Sequential Construction Planning of Electric Taxi Charging Station Considering the Development of Charging Demand

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Abstract

The charging infrastructure, especially the planning and construction of fast charging stations, is extremely important in the process of electric vehicle (EV) marketization. This paper proposes a method which selects the constructing plan of charging stations with the lowest social costs from the candidate sets of constructing plans. First of all, the optimization model of siting and sizing of charging stations is created and the optimal number and location of the charging station (CS) in the unplanned areas and the optimal charging facility configuration can be obtained by solving the model. After that, the sequential construction strategy is proposed considered two development trends of the charging demand. According to the case results, the sequential construction strategy of charging stations can effectively reduce the growth rate of user's waiting time cost and total social cost and promote the charging facility utilization rate, which helps to avoid the loss of funds and waste of resources.

Keywords: charging station, sequential construction, charging facility configuration, charging demand

Nomenclature

Abbreviation
EV Electric vehicle
CS Charging station

Symbols
Q Total social cost of CS construction
L The user's travel-to-station cost
Ak The the decision-making variable of whether to build the CS k
Fk The in-station social cost of CS k
Fwk The user’s waiting time cost of CS k
m Number of candidate sites
n Number of time periods in one day
l Number of charging demand points
ε Nonlinear coefficient of urban roads
h Number of charging taxis
Dminj The distance between the charging demand point j and its nearest construction site
Cw The average travel time cost per hour of electric taxi users
V Average driving speed of electric taxis
c Charging price per kilowatt hour
SE Battery capacity of electric taxis
M Driving mileage of electric taxi
Tki The length of time period i at the CS k
r Operating life of the CS
d Discount rate
Crd Land cost of non-charging parking spaces in the station
Cyu Operating cost of the station
Czmg Distribution cost of lighting and working
Cgm Purchase cost of a charging facility
Cwa Installation and maintenance cost of a single charging facility
Cw Land cost of a single parking space
Cpd Distribution cost of a charging facility
sk Number of charging facilities in CS k
Pk The power of charging facility in CS k
Wq Average queuing time
H Average charging time of electric taxis
Ds Service radius of CS
gjk The decision-making variable of whether electric taxis at the charging demand point j will charge at CS k
Djk The distance between the charging demand point j and the CS k
SOC_{alarm} \quad \text{The lowest limit of SOC alarm of EVs}
SOC_{min} \quad \text{The lowest state of charge (SOC)}
when electric taxis reach CS
E(SOC_{min}) \quad \text{The expected value of SOC}_{min}
T \quad \text{Average user-tolerable time of finding}
the station
p \quad \text{Charging facility utilization rate}
\rho_i \quad \text{Minimum limit of facility utilization rate}
W_t \quad \text{Maximum user-tolerable queuing time}
S_{nk} \quad \text{Distribution capacity of } CS \text{ } k
S_k \quad \text{Upper limit of } S_{nk}
K_k \quad \text{Simultaneity work coefficient of}
charging facilities in } CS \text{ } k
S_{sk} \quad \text{Upper limit of } s_k

Subscript
k \quad k\text{-th fast charge station (} k=1,2, ..., m \text{)}
i \quad i\text{-th time period (} i=1,2, ..., m \text{)}
j \quad j\text{-th charging demand point}

1. Introduction
The fast charging station construction in public areas can effectively eliminate the limitation of battery capacity and greatly increase the driving mileage of EVs. However, constructing the fast CSs without planning will cause unbalanced service among stations and low charging facility utilization rate in CS\textsuperscript{1,2}.

The planning issues of the fast CS include two aspects: site selection and facility configuration. The existing CS construction planning method divides the EV driving route by distance to obtain the potential location of CS\textsuperscript{3,4} or uses the nodes of road network and distribution network as the candidate sites of CS\textsuperscript{5,6}. Based on the siting optimization model, the optimal location of CSs is determined under a certain objective function. For instance, Ref.[7] tracks and analyses the potential construction sites along the driving route of EVs and obtains the optimal CS construction plan by finding the solution to the optimization model whose objective function is to minimize the installation cost of charging facilities. Ref.[8] establishes the optimization model which takes the optimization of CS investment and energy loss cost as the objective function and finds the optimal construction sites on the user’s travel path. However, the methods proposed do not consider the construction feasibility of those sites, thus the optimization results can only serve as a theoretical plan.

Ref.[9] uses the objective function of minimizing the total cost of investment, operation and energy loss in the station and determines the number of charging facilities by combining the queuing theory and the constraints of the distribution network. There are also studies on the optimal construction plan of stations under different government policies\textsuperscript{10}. The above research is limited to the number optimization of charging facilities. However, the charging facility power is a key factor affecting the equipment cost and the user’s charging time. Moreover, the optimal location of CSs construction may change with the increase of EV penetration\textsuperscript{11}, which makes the optimal plan at the current stage no longer applicable and more funds are required for CS re-construction.

In this paper, firstly the charging station siting and sizing optimization model (SSOM) is created. Then the optimal construction number and location of CSs are selected from candidate sites and the number and power of charging facilities are optimized based on the model. Considering the change of EV penetration and the case that the existing CSs are not sufficient to meet the demands or charging service quality, the optimal downsizing or expansion plan of existing stations and the optimal construction plan of charging facilities are obtained based on the sequential construction strategy, which ensures the sustainable development of CSs and avoids the waste of resources.

2. Charging Station Siting and Sizing Optimization Model

2.1 Objective Function of Charging Station Siting and Sizing Optimization Model
The total social cost of the CS construction in the planning area is } Q, \text{ which includes the user’s travel-to-station cost and the investment cost and the user’s waiting time cost of each station. By converting each cost to one-hour-resolution (i.e. converted to Yuan/h), the objective function of the siting and sizing optimization model can be obtained as:

\[
\min Q = L + \sum_{k=1}^{m} A_k (\min F_{sk} + F_{wk}) = L + \sum_{k=1}^{m} A_k [\min (F_{sk} + F_{wk})]
\]
\[
L = \left[ \sum_{j=1}^{l} \sum_{i=1}^{n} (l_{ij} D_{minj}) \right] \times \left( C_{w_i} / V + c_{S_E} / M \right) \left/ \sum_{i=1}^{n} T_{ki} \right.
\]
\[
F_{sk} = \frac{d(1+d)^t}{(1+d)^t - 1} \times \left( \frac{C_{ld} + C_{yu} + C_{zm}}{365 \times 24} + \frac{C_{zm} + C_{wa} + C_{rn} + C_{pd}}{365 \times 24} \times s_k \right)
\]
\[
F_{wk} = C_w \left[ \sum_{i=1}^{n} \left( W_{gki} \times \eta \right) \times H_{ki} \right] \left/ \sum_{i=1}^{n} T_{ki} \right.
\]
\[
L \quad \text{includes electricity cost and time cost of users on the way to find the CS, } F_{sk} \quad \text{includes the land cost and operation cost of the CS } k, \text{ the distribution cost of lighting and working in the station, the purchasing, installation and maintenance costs of charging facility,}
\]
the land cost of parking spaces and the distribution cost of charging facilities. Combined with the charging demand at different time periods, the user’s waiting time cost of each period is calculated and then weighted to obtain $F_{wk}$, the user’s waiting time cost per unit time in the CS. Constraints of Charging Station Siting and Sizing Optimization Model

To ensure that EVs can arrive at the charging station before the battery runs out, the service radius of the charging station is limited as:

$$D_s = \min \{M(SOC_{alarm} - E(SOC_{min}))/\varepsilon, TV/\varepsilon \}$$

$$g_{jk}D_{jk} \leq D_s$$

The facility utilization rate reflects not only the rationality of the charging facility configuration, but also the economy of distribution capacity. The facility utilization rate needs to be limited as:

$$P_{ki} \geq P_i$$

The user-tolerable queuing time is considered from the user's psychological point of view:

$$W_{qi} \leq W_i$$

A fast charging station is a charging place with fixed floor space and distribution capacity, so the constraints of distribution capacity and chargeable parking space need to be considered:

$$S_{Nk} \leq S_{ik}$$

$$s_k \leq s_{ik}$$

In summary, the siting and sizing optimization model is established as follows:

$$\begin{align*}
\min Q &= L + \sum_{k=1}^{m} A_k \left[ \min \left( F_{ik} + F_{wk} \right) \right] \\
\text{s.t.} & \quad g_{jk}D_{jk} \leq D_s \\
& \quad W_{qi} \leq W_i, P_{ki} \geq P_i, S_{Nk} \leq S_{ik}, s_k \leq s_{ik} \\
& \quad j = 1,2 \ldots t; k = 1,2 \ldots m; i = 1,2 \ldots n;
\end{align*}$$

3. Sequential Construction Strategy of Charging Station

As the penetration rate of electric vehicles in the planning area continues to develop and change, the initial planned charging facilities may no longer meet the expanded charging demand. It is necessary to downsize or expand the existing charging stations based on the original charging facilities so that the charging facilities match charging needs.

As shown in Figure 1, for the sudden increase and fall of charging demand in short time in the planned area, a sequential downsizing strategy of CS construction is proposed to balance the demand change. For the cumulative growth of charging demand over years, a sequential expansion strategy of CS construction is proposed to meet the growth.

![Figure 1](image1.png)

**Figure 1** A possible development trend of charging demand

3.1 Sequential Downsizing Strategy of Charging Station Construction

For the area where large-scale events are held, the charging demand will drop suddenly after the end of the event. By analyzing the charging demand during the peak period and normal period of the planning area, generate a new CS construction plan matrix based on the location of existing charging stations and obtain the CS construction planning of normal period. The difference in the distribution capacity of CSs between the two plans is adjusted by the energy storage system.

![Figure 2](image2.png)

**Figure 2** The sequential downsizing strategy of charging station construction

3.2 Sequential Expansion Strategy of Charging Station Construction

With the increasing of EV penetration rate in the planned area year by year, existing charging facilities may no longer meet the increased charging demand. In this case, the CS construction needs to be expanded. Considering the cost discount and the income growth of taxi drivers in $p$ years after the initial planning, the objective function of SSOM should be improved.
The total social cost of the CS construction after expansion is $Q_{new}$, which includes the user's travel-to-station cost at the $p^{th}$ year after the initial planning, the in-station social cost of existing stations and new stations at the $p^{th}$ year after the initial planning. By converting each cost to one-hour-resolution, the objective function improved can be obtained as:

$$
\min Q_{new} = L_{new} + \sum_{t=1}^{n} \min F_{t,yet} + \sum_{k=1}^{m} A_k \left[ \min F_{k,new} \right] 
$$

(12)

$$
L_{new} = \left[ \sum_{j=1}^{l} \sum_{i=1}^{n} \left( c_{ij} D_{min,j} \right) \right] \left[ \frac{C_w (1+f)^p}{V} + \frac{cS_E}{M} \right] + \sum_{t=1}^{n} T_{ki} 
$$

(13)

$$
\min F_{t,yet} = F_{st,yet} + F_{st,new} + F_{wt} \times (1+f)^p 
$$

(14)

$$
F_{st,yet} = \frac{d(1+d)r}{(1+d)^r - 1} \left[ \frac{C_{id} + C_{wu} + C_{cw}}{365 \times 24} 
+ \frac{[C_{gm} + C_{wu} + C_{cw} + C_{pd}] \times s_{t,yet}}{365 \times 24} \right] 
$$

(15)

$$
F_{st,new} = \frac{d(1+d)r}{(1+d)^r - 1} \left[ \frac{C_{gm} + C_{wu} + C_{cw} + C_{pd}}{365 \times 24} \right] 
$$

(16)

$$
\min F_{k,new} = F_{sk} \left[ (1+d)^r \right] + F_{wk} \times (1+f)^p 
$$

(17)

where, $F_{t,yet}$ is the in-station social cost of existing CS $t$ ($t = 1, 2, \ldots, u$) and $F_{k,new}$ is the in-station social cost of new CS $k$. $f$ is the annual income growth rate of electric taxi driver. $F_{st,yet}$ is the initial investment cost of the existing CS $t$; $F_{st,new}$ is the investment cost of expanding the CS $t$ and $F_{wt}$ is the user waiting time cost at the $p^{th}$ year; $s_i$ is the number of charging facilities of the existing CS $t$ after the expansion and $s_{t,yet}$ is the initial number of charging facilities.

**4. Case Study**

The case study takes the Chongli District as the object of electric taxi fast CS planning, where most skiing events of 2022 Winter Olympics will be held. During the Olympics, Chongli will bear the charging demand for a large number of EVs. After the Olympics, the charging demand will drop rapidly, but the charging demand will increase cumulatively year by year.

The paper takes the electric taxi in Chongli District as the service object. Based on the CS planning method proposed before, the sequential construction planning of electric taxi CS in Chongli District is carried out.

**4.1 Parameter Setting**

The parameters of the in-station facility configuration optimization model can be obtained as follows. $\varepsilon=1.2$, $c=0.8$ Yuan/kWh, $S_c=29$ kWh, $M=120$ km, $SOC_{alarm}=0.3$, $E(SOC_{min})=0.23$, $V=32$ km/h, $T=10$ mins $=0.167$h, $r=10$ years, $d=5\%$, $C_{id}=2.4$ million Yuan. $C_{cw}=200$ thousand Yuan, $C_{yp}=210$ thousand Yuan, the unit purchase cost of charging facility is 2 thousand Yuan/kW and the maintenance installation cost is 1.5%/year of purchase cost. Considering the affordability of battery, the optimization range of $P$ is 30kW~120kW and the optimized gradient is 10kW. According to Ref.[12], $C_{w}=16$ Yuan/h. Set $W=10$ min $=0.167$h, $p=0.5$.

Having researched the construction requirements, 10 CS candidate sites and charging demand points have been selected. Fig.4 shows the distribution of charging demand points and CS candidate sites.

**4.2 Siting and Sizing of Charging Station**

Based on SSOM shown in Eq.11, the optimal sites for construction are No. 2 and No. 8. The service area distribution of charging stations is shown in Fig.5 and the optimal siting and sizing parameters of each station during the Olympic Games are shown in Tab.1.

![Figure 3](image3.png) **Figure 3** The sequential expansion strategy of the charging station construction

![Figure 4](image4.png) **Figure 4** The distribution of charging demand points and CS candidate sites in Chongli District

![Figure 5](image5.png) **Figure 5** The service area distribution of charging stations during the Olympic Games
Table 1 The optimal siting and sizing parameters of charging stations

<table>
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<th>Station No.</th>
<th>$S_k$</th>
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<th>$S_{1k}$</th>
<th>$P_{1k}$</th>
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Table 2 The optimal siting and sizing parameters of charging stations after downsizing

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Table 3 The optimal siting and sizing parameters of charging stations after expansion

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4.3 Sequential Downsizing of Charging Station

After the Olympics, the charging demand will reduce, and charging facilities will be too excess for EVs if no downsizing takes place. By applying the sequential downsizing strategy in 3.1, the optimal siting and sizing parameters of each station after the Olympic Games are shown in Tab.2. The charging facility utilization rate comparison of Station No.2 in 4 periods is shown in Fig.6. According to Fig.6, the charging facility utilization rate will reduce to less than 20% and result in the waste of charging resource and distribution capacity, while the sequential downsizing strategy of charging station can promote the charging facility utilization rate significantly.

4.4 Sequential Expansion of Charging Station

It is assumed that the EV penetration has increased by 20% in the third year after the initial planning. The revenue of electric taxi drivers grew at an annual rate of 1.5% during these three years. The existing charging facilities will not be able to meet the increased charging demand. The costs comparison of charging stations in the following three cases are shown in Fig.7:

Case 1: Initial planning after Olympic Games;
Case 2: The 3rd year after the Olympic Games with 20% increase in EV penetration;
Case 3: The 3rd year after Olympic Games with sequential expansion of charging stations based on the increased charging demand.

According to Fig.7, the user waiting time cost and total social cost will increase dramatically if the charging stations are not expanded after the EV penetration has increased, which leads to a poor charging service quality. The CSs in the planned area
are expanded based on the sequential expansion strategy in 3.2. The optimal siting and sizing parameters of each station is shown in Tab.3. As can be seen from Fig. 7, compared to the case of non-expansion, adding a new charging station can effectively reduce the growth rate of user's waiting time cost and total social cost. This helps to avoid the unbalanced services among stations and fund waste caused by blind construction of charging stations.

5. Conclusions

This paper proposes a method to optimize the CS sequential construction planning. Taking electric taxis as the research object, the method is applied in the charging station planning of Chongli District. Considering the change of EV penetration, the sequential construction strategy of CS is proposed to downsize or expand the scale of the existing CS construction based on the charging demand, which avoids the resources waste caused by blind construction. In fact, the environmental pollution cannot be solved by simply increasing the EV penetration; the integration with renewable energy is the effective way to reduce the environmental pollution. The future work will consider the management of dispatching of the electric taxi and the energy storage configuration in the fast charging station, investigates the economical and efficient dispatching of the energy storage in charging stations.

Acknowledgement

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Reference


