}}p_{\text{un},i,\omega,t}^{\text{ev}}\Delta t\right), \tag{12d}$$

subject to:

$\forall i\in\Psi^{\text{tn}}, \forall m\in\Psi^{\text{dn}}, \forall\,(m,n)\in\Psi^{\text{db}}, \forall\omega\in\Omega, \forall t:$

PV power constraints: (5)–(7),

transportation constriants of CFRLM: (8)–(11),

$$P_i^{\text{sub}} = \max(0, \overline{P_i^{\text{ev}}} - P_{i,0}^{\text{sub}}), \tag{13}$$

$$S_{mn,\omega,t} = s_{m,\omega,t} + \sum_{h\in\Psi^{\text{dn}}_{\to m}} (S_{hm,\omega,t} - z_{hm}l_{hm,\omega,t}), \tag{14}$$

$$0 = s_{0,\omega,t} + \sum_{h\in\Psi^{\text{dn}}_{\to 0}} (S_{h0,\omega,t} - z_{h0}l_{h0,\omega,t}), \tag{15}$$

$$v_{m,\omega,t} - v_{n,\omega,t} = 2\text{Re}(z_{mn}^{*}S_{mn,\omega,t}) - |z_{mn}|^2 l_{mn,\omega,t}, \tag{16}$$

$$|S_{mn,\omega,t}|^2 \le l_{mn,\omega,t}v_{m,\omega,t}, \tag{17}$$

$$s_{m,\omega,t} = s_{m,\omega,t}^{\text{ev}} - s_{m,\omega,t}^{\text{pv}} + s_{m,\omega,t}^{\text{b}}, \tag{18}$$

$$l_{mn,\omega,t} \le |\overline{I_{mn}}|^2, \tag{19}$$

$$|\underline{V_m}|^2 \le v_{m,\omega,t} \le |\overline{V_m}|^2, \tag{20}$$

$$s_{m,\omega,t}^{\text{ev}} = p_{m,\omega,t}^{\text{ev}} = \sum_{i\in\Psi_m^{\text{tn}}} p_{i,\omega,t}^{\text{ev}}, \tag{21}$$

$$p_{i,\omega,t}^{\text{ev}} + p_{\text{un},i,\omega,t}^{\text{ev}} = p^{\text{sp}}\sum_{q\in Q_i}\sum_{k\in K} T_k\lambda_{q,i,k,\omega,t}\gamma_{q,i,k}, \tag{22}$$

$$\overline{p_{m,\omega,t}^{\text{pv}}} = p_{m,\omega,t}^{\text{PV,fore}}\overline{s_m^{\text{pv}}}, \tag{23}$$

$$\underline{S_m^{\text{pv}}}x_m^{\text{pv}} \le \overline{s_m^{\text{pv}}} \le \overline{S_m^{\text{pv}}}x_m^{\text{pv}}, \tag{24}$$

$$\sum_{m\in\Psi^{\text{dn}}} x_m^{\text{pv}} \le N^{\text{pv}}, \tag{25}$$

$$\sum_{m\in\Psi^{\text{dn}}} \overline{s_m^{\text{pv}}} \le \overline{S^{\text{pv}}}. \tag{26}$$

TABLE I

Notation Used in the Planning Model

	Indices/sets
$i/\Psi^{\text{tn}}_{(o)}$	Index/set of transportation nodes (on sub-path o), $i\in\Psi^{\text{tn}}_{(o)}$.
$m/n/h$	Index of buses of the distribution network. $m/n/h\in\Psi^{\text{dn}}$. For the substation bus (reference bus), $m/n/h=0$.
$(m,n)/\Psi^{\text{db}}$	Index/set of lines of the distribution network. (m,n) is in the order of bus m to bus n, i.e., $m\to n$, and bus n lies between bus m and bus 0. $(m,n)\in\Psi^{\text{db}}$.
$o/O_{(q,k)}$	Index/set of sub-paths (of PEV type k on path q), $o\in O_{(q,k)}$.
$\Psi^{\text{dn}}_{(\to m)}$	Set of buses of the distribution network (that are connected to bus m and bus m lies between them and bus 0).
Ψ^{tn}_m	Set of transportation nodes connected to distribution bus m.
	Parameters of the planning model
$c_{1,i}$	Fixed costs for building a new station at node i, in \$.
$c_{2,i}$	Costs for adding an extra spot in a station at node i, in \$.
$c_{3,i}$	Per-unit cost for distribution line at i, in \$/(kVA·km).
$c_{4,i}$	Per-unit cost for substation capacity expansion at i, in \$/kVA.
$c_{5,m}$	Fixed costs for building a PV generation at bus m, in \$.
$c_{6,m}$	Costs for adding extra PV panels at bus m, in \$/kVA.
c_{e}	Per-unit cost for energy purchase, in \$/kWh.
c_{p}	Per-unit penalty costs for unsatisfied PEV power, in \$/kWh.
$\overline{I_{mn}}$	Upper limit of branch current of line (m,n), in kA.
l_i	Required distribution line length to install a charging station at node i, in km.
N^{pv}	Maximum PV generation number.
$p_{m,\omega,t}^{\text{PV,fore}}$	Per unit PV power output during t in scenario ω.
$P_{i,0}^{\text{sub}}$	Initial substation capacity available at node i, in kVA.
$s_{m,\omega,t}^{\text{b}}$	Apparent base load at bus m, in kVA.
$\overline{S^{\text{pv}}}$	Maximum total PV power capacity in the system, in kVA.
$\underline{S_m^{\text{pv}}}/\overline{S_m^{\text{pv}}}$	Minimum/maximum PV power capacity at bus m, in kVA.
$\underline{V_m}/\overline{V_m}$	Lower/upper limit of nodal voltage at bus m, in kV.
$\underline{y_i^{\text{cs}}}/\overline{y_i^{\text{cs}}}$	Minimum/maximum number of charging spots in station i.
$Y^{\text{ev/pv}}$	Service life of the charging stations/PV generation, in year.
z_{mn}	Impedance of branch (m,n), in ohm. z_{mn}^{*} is its conjugate.
Δt	Time interval, one hour in this paper.
$\zeta^{\text{ev/pv}}$	Capital recovery factor, which converts the present investment costs into a stream of equal annual payments over the specified time of $Y^{\text{ev/pv}}$ at the given discount rate r. $\zeta = (r(1+r)^{Y^{\text{ev/pv}}})/((1+r)^{Y^{\text{ev/pv}}}-1)$.
$\lambda_{q,i,k,\omega,t}$	Volume of type k PEV traffic flow on path q, at node i, during time t, in scenario ω, in h^{-1}.
π_ω	Probability of scenario ω.
ω/Ω	Index/set of scenarios. $\omega\in\Omega$.
	Optimization Variables
x_i^{cs}	Binary variable denoting charging station location at node i: $x_i^{\text{cs}}=1$, if there is a station at node i; $x_i^{\text{cs}}=0$, otherwise.
x_m^{pv}	Binary variable denoting PV generation location at bus m: $x_m^{\text{pv}}=1$, if there is PV at bus m; $x_m^{\text{pv}}=0$, otherwise.
y_i^{cs}	Integer variable denoting number of charging spots at node i.
$l_{mn,\omega,t}$	Continuous variable denoting square of the magnitude of line (m,n)'s apparent current during t in scenario ω, in kA^2.
$p_{(\text{un},)i,\omega,t}^{\text{ev}}$	Continuous variable denoting (unsatisfied) active PEV charging power at node i during t in scenario ω, in kW.
$p_{m,\omega,t}$	Continuous variable denoting total active load at bus m during t in scenario ω, in kW.
P_i^{sub}	Continuous variable denoting substation capacity expansion at node i, in kVA.
$s_{m,\omega,t}$	Continuous variable denoting total apparent load at bus m during t in scenario ω, in kVA. For the distribution system, $s_{0,\omega,t}$ (at bus 0) is also the power consumption of the whole distribution system [13].
$s_{m,\omega,t}^{\text{ev}}$	Continuous variable denoting apparent PEV power at bus m during t in scenario ω, in kVA.
$\overline{s_m^{\text{pv}}}$	Continuous variable denoting invested capacity (maximum nameplate apparent power) of PV panels at bus m, in kVA.
$S_{mn,\omega,t}$	Continuous variable denoting apparent power flow in line (m,n) (from bus m to bus n) during t in scenario ω, in kVA.
$v_{n,\omega,t}$	Continuous variable denoting nodal voltage at bus n during t in scenario ω, in kV.
$\lambda_{i(,k,\omega,t)}$	Continuous variable denoting volume of (type k) PEVs that require charging at node i (during t, in scenario ω), in h^{-1}.

The first two terms in (12a) represent upfront fixed cost of building charging stations and the variable cost in proportion with the number of charging spots. The last two terms in (12a) together account for power distribution network upgrade costs, which include the costs for distribution lines and the costs for substation capacity expansion. The two terms in (12b) represent the fixed cost per PV plant and the cost per kVA PV panel. The two terms in (12c) are the annual expected energy purchase and selling costs of the system and the term in (12d) is the penalty for unsatisfied PEV charging demands.

The substation capacity expansion is calculated by (13). The branch currents and nodal voltages of the distribution network must satisfy AC power flow constraints (14)–(18) and cannot violate their permitted ranges, i.e., constraints (19)–(20). In this paper, the second order cone relaxation of AC power flow [13] is adopted. We assume that the PEV charging stations' power factors are all 1.0. Note that we consider hourly power balance in the planning model. The hourly average PEV charging power is calculated by equations (21)–(22). When the PEV traffic is low, $P^{\mathrm{ev}}_{\mathrm{un},i,\omega,t} = 0$; when the traffic flow grows beyond the system's service ability, some charging demands are not fulfilled and $P^{\mathrm{ev}}_{\mathrm{un},i,\omega,t} > 0$.

The maximum active power of each PV generation constrained in (23) depends on the installed PV capacity and the solar irradiation. Equation (24) bounds each installed PV generation capacity. Equation (25) and (26) constrain the total number and the total capacity of the PV plants in the system, respectively. The base loads $s^{\mathrm{b}}_{m,\omega,t}$ are required to be satisfied.

V. Case Studies

A. Case Overview and Parameter Settings

We consider a 25-node transportation network coupled with a 14-node 110 kV high voltage distribution network to illustrate the proposed planning method. Due to limited space, the detailed parameters of the distribution and the transportation networks are omitted in this paper, but can be found in [11].

Sixteen representative scenarios, i.e., two types of weather (cloudy, sunny) in weekday and weekend of four seasons, of hourly base load, traffic flow and PV power profiles are generated based on PG&E load profiles [14], the NHTS data [15], and the National Solar Radiation Data Base [16].

We assume there are four types of PEVs on road with equal market share, and their driving ranges per charge are respectively 200, 300, 400 and 500 km. The rated charging power p^{sp} is 44 kW, and the average service time to charge the four types of PEVs with empty batteries is about 42, 63, 84, 105 minutes. We also assume $D_a = 100$ km, $D_d = 100$ km for all PEVs, $\underline{y^{\mathrm{cs}}_i} = 0$, $\overline{y^{\mathrm{cs}}_i} = 200$ and $\alpha = 80\%$.

The costs of PEV charging stations $c_{1,i} = \$163,000$ and $c_{2,i} = \$31,640$; the distribution line cost $c_{3,i} = 120$ \$/(kVA·km). The line distance l_i is assumed to be 10% of the distance between the PEV charging station and its nearest 110 kV distribution node. The substation expansion cost $c_{4,i} = 788$ \$/kVA. We assume each original 25 transportation node has 1 MVA surplus substation capacity. The electricity purchase cost $c^{+}_{\mathrm{e}} = 0.094$ \$/kWh [17] and the selling price c^{-}_{e} is 30% lower.

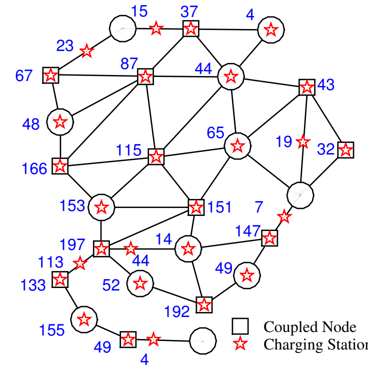

Fig. 2. Charging station locations and capacities in Case 1.

The per-unit penalty cost for unsatisfied charging demand $c_{\mathrm{p}} = 10^3$ \$/kWh. We assume all the nodes (except node 1) in the distribution network are candidate PV locations. The PV generation investment costs $c_{5,m} = 0$ \$/VA, $c_{6,m} = 1,770$ \$/kVA [18]. We also assume that $Y^{\mathrm{ev/pv}} = 15$, $r = 8\%$, $\overline{S^{\mathrm{pv}}} = 90$ MVA, $\underline{S^{\mathrm{pv}}_m} = 0$ MVA, $\overline{S^{\mathrm{pv}}_m} = \infty$ MVA, $\forall m$.[1]

We design four cases, with different PEV populations and maximum PV generation numbers to illustrate the proposed planning method. Case 1 is the baseline case where the PEV traffic flow is 20,000 PEVs/day and the PV generation number $N^{\mathrm{pv}} = 5$. In case 2, the PEV traffic flow is 40,000 PEVs/day and $N^{\mathrm{pv}} = 5$. Case 3 and case 4 do not allow building PV generation, i.e., $N^{\mathrm{pv}} = 0$, and the PEV traffic flows are respectively 20,000 PEVs/day and 40,000 PEVs/day.

We use CPLEX [19] to solve the problem on a laptop with a 12 core Intel Xeon E5-1650 processor and 64 GB RAM. To accelerate the optimization speed, we relaxed y^{cs}_i to be continuous. The optimization stops when the relevant gap decreases below 0.5% taking about 30 minutes.

B. Planning Results and Analysis

The summary of the planning results for the four cases are given in Table II. The locations and capacities of PEV charging stations in Case 1 are given in Fig. 2 for demonstration. The PV generation and their capacities in Case 1 and Case 2 are illustrated in Figs. 3–4. The ratio of a line's current to its thermal capacity, i.e., $\sqrt{l_{mn}/\overline{I_{mn}}}$, represents its thermal congestion level. The maximum congestion level, i.e., $\max_{\omega,t}\left(\sqrt{l_{mn,\omega,t}/\overline{I_{mn}}}\right)$, of each distribution line in the four cases are depicted by Colorbars in Figs. 3–6.

The planning results show that by jointly building PEV charging stations with PV generation, the total costs of the system decrease: the total costs in Case 1 are less than those in Case 3 by 2.78% and the total costs in Case 2 are less than those in Case 4 by 8.56%. The total PV generation capacity and the economic benefits of integrating PEV charging stations with PV generation increase as the PEV population increases.

By utilizing distributed PV generation to supply power locally, the planner has larger flexibility to build PEV charging stations. Compared to Case 3 and Case 4, the total number of charging spots and the overall investment costs on PEV charging stations in both Case 1 and Case 2 are decreased.

[1]Note that there are usually enough lands available in highway networks to build PV plants. Therefore, we do not limit the $\overline{S^{\mathrm{pv}}_m}$ here.

TABLE II
THE PLANNING RESULTS OF DIFFERENT CASES

Case	Station no.	Spot no.	PV no.	PV capacity (MVA)	Investment costs (M$/year) PEV Station	Grid upgrade	PV Panels	Electricity costs (M$/year)	Total costs (M$/year)	Unsatisfied PEV load (%)
1	25	1158	5	77.28	5.05	4.62	15.98	22.24	47.89	0
2	30	2238	5	90.00	9.32	11.41	18.61	30.31	69.66	0
3	25	1162	0	0	5.05	4.64	0	39.56	49.26	0
4	45	2341	0	0	9.98	15.22	0	50.98	76.18	2.24

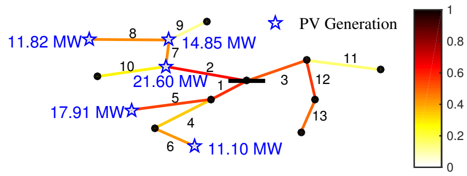

Fig. 3. Distribution line congestion level and PV generation in Case 1.

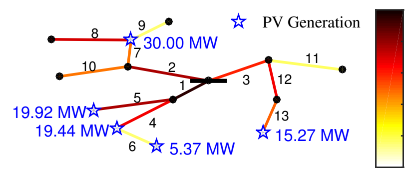

Fig. 4. Distribution line congestion level and PV generation in Case 2.

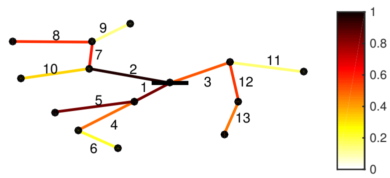
Fig. 5. Distribution line congestion level in Case 3.

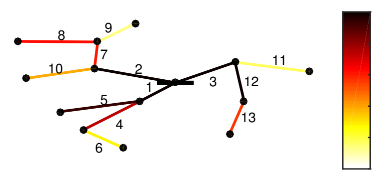
Fig. 6. Distribution line congestion level in Case 4.

Figs. 3–6 show that investing distributed PV generation can significantly ease distribution line congestion, and thereafter, defer distribution system investment. In Case 4, some distribution lines' capacity constraints are binding, and as a result, 2.24% of PEV charging demands cannot be satisfied. Without building new PV generation, the planner will have to upgrade the congested distribution lines at a much higher cost.

VI. CONCLUSION

We propose a mixed integer SOCP model for joint PEV charging station and distributed PV generation planning considering both transportation and electrical constraints. The model can be solved by off-the-shelf solvers and numerical experiments validate its effectiveness.

Simulation results show that utilizing the proposed method can significantly ease distribution system congestion, reduce total system costs, and defer power system investment. The advantages of the proposed method are especially pronounced under heavy load (high PEV population) scenarios.

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