Optimal pricing and location of electric vehicle charging stations

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1 Literature revue

Electric vehicles (EVs) are becoming more and more common and charging stations are a growing infrastructure, especially in urban areas. In recent years, there has been a rapid growth of studies on EVs accompanying with the rising popularity of the smart city concept [13].

Among the existing works on EV charging stations, most of them are focused on charging stations placement (design problem). In these works, optimization models from different point of views are proposed. Used approaches vary in objective functions, decision types, station types, application sizes, and also the type of the optimization model. In terms of the objective function, maximizing the number of EV users [2, 12], maximizing profit [6, 10, 11], and minimizing the total costs (energy and social costs) [9, 4, 16, 5, 14, 15] are very common. The demand in these works is defined in different ways: traffic flow, queuing models, etc.

The proposed optimization problems are formulated as: bi-level optimization models [6, 11, 16, 15, 17], Multi-objective model [4] and stochastic models [8, 9, 10, 12, 17]. Most of models are solved using heuristic algorithms. Table 1 summarizes recent works on EVCS pricing and location problems and the different characteristics of the model (type of the models, objective functions, decision variables, constraints and the proposed algorithms).
In this work we propose a strategic bi-level optimization model combining the location and the energy pricing problems and based on dynamic preference lists for users.

2 Problem description

In this work, we study the problem to find the optimal pricing and location of electric vehicles charging station. We consider a bi-level model, where the problem involves two distinct agents acting simultaneously rather than sequentially when making decisions. On the upper level, the energy provider (first agent) is in charge of selecting the location of charging stations and how many charging spot in each CS, as well as defining the energy

Paper	Problem	1-level	bi-level	Multi-obj	St	Design	Pricing	Objectives	Var(typ)	Constraints	Alg	others
[7]	Design of EVFCS	×	-	-	-	×	-	Max-net			Genetic	Renewable
[8]	EVCND	× 2stg	-	-	×	×	-	Max expected access then	CS st+nb bin		heur	
[9]	Opt placement & operation of EVCS	× 2stp	-	-	×	×	-	min avg energy price	EVCS inst bin price(time) t uncert	chergin modes	-	
[6]	FCS placement	-	×	-	-	×	- fixed	Max profit + Opt cap	Design var+ assign	D_{ij}, M/M/r	heur	zones
[1]	Opt placement	×	-	-	-	×	-	Opt cap& placement		bin Design var		zones,urban areas,openchal, survey
[3]	Opt distribution	×	-	-	-	-	×	Dynamic energy pricing	-	-	-	-
[16]	Opt pricing	-	× Nash equ	-	-	-	×	Min social cost	congestion	stratigy var	rules alg	scalability robustness
[4]	Opt allocation FCS	-	-	×	-	×	-	Min cost+WT, Max TF			genetic	traffic flow
[2]	Opt planning	×	-	-	-	×	-	max nbr of EV	nbr of EV	budget, EV nbr ..	greedy	
[17]	EVCS layout research	-	×	-	×	×	-	Min cost(operator+ users), Max traffic flow	path var	1-cost, capacity, energy 2-traffic flow const	ICA and ILP alg	traffic flow
[5]	optimal EVCND	×	-	-	-	×	-	Min system cost	Assignment var bin	M/M/c	B&B	non-linear
[15]	EVFCS	-	×	-	-	×	-	Min social cost, charging cost of users	Design var	budget, equilibrium strategy	heuristic	flow
[10]	EVFCS, elastic demand	× (NL)	-	-	×	×	-	Max profit R-C	design var bin	distance penalty, elastic demand, WT	genitic	fixed price
[14]	Economic planning	×	-	-	-	×	-	Min cost	design	traffic, capacity		flow
[12]	EVCS location	× (NL)	-	-	×	×	-	Max expected demand	design+Flow var	Flow	Benders&price	
[11]	EVCS location with elastic demand	-	×	-	-	×	- fixed	Max profit, Assignment	design + path var	flow	Genitic	

price in order to maximize his profit. In response, on the lower level, each EV user (second agent) choose in the first step a set of charging stations (preference list) from the ones selected by the leader minimizing the charging costs and the distance to these CSs. Then, in the second step, each user is affected to a charging station in its preference list if it is available.

Let we consider a charging system consisting of EV users and charging service provider. The provider is responsible for furnishing charging services for EV users in urban region G. The problem is divided on three steps as following:

Step 01: Pricing and design

In the first step, the service provider is in charge to define the energy price and to select locations to install charging stations from a given set of candidates and also how many charger in each location.

Step 02: Preference list

Based on the decision of the service provider in step 01, each user will define its preference list (a finite and ordered set of charging stations) minimizing the charging cost and the distance to each CS.

Step 03: affectation problem

Finally, each user will select the first CS available in his preference list.

3 Bi-level optimization model

To formulate the problem, we consider a set of candidate locations $K = \{k_1, \ldots, k_m\}$ and a set of EV users $I = \{i_1, \ldots, \imath_n\}$. We suppose that some user are could be able to charge at home. To this end, we define an additional set of charging spots $K' = \{k'_i,\ \forall i \in I,\ \text{ if i possesses a home charger}\}$. For each CS $k \in K$ we have a limited number of charging spots to install δ^k, and a capacity of charging γ^k.
We suppose that The day is divided on time intervals: $T = \{t_1, t_2, \ldots, t_r\}$. The matrix $D = \{d_i^{kt} :\ i \in I, j \in K, t \in T\}$ denotes the distance between the EV users $i \in I$ and charging station $k \in K$ at $t \in T$.

The optimization problem consists to:

- Select a set of CS candidates to build CS.
- Define the number of charging spots in each selected CS.
- Define the optimal price of the energy in each time period.
- Define a preference list for each user according to the price and the locations of CSs.

- Select a charging station for each user in his preference list according to the availability of CSs.

The problem can be presented as a two levels optimization problem, where the upper level consists to select the locations and define the energy price in order to maximize the total profit. Then, in the second level problem, each user define his preference list of CSs and selects the first available one.

3.1 Decision variables

For each $k \in K$ we define a binary and an integer variables z^k and y^k that represent if the candidate k is selected by the leader and the number of installed chargers in k, respectively. A positive variable p_k^t is introduced to represent the energy price in the CS k at the period time t of the day.
We use also the binary variable x_{ik}^t to track the CS k selected by the user i to charge at time t

$$x_{ik}^t = \begin{cases} 1, & \text{if the charging station } k \in K \text{ is selected by by the user } i \text{ to charge at time } t, \\ 0, & \text{otherwise.} \end{cases}$$

3.2 Objective function

The objective function of the leader can be given by the difference between the revenue and the costs:

$$\max_{p,x,y,z} \quad \sum_{i \in I} \sum_{k \in K} \sum_{t \in T} p_k^t x_{ik}^t - cost(y^k) - energy\_cost(x_{ik}^t)$$

3.3 Preference lists

According to the decision of the leader, Each user select its own preference list in the set $K \cup \{k_i'\}$. These preference lists are found minimizing the combination of many criteria: the price, the distance to the charging stations and the number of charging spots. Here, we consider the case of selecting a fixed number m of CS for each user.
The problem is formulated as a multi-objective optimization problem:

$$\begin{aligned} \min_{x} \quad & \Big(\sum_{k \in K \cup K_i'} \sum_{t \in T} p_k^t v_{ik}^{tl} \; ; \; \sum_{k \in K \cup K_i'} \sum_{t \in T} (d_i^k)^t v_{ik}^{tl} \Big) && \forall i \in I, \\ \text{s.t.} \quad & \sum_{k \in K \cup K_i'} \sum_{t \in T} v_{ik}^{tl} = m, && \text{(1a)} \\ & v_{ik}^{tl} \in \{0,1\}, \qquad \forall k \in K \cup K_i', \forall t \in T. && \text{(1b)} \end{aligned}$$

- **First objective:** minimize the price.

- **Second objective:** minimize the distance.

To find the preference lists, we suppose that we suppose that there are three types of users $I = S_1 \cup S_2 \cup S_3$
S_1: the set of users who prefer to minimize the price.
S_2: the set of users who prefer to minimize the distance.
S_3: the set of users who prefer to minimise the sum of the price and the distance.
according to the type of the user, we can define the parameters α_i ($\beta_i = 1 - \alpha_i$) in the objective function. The preference list problem of each user $i \in I$ is given by:

$$
\begin{aligned}
& && \forall l \in \{1, \dots, m\} && \\
& \min_{v} && \sum_{t \in T} (\sum_{k \in k} \alpha_i p_k^t v_{ik}^{tl} + \beta_i d_i^k)^t v_{ik}^{tl} + \sum_{k \in k_i'} C_i^{kt} v_{ik}^{tl}) && \\
& \text{s.t.} && \sum_{k \in k} \sum_{t \in T} v_{ik}^{tl} = 1, && \quad (2a) \\
& && v_{ik}^{tl} \leq 1 - v_{ik}^{tl'}, && \forall k \in K \cup k_i', \forall t \in T, \forall l' \leq l-1, \quad (2b) \\
& && v_{ik}^{tl} \in \{0, 1\}, && \forall i \in I, \forall k \in K \cup k_i', \forall t \in T. \quad (2c)
\end{aligned}
$$

For each step l the optimization problem find the l^{th} CS in the preference list of user i. The binary variable $v_{ik}^{tl} = 1$ means that the CS k is in the preference list of user i at period t. Constraints (2a) insure to find only one CS in each step l. Then, constraints (2b) allow the problem to classify the CSs in the preference list according to the objective value.

3.4 Affectation problem

After getting the decision of the leader (price and locations) and the preference list found in **Step 01**, each user will choose a first available charging station from his preference list. The problem can be formulated as:

$$
\begin{aligned}
& \min_{x} && \sum_{t \in T} \sum_{i \in I} \sum_{k \in K \cup K'} (\lambda_i^k + \sum_{l=1}^{m} l v_{il}^{kt}) x_{ik}^t && \\
& \text{s.t.} && \sum_{i \in I} x_{ik}^t \leq \gamma^k y^k, && \forall k \in K \cup K', \forall t \in T, \quad (3a) \\
& && \sum_{t \in T} \sum_{k \in K \cup K'} x_{ik}^t = 1, && \forall i \in I, \quad (3b) \\
& && x_{ik}^t \leq \sum_{l=1}^{m} v_{il}^{kt}, && \forall i \in I, \forall t \in T, \forall k \in K \cup K', \quad (3c) \\
& && x_{ik}^t \in \{0, 1\}, && \forall i \in I, \forall k \in K \cup K', \forall t \in T. \quad (3d)
\end{aligned}
$$

Where λ_i^k is a random parameter represents the expected arriving time of user i to the CS k (it can also represents the number of zones between i and k). Constraints (3a) are the capacity constraints. Constraints (3b) and (3c) insure to select only one CS for each user i in his preference list. In this problem, we assume that $\lambda \in [0, 1]$ to not affect the order of CSs in the preference lists.

Bi-level optimization model

The bi-level optimization can be given by:

$$
\begin{aligned}
\max_{p,x,y,z} \quad & \sum_{i \in I} \sum_{k \in K} \sum_{t \in T} p_k^t x_{ik}^t - cost(y^k) - energy\_cost(x_{ik}^t) && && \text{(4a)} \\
\text{s.t.} \quad & y^k \leq \delta^k z^k, && \forall k \in K, && \text{(4b)} \\
& \sum_{k \in K} \mathcal{C}^k y^k \leq \beta, && && \text{(4c)} \\
& y^k \in \mathbb{Z}, && \forall k \in K, && \text{(4d)} \\
& p_k^t \geq 0, && \forall k \in k, \forall t \in T, && \text{(4e)} \\
& \min_v \ \sum_{t \in T} \Big(\sum_{k \in k} (\alpha_i p_k^t v_{ik}^{tl} + \beta_i d_i^k)^t v_{ik}^{tl} + \sum_{k \in k_i'} C_i^{kt} v_{ik}^{tl} \Big), && \forall i \in I, \ \forall l \in \{1, .., m\}, && \\
& \quad \text{s.t.} \quad \sum_{k \in k} \sum_{t \in T} v_{ik}^{tl} = 1, && && \text{(4f)} \\
& \quad \phantom{\text{s.t.}} \quad v_{ik}^{tl} \leq 1 - v_{ik}^{tl'}, && \forall k \in K \cup k_i', \forall t \in T, \forall l' < l, && \text{(4g)} \\
& \quad \phantom{\text{s.t.}} \quad v_{ik}^{tl} \in \{0, 1\}, && \forall i \in I, \forall k \in K \cup k_i', \forall t \in T, && \text{(4h)}
\end{aligned}
$$

$$
\begin{aligned}
\min_x \quad & \sum_{t \in T} \sum_{i \in I} \sum_{k \in K \cup k_i'} (\lambda_i^k + \sum_{l=1}^{m} l v_{il}^{kt}) x_{ik}^t && && \\
\text{s.t.} \quad & \sum_{i \in I} x_{ik}^t \leq \gamma^k y^k, && \forall k \in K \cup k_i', \forall t \in T, && \text{(4i)} \\
& \sum_{t \in T} \sum_{k \in K \cup k_i'} x_{ik}^t = 1, && \forall i \in I, && \text{(4j)} \\
& x_{ik}^t \leq \sum_{l=1}^{m} v_{il}^{kt}, && \forall i \in I, \forall t \in T, \forall k \in K \cup k_i', && \text{(4k)} \\
& x_{ik}^t \in \{0, 1\}, && \forall i \in I, \forall k \in K \cup k_i', \forall t \in T. && \text{(4l)}
\end{aligned}
$$

To avoid the price bounds constraints, we can suppose that for $t \in T$, the user $i \in T$ has an alternative option to charge (other service provider or charging at home) with a cost $\mathcal{D}_i^t$. In the preference list, if $v_{ik}^{tl} = 1$ and $\alpha p_k^t + \beta (d_i^k)^t > \mathcal{D}_i^t$, then, this choice will be removed from the preference list of user i.
To formulate this, we can add an auxiliary binary variable:

$$w_{ik}^{tl} = \begin{cases} 1, & \text{if: } v_{ik}^{tl} = 1 \text{ and } \alpha p_k^t + \beta (d_i^k)^t \leq \mathcal{D}_i^t \\ 0, & \text{otherwise.} \end{cases}$$

and we replace v by w in Constraint (4k).

Special case: Predefined preference list

In this section, we consider a special case of the problem, where the preference list of each user is supposed to be predefined and the arriving time is fixed. The problem consists then to design the CS network and to define the energy price in the first level. The in the second level problem each user will be affected to one of the charging station in his preference list according to the availability of CSs. We consider also her one type of users (we eliminate the home chargers).
The bi-level optimization is given by:

$$\begin{aligned}
\max_{p,x,y,z} \quad & \sum_{i \in I} \sum_{k \in K} \sum_{t \in T} p_k^t x_{ik}^t - cost(y^k) - energy_cost(x_{ik}^t) && && \text{(5a)} \\
\text{s.t.} \quad & y^k \leq \delta^k z^k, && \forall k \in K, && \text{(5b)} \\
& \sum_{k \in K} \mathcal{C}^k y^k \leq \beta, && && \text{(5c)} \\
& y^k \in \mathbb{Z}, && \forall k \in K, && \text{(5d)} \\
& p_k^t \geq 0, && \forall k \in k, \forall t \in T, && \text{(5e)} \\
& \min_x \quad \sum_{t \in T} \sum_{i \in I} \sum_{k \in K} (\lambda_i^k + \sum_{l=1}^{m} l v_{il}^{kt}) x_{ik}^t \\
& \quad \text{s.t.} \quad \sum_{i \in I} x_{ik}^t \leq \gamma^k y^k, && \forall k \in K, \forall t \in T, && \text{(5f)} \\
& \quad \quad \sum_{t \in T} \sum_{k \in K} x_{ik}^t = 1, && \forall i \in I, && \text{(5g)} \\
& \quad \quad x_{ik}^t \leq \sum_{l=1}^{m} v_{il}^{kt}, && \forall i \in I, \forall t \in T, \forall k \in K, && \text{(5h)} \\
& \quad \quad x_{ik}^t \in \{0,1\}, && \forall i \in I, \forall k \in K, \forall t \in T. && \text{(5i)}
\end{aligned}$$

The second level problem is written as: $\{\min_x cx,\ \text{s.t.} Ax \leq b,\ x \in \{0,1\}\}$ with:

$$A = \begin{pmatrix} I_{|K|\times|T|} & I_{|K|\times|T|} & \cdots & I_{|K|\times|T|} \\ \\ \mathbb{1}_{|K|\times|T|} & \mathbf{0} & \cdots & \mathbf{0} \\ \mathbf{0} & \mathbb{1}_{|K|\times|T|} & \cdots & \mathbf{0} \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{0} & \mathbf{0} & \cdots & \mathbb{1}_{|K|\times|T|} \\ \\ & I_{|I|\times|K|\times|T|} & & \end{pmatrix}$$

where I_n is the identity matrix and $\mathbb{1}_n$ is a ones-vector of size n.

3.5 Problem reformulation

It is easy to check that the matrix A is totally unimodular. Hence, the constraint (5i) can be replaced by non-negativity constraints.

Then, the problem can be reformulated to one-level optimization model using KKT optimality conditions as:

$$
\begin{aligned}
\max_{p,x,y,z} \quad & \sum_{i\in I}\sum_{k\in K}\sum_{t\in T} p_k^t x_{ik}^t - cost(y^k) - e\_cost(x_{ik}^t) && && \text{(6a)}\\
\text{s.t.} \quad & y^k \le \delta^k z^k, && \forall k \in K, && \text{(6b)}\\
& \sum_{k\in K} \mathcal{C}^k y^k \le \beta, && && \text{(6c)}\\
& y^k \in \mathbb{Z}, && \forall k \in K, && \text{(6d)}\\
& p_k^t \ge 0, && \forall k \in k, \forall t \in T, && \text{(6e)}\\
& \lambda_i^k + \sum_{l=1}^{m} l v_{il}^{kt} + \pi_k^t + \rho_i + \phi_{ik}^t \ge 0, && \forall i \in I, \forall k \in K, \forall t \in T, && \text{(6f)}\\
& (\lambda_i^k + \sum_{l=1}^{m} l v_{il}^{kt} + \pi_k^t + \rho_i + \phi_{ik^t}) x_{ik}^t = 0, && \forall i \in I, \forall k \in K, \forall t \in T, && \text{(6g)}\\
& \sum_{i\in I} x_{ik}^t \le \gamma^k y^k, && \forall i \in I, \forall k \in K, \forall t \in T, && \text{(6h)}\\
& (\sum_{i\in I} x_{ik}^t - \gamma^k y^k) \pi_k^t = 0, && \forall i \in I, \forall k \in K, \forall t \in T, && \text{(6i)}\\
& \sum_{t\in T} \sum_{k\in K\cup k_i'} x_{ik}^t = 1, && \forall i \in I, && \text{(6j)}\\
& x_{ik}^t \le \sum_{l=1}^{m} v_{il}^{kt}, && \forall i \in I, \forall t \in T, \forall k \in K, && \text{(6k)}\\
& (x_{ik}^t - \sum_{l=1}^{m} v_{il}^{kt}) \phi_{ik}^t = 0, && \forall i \in I, \forall t \in T, \forall k \in K, && \text{(6l)}\\
& x_{ik}^t \ge 0, && \forall i \in I, \forall k \in K, \forall t \in T, && \text{(6m)}\\
& \rho_i \in \mathbb{R}, && \forall i \in I, && \text{(6n)}\\
& \pi_k^t,\ \phi_{ik}^t \ge 0, && \forall i \in I, \forall k \in K, \forall t \in T. && \text{(6o)}
\end{aligned}
$$

$$
\begin{aligned}
\max_{p,x,y,z} \quad & \sum_{i\in I}\sum_{k\in K}\sum_{t\in T} p_k^t x_{ik}^t - cost(y^k) - e\_cost(x_{ik}^t) && && \text{(7a)}\\
\text{s.t.} \quad & y^k \le \delta^k z^k, && \forall k \in K, && \text{(7b)}\\
& \sum_{k\in K} \mathcal{C}^k y^k \le \beta, && && \text{(7c)}\\
& y^k \in \mathbb{Z}, && \forall k \in K, && \text{(7d)}\\
& p_k^t \ge 0, && \forall k \in k, \forall t \in T, && \text{(7e)}\\
& \lambda_i^k + \sum_{l=1}^{m} l v_{il}^{kt} + \pi_k^t + \rho_i + \phi_{ik}^t \ge 0, && \forall i \in I, \forall k \in K, \forall t \in T, && \text{(7f)}\\
& \lambda_i^k + \sum_{l=1}^{m} l v_{il}^{kt} + \pi_k^t + \rho_i + \phi_{ik^t} \le M - M x_{ik}^t && \forall i \in I, \forall k \in K, \forall t \in T, && \text{(7g)}\\
& \sum_{i\in I} x_{ik}^t \le \gamma^k y^k, && \forall k \in K, \forall t \in T, && \text{(7h)}\\
& (\gamma^k y^k - \sum_{i\in I} x_{ik}^t) \le (1 - u_k^t) M_5, && \forall k \in K, \forall t \in T, && \text{(7i)}\\
& \pi_k^t \le u_k^t M_5, && \forall k \in K, \forall t \in T, && \text{(7j)}\\
& \sum_{t\in T}\sum_{k\in K} x_{ik}^t = 1, && \forall i \in I, && \text{(7k)}\\
& x_{ik}^t \le \sum_{l=1}^{m} v_{il}^{kt}, && \forall i \in I, \forall t \in T, \forall k \in K, && \text{(7l)}\\
& \phi_{ik}^t \le M_6(1 - x_{ik}^t + \sum_{l=1}^{m} v_{il}^{kt}), && \forall i \in I, \forall t \in T, \forall k \in K, && \text{(7m)}\\
& x_{ik}^t \in \{0,1\}, && \forall i \in I, \forall k \in K, \forall t \in T, && \text{(7n)}\\
& \rho_i \in \mathbb{R}, && \forall i \in I, && \text{(7o)}\\
& \pi_k^t,\ \phi_{ik}^t \ge 0, && \forall i \in I, \forall k \in K, \forall t \in T && \text{(7p)}\\
& u_k^t \in \{0,1\}, && \forall k \in K, \forall t \in T. && \text{(7q)}
\end{aligned}
$$

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