Planning of Charging Facilities Considering Terrain Characteristics

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Abstract. The existing studies on the planning of charging facilities generally neglect the influence of terrain characteristics. First, this study quantifies the transportation characteristics based on the relative height to calculate the travel energy consumption of electric vehicles (EVs) users. Then, the charging demand of EVs is estimated and assigned according to urban traffic flow. Finally, a land purchasing coefficient is proposed based on a functional agglomeration phenomenon. The coefficient is integrated into formulating a planning model with the objective of minimising the total annual social costs. Numerical experiments are conducted to validate the novel planning method. The experimental results verify that the terrain characteristics increase users’ travel energy consumption and limit their driving range.

1. Introduction

According to a report from the Argonne National Laboratory, electric vehicles (EVs) can significantly mitigate the energy crisis and relieve climate change [1]. With the large-scale adoption of EVs, the problems of the limited battery capacity and driving range of EVs have occurred. Therefore, the reasonable planning of charging facilities has become extremely important, which are generally divided into two categories, i.e. 1) facilities located in private areas with slow power chargers and 2) fast charging facilities beside roads with high power chargers [2].

While the fast charging stations mainly serve the EVs on roads when the battery capacity of the EVs reaches the lower limit or the journey cannot be completed using the surplus capacity, which play a key role in supporting the daily operation of EVs and have been extensively investigated on the reasonable planning by the specialists and scholars. In [3], the operational data of taxis in the city of Vienna were studied to locate charging facilities. Reference [4] proposed a model that ensured the number of chargers at each charging station based on the objective of minimising the total...
construction cost. The different types of costs of charging facilities were considered in [5], such as operation cost, maintenance cost, waiting cost, and user cost. [6] considered the expansion costs of power grids and analysed the physical traits of charging facilities to optimise sites. Reference [7] formulated a multi-objective decision model of charging facility location, including maximising traffic flow and minimising network loss and node voltage offset. Reference [8] adopted PSO to solve the problem of charging facility location while ensuring that the operation stability of power grids and the charging demand of EV users are simultaneously satisfied. A charging facility location model with a smart load management system was formulated in [9]. The objectives of peak load shifting, voltage curve improvement, and power loss reduction were considered without consideration of the effects of the terrain characteristics of cities, decreasing the application range of the proposed planning model.

2. The terrain characteristics of cities

In this paper, we present a novel planning model of fast charging facility location. First, a quantified transportation model is established based on the terrain characteristics of mountainous cities which shown in figure1. A modified Floyd shortest path algorithm is proposed to accurate calculate the energy consumption of EVs on roads. Second, based on the functional agglomeration phenomenon, a modified P-center location model is proposed to establish a three-dimensional planning model of fast charging facility location with different land purchasing prices. Finally, experiments are conducted to validate the proposed planning method.

Figure 1. Diagram of the characteristics of mountainous city.

Figure 1(a) shows the vertical view of an EV that starts its travel from A to C. In this view, it is difficult to distinguish the differences between the terrains of a mountainous city and a plain city. Conventional optimisation models always assume that users are rational and that they always select the lowest power consumption path to reach their destination. In Figure 1(a), the [A-B-C] pair is clearly shorter than the [A-D-C] pair. Figure 1(b) shows the lateral view of the EV from A to C, which can reflect the actual spatial distance between A and C because of the relative height is presented clearly. Based on these two figures, it is easy to understand that utilising conventional models to optimise charging facility location would lead to significant errors, decrease the precision of planning, and waste public resources.
3. Mathematical Model

3.1 objective function

We formulate the programming model to determine the optimal location of fast charging facilities in a mountainous city considering the minimisation of the total costs, including construction costs, maintenance costs, expansion costs of power grids, users’ energy consumption costs on roads, and electricity purchasing costs. The objective function is as follows:

$$\min Z = C_{\text{con}} + C_{\text{main}} + C_{\text{exp}} + C_{\text{road}} + C_{\text{ep}}$$

(1)

where $C_{\text{con}}$, $C_{\text{main}}$, $C_{\text{exp}}$, $C_{\text{road}}$, and $C_{\text{ep}}$ denote construction costs, maintenance costs, expansion costs of power grids, users’ energy consumption costs on roads, and electricity purchasing costs, respectively. In engineering practice, the maintenance cost of charging facilities and the expansion cost of power grids are a certain percentage of investment cost. In addition, most studies do not consider that land prices are different because of different types of land utilisation in various areas. Therefore, construction costs, maintenance costs, and the expansion costs of power grids can be integrated into (2), as follows:

$$C_{vt} = \sum_{i \in N_i} (\gamma (1 + \gamma)^b - 1) \left( \theta C_E + f_{\text{main}} C_E + w_{\text{exp}} C_E \right) + \theta c_p$$

(2)

where $C_{vt}$ is the total cost of construction and maintenance, $C_E$ is the fixed cost of charging facilities, $\gamma$ is the discount rate, $b$ denotes depreciable life, $f_{\text{main}}$ and $w_{\text{exp}}$ denote the maintenance cost coefficient and expansion cost coefficient, respectively, $n_i$ represents the number of charging devices at charging facility $i$, $c_p$ is the price of a charging device, and $n_i$ is a binary variable. $n_i=1$ implies that a charging facility is constructed at node $i$, while $n_i=0$ implies that a facility is not constructed. Based on various functions, a city can be classified into an upscale living area (UL), an ordinary living area (OL), an industrial area (ID), a commercial area (CM), and a leisure area (LS). We propose $\theta$ as the land price coefficient at node $i$. It is easy to understand that different areas have different land price coefficients. According to [10], one charging spot requires 20 m² of land, therefore, the investment of charging devices are also corresponding to land purchasing price.

The P-center location model selects $P$ nodes and minimises the distance of all charging demand nodes to these $P$ nodes [11]. However, in this work, the most important factor that effects the travel path and travel energy consumption of EVs is the relative height of different areas and not the horizontal distance between an origin and a destination. Hence, we modify the P-center location model by using users’ energy consumption costs on roads to substitute the distance, as follows:

$$C_{\text{road}} = H \sum_{k \in N_k} \sum_{i \in N_i} \sum_{d \in N_d} \delta_{d,i} c_D E_{d,i}(k)$$

(3)

where $c_D$ is electricity price (USD/kWh). $H$ denotes the days of a year, $E_{d,i}(k)$ denotes the energy consumption of driver $k$ at road node $d$ to charging facility $i$, $N_k$ is the set of EV users, and $N_C$ is the set of candidate sites of charging facilities. $\delta_{d,i}$ is a binary variable. $\delta_{d,i}=1$ implies that the charging demand node $d$ is satisfied by charging facility $i$, while $\delta_{d,i}=0$ implies that the charging demand of node $d$ is not satisfied by charging facility $i$.

The total charging demand includes the charging demand at road node $d$ and the energy consumption on roads from node $d$ to charging facility $i$. Therefore, electricity purchasing costs equal to the charging demand at road node $d$ plus the energy consumption from node $d$ to charging facility $i$, which can be expressed as (4).

$$C_{\text{ep}} = H \sum_{k \in N_k} \sum_{i \in N_i} \sum_{d \in N_d} c_D (S_d(k) + E_{d,i}(k))$$

(4)
3.2 Constraints

Each EV user can only be served by one charging facility. This problem can be written as
\[ \sum_{i \in N_d} \delta_{d,i} = 1, \forall d \in N_d \] (5)

In addition, EV users can select the charging facility at road network node i only when the facility is constructed. This problem can be expressed as
\[ \delta_{d,i} \leq n_i \] (6)

The amount of charging facilities constraint is as follows:
\[ N_{\text{min}}^{FC} \leq \sum_{i \in N_d} n_i \leq N_{\text{max}}^{FC} \] (7)

where \( N_{\text{min}}^{FC} \) and \( N_{\text{max}}^{FC} \) are the lower limit and upper limit of the amount of charging facilities, respectively. The entire charging demand should be satisfied by charging facilities. Thus, the constraint of charging demand is as follows:
\[ \sum_{k \in N_d} \sum_{d \in N_d} \delta_{d,i}(S_d(k) + E_{d,i}(k)) \leq r_i P_{\text{cha}}(1 - \eta)T_{\text{cha}} \] (8)

where \( N_{\text{min}}^p \) and \( N_{\text{max}}^p \) are the lower limit and upper limit of the number of charging piles in a charging facility, respectively.

It is worth noting that the location of a charging facility should be ensured that the surplus energy of an EV battery is sufficient for reaching the charging facility. This leads to the following driving range constraint:
\[ C_{\text{apd}}(k) - S_d(k) \geq \delta_{d,i}E_{d,i}(k) \] (10)

4. Results & Discussion

According to the proposed calculation method considering the characteristics of the mountainous city, the travel energy consumption of users between different transportation nodes is shown in Figure 2(a). Figure 2(b) shows the results obtained when the terrain characteristics of the city are neglected.
Figure 2. Users’ travel energy consumption.

In Figure 2, the change in colour from blue to red implies that the travel energy consumption increases. The travel energy consumption of an EV user increases sharply when the mountainous city terrain is considered. Therefore, for ensuring the EVs have enough capacity to reach the certain charging facility, it is necessary to carry out the planning of charging facilities in mountainous cities. The planning model is shown in figure 4, figure 3 is the original unplanned transportation network information.
Figure 4. Charging facility locations

In addition, the maximum service duration of charging facilities determines the number of charging piles as we can see from formula (10). On the one hand, in the case of a certain charging demand of a day, the greater the maximum service duration, the less the number of charging piles to be built, and the lower the investment cost; on the other hand, the smaller the number of charging piles, the smaller the number of electric vehicles to be charged at the same time, and the lower the pressure on the distribution network. The results of this planning problem are shown in the Table 1.

Table 1. Planning results for different maximum service duration.

| Case   | T_{cha} | Locations          | No. of Piles | Total Costs(USD) |
|--------|---------|--------------------|--------------|------------------|
| Case 1 | 24      | Node 1             | 26           | 3.396x10^6       |
|        |         | Node 10            | 30           |                  |
| Case 2 | 20      | Node 1             | 31           | 3.998x10^6       |
|        |         | Node 10            | 36           |                  |
| Case 3 | 16      | Node 1             | 39           | 4.094x10^6       |
|        |         | Node 10            | 45           |                  |

T_{cha} stands for charging time capacity, the total social annual costs of charging facilities are decreasing with the growth of the maximum service duration of charging facilities. The number of charging piles tends to increase with the decreasing of maximum service duration of charging facilities. However, when the number of charging piles increases beyond the upper limit, the planning model have to replan the charging facility locations and increase the number of charging facilities to satisfy the fast charging demand, as we can see from the Table 5 above. Therefore, reasonable determination of the maximum service duration of the charging facilities are significant to the economics of the charging facilities planning and the stable operation of the distribution network.

5. Conclusions
We propose a three-dimensional planning framework for determining the siting and sizing of fast charging facilities in mountainous cities, which can play a guiding role for charging facility planning in other cities with special terrain. We quantify the transportation characteristics of mountainous cities based on the climbing coefficient and establish a model for calculating the travel energy consumption of EV users using a modified Floyd shortest path algorithm. In addition, we use the traffic flow data to estimate the quantity and distribution of fast charging demand, with the objective of minimising the total annual social costs, including construction costs, maintenance costs, expansion costs of power...
grids, electricity purchase costs of EV users, and users’ energy consumption on roads. Numerical experiments are performed to validate and verify the proposed planning method. Such methods can effectively guide the planning of EV fast charging infrastructures without violating constraints. The results obtained for these cases show that the terrain characteristics of the city increase the travel energy consumption of EV users and limit their driving range, which leads the results for charging facility siting and sizing to be changed.

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