OPTIMAL LAYOUT AND SCALE OF CHARGING STATIONS FOR ELECTRIC VEHICLES

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ABSTRACT

Considering energy security and environmental protection, electric vehicles will become a major choice for developing China's automobile industry. The popularization of electric vehicles depends on convenient charging. As the theoretical basis for charging stations, a dynamic traffic network method is used to build a multi-objective optimization model with hard-time-window constraint to obtain the optimal layout and scale of these charging stations. In this model, a minimum capital and charging cost is considered as the optimal objective, and a two-phase heuristic algorithm is proposed to solve this model. Finally, a case study on a simple example verifies the correctness and effectiveness of the proposed model. Results show that the layout of electric vehicle charging stations is determined by the charging demand of different locations and charging time constraints, and that the scale of charging stations is related to the number of electric vehicles, layout of charging stations and duration of charging at peak hours.

1 INTRODUCTION

Considering energy security and environmental protection, electric vehicles will become a major choice for developing China's automobile industry. The popularization of electric vehicles depends on convenient charging. Therefore, the Chinese Government has introduced a series of incentive policies to encourage the purchase of electric vehicles, and made great efforts in areas like the planning and construction of electric vehicle charging stations. However, there is a lack of effective theoretical foundation for planning charging stations.

In considering charging station features and urban planning, grid layout and other factors, the paper [1] proposes a multi-objective programming model. Paper [2] summarizes several typical electric vehicle charging facility location models, and by adding different constraints, establishes a variety of extended models. Paper [3] considers the construction of charging stations should take into account the reliability of power supply, the scale of construction, and the cost of construction. Paper [4] points out that the main indicator of demand for charging stations is traffic and service radius, taking also into account transportation, environmental protection and regional distribution capabilities and other external environmental conditions, plus the region's road network planning and construction

planning. The above papers view charging stations as ordinary electric power facilities. In fact, to determine the location and scale, the investor should consider not only the selected area's land purchase price, the cost of power grids and other factors; moreover, they should meet the needs of maximum charging, taking by the charging process and the road travel time into account. Particularly in the promotion stage of electric vehicles, whether electric vehicle charging are convenient or not will determine the buyers' behaviour.

As the theoretical basis for charging stations, a dynamic traffic network method is used to build a multi-objective optimization model with hard-time-window constraint to obtain the optimal layout and scale of electric vehicles' charging stations [5]. On this basis, the author proposes the corresponding algorithms and empirical analysis.

2 DISCRIPTION BETWEEN THE CHARGING STATION AND CHARGING COSTS

The location and scale of charging stations, should not only consider the economic benefits, but also consider the social benefits after the completion of the charging station.
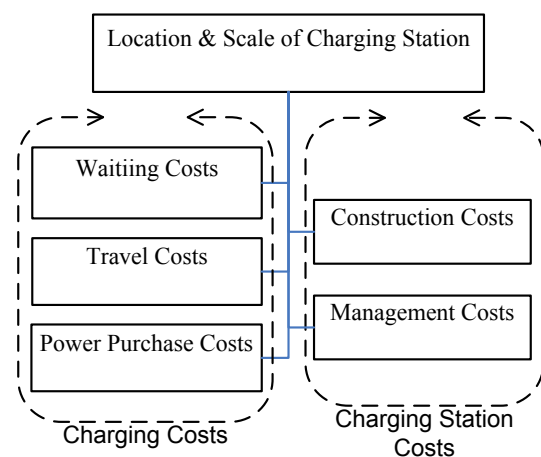
Figure 1: Illustration of cost of charging station and electric vehicle charger

Moreover, the price of charging electric vehicles will affect the cost of purchasing electric power [6]. The location of charging stations and its scale must take into account the dual benefits of charging companies and customers, and analyse the possible minimum of gross social cost. In this paper, an assumption is made that all charging stations will be invested in, constructed and

operated by one charging company, irrespective of competition between stations.

As shown in Figure1, charging cost of customers includes the cost of driving to the station, the cost of waiting to charge electric vehicles and the cost of charging the vehicles. The charging cost of a charging company includes the cost of station construction and variable management cost arising from vehicle charging (station staff salary, the cost of buying electric power from local power companies, etc.).

3 MODEL CONSTRUCTION

Suppose N as the collection of nodes for transportation network as the abstract system of possible stations, each representing a dense area of electric vehicles; $r(r \in N)$ is any single node of the network; $S(S \subset N)$ is the collection of nodes with stations; $s(s \in S)$ is any single node with stations; P_{rs} is the collection of all routes connecting Node r to Node s, with $p(p \in P_{rs})$ representing any single route. For a set duration of time $[0, T]$, the charging need of every electric vehicle in waiting can be satisfied.

Considering that the convenience of charging stations has a direct influence over the purchase of electric vehicles, this paper's discussion of the total time of charging (driving, waiting and charging) is put in a hard-time-window $[0, \tau](\tau > 0)$.

3.1 Choice of routes and charging stations

Suppose the decision-making of future car-owners who want to charge vehicles is similar to that of car-drivers in their choice of destinations and routes. Their choice of charging stations and routes relies on their experience and external information [7]. Charging cost may vary according to the time of charging, the choice of stations and routes, as shown below:

$$\begin{cases} C_{p,rs}(t) = J\upsilon(t + \tau_{p,rs}(t)) + \beta_{s,r}\tau_s(t + \\ \qquad \tau_{p,rs}(t)) + \beta_{p,r}\tau_{p,rs}(t) \\ \qquad \beta_p > 0 \\ \qquad \beta_s > 0 \end{cases} \quad (1)$$

Where $C_{p,rs}(t)$ stands for the overall cost of driving from r to s via the route of p at the time t; J stands for the charging price, a value based on the total investment of the charging company; $\tau_{p,rs}(t)$ stands for the time it takes to drive from r to s at the time of t via the route of p, supposing that it takes no time to drive from s to the station to charge the vehicle; $t + \tau_{p,rs}(t)$ is the moment of arrival at s; $\upsilon(t + \tau_{p,rs}(t))$ is the amount of electric

power it takes to reach a charging station; $\tau_s(t + \tau_{p,rs}(t))$ is the time it takes to charge an electric vehicle (including the time of waiting and charging); $\beta_{p,r}$ and $\beta_{s,r}$ respectively refer to the conversion coefficient of time it takes to reach the station and charge a vehicle.

The first item at the right of the above equation is the cost of buying electric power, followed by the cost of waiting and driving. This paper suppose υ, the electric power it takes to reach the charging station, as constant, the charging power η as constant. Therefore, the time of charging is a constant: υ / η.

The above statistics may lead to the optimal dynamic definitions of charging conditions.

Definition: at any given moment of t in a random site of r, the cost of charging determined by the choice of s the destination and p the route is smaller than the minimum charging cost. Any unchosen station or route leads to a charging cost no smaller than the minimum value [8], which can be expressed in the following equation:

$$C_{rs,min} = \inf \begin{Bmatrix} C_{p,rs}(t) \mid p \in P_{rs}, t \in [0, T], \\ s \in S, r \in N \end{Bmatrix} \quad (2)$$

3.2 Scale and layout of charging stations for electric vehicles

3.2.1 Scale of charging station

$\tau_s(t)$, the amount of time it takes to reach the station at t, is determined by g_s the number of charging machines in the station and $x_{s,s}(t)$ the number of waiting vehicles. When $x_{s,s}(t) \leq g_s$, $\tau_s(t) = \upsilon / \eta$. When $x_{s,s}(t) > g_s$, there will be vehicles waiting to be charged, hence the maximum amount of time it takes to charge a vehicle:

$$\tau_s(t) = \left\lceil \frac{x_{s,s}(t)}{g_s} \right\rceil \frac{\upsilon}{\eta} + \frac{\upsilon}{\eta} \quad (3)$$

Where $\lceil \bullet \rceil$ mean taking the closest integer no smaller than the numeric value.

The first item at the right of the third equation is the time of waiting, the second item the time of charging.

Therefore, the required load on the grid arising from the charging at t is:

$$Q_s(t) = \begin{cases} x_{s,s}(t)\eta & x_{s,s}(t) < g_s \\ g_s\eta & x_{s,s}(t) \geq g_s \end{cases} \quad (4)$$

In the equation, $Q_s(t)$ is the required load on the grid arising from the charging at t the time in s the site.

When vehicles to be charged are outnumbered by charging machines, the required load on the grid in s is equal to the multiplication of the number of charging machines in operation and the charging power; or the required load on the grid equals the power requirement of all charging machines in operation. It can be learned that in the time frame of $[0,T]$, the electric demand of electric vehicles D is:

$$D = \sum_s D_s = \sum_s \int_0^T Q_s(t)dt \qquad s \in S \qquad (5)$$

The scale of stations has a direct influence on the variable management cost (staff salary, the cost of stations' buying electric power from local power companies) in the time frame of $[0,T]$, which can be seen as follows:

$$K_{sv} = \int_0^T k_{sv} Q_s(t)dt \qquad s \in S \qquad (6)$$

Where k_{sv} stands for the average cost arising from charging load in the time frame of $[0,T]$, namely the price of electric power offered by the local power company, maintenance cost and other operation fees.

3.2.2 Station layout and pricing
Given the constancy of D the charging demand, the layout of the station will influence the investment and pricing of charging on the part of the charging company. Most of the cost of a charging station stems from station expansion, transformer capacity expansion and smart control devices. A charging company can recover the above cost by pricing, as shown in the 7th and 8th equations below.

$$K_s = K_{sf} + K_{sv} = k_{sf} g_s + \int_0^T k_{sv} Q_s(t)dt$$
$$s \in S \qquad (7)$$

In the 7th equation, K_s is the gross cost of each station in s in the time frame of $[0,T]$; K_{sf} is the fixed cost of investment in station construction in s; K_{sv} is the variable cost of investment in station construction in s; k_{sf} is the average fixed cost of investment in station construction in s (converted to the average fixed cost of investment in each charging machine in the time frame of $[0,T]$), which may vary according to the load capacity of local power grids and transformers' capacity [9].

With the station's cost function, we can conclude that J the price of charging on the part of charging companies follows the rule below:

$$J = (1+R)\frac{K}{D} = (1+R)\frac{\sum_{s \in S} K_s}{D} \qquad 0 \le R \le 1 \qquad (8)$$

Where K stands for the total investment of the charging company, R stands for the cost-plus coefficient.

The 8th equation is under the assumption that the charging company will take cost-plus pricing strategy, by which there is a margin of profit after the recovery of investment cost.

3.3 Objective function
The layout and scale of charging stations not only determine the cost of investment on the part of the charging company, also they influence the cost of driving to and waiting in the station. Investment in the station and its operation cost will translate into the price of charging vehicles as the cost of purchasing electric power for car=owners. In the time frame of $[0,T]$, we have as objective function the minimum amount of cost for the charging company and the car-owner, and have as decision variables S the station's layout and g_s the station's scale. Hence the following equation:

$$\min_{S,g_s} Z = K + C \qquad (9)$$

$$C = \sum_{r \in N} \int_0^T f_{p,rs}(t) C_{p,rs}(t)dt \qquad p \in P_{rs} \qquad (10)$$

In the 10th equation above, C is the function of overall cost on the part of the car-owner; $f_{p,rs}(t)$ represents the number of vehicles following the route of p from r to s at the time of t.

3.4 Dynamic network constraint

3.4.1 Time window constraint
Time window constraint is as follows:

$$\tau_s + \tau_{p,rs} \le \tau \qquad (11)$$

The 11th equation right above means that the total amount of time it takes to drive and charge the vehicle shall not exceed τ .

3.4.2 Flow conservation constraint of electric vehicles
Flow conservation constraint of electric vehicles is as follows:

$$e_s(t) = \sum_{r,s,p} f_{p,rs}(t - \tau_{p,rs}(t)) \qquad (12)$$

$$u_s(t) =$$

$$\begin{cases} e_s(t - \tau_s) < g_s - x_{s,s}(t - \tau_s) \\ e_s(t - \tau_s) \ge g_s - x_{s,s}(t - \tau_s) > 0 \\ e_s(t - \tau_s) > 0 > g_s - x_{s,s}(t - \tau_s) \end{cases} \qquad (13)$$

Where $f_{p,rs}(t - \tau_{p,rs}(t))$ represents the number of vehicles following the route of p in driving from r to s for charging at the moment of $t - \tau_{p,rs}(t)$; $e_s(t)$ is the number of vehicles arriving at stations at the time of t to

be charged; $u_s(t)$ is the number of electric vehicles leaving the station after being charged.

The 12th equation describes the relationship between the number of electric vehicles to be charged in s at different moments and the number of cars driving from the dense area of r where electric areas are running.

The 13th equation describes the status of leaving the station after being charged under different conditions of awaiting charging service.

3.4.3 Flow propagation constraint

Flow propagation constraint is as follows:

$$\frac{dx_{s,s}(t)}{dt} = e_s(t) - u_s(t) \qquad s \in S \qquad (14)$$

The 14th equation describes the dynamic change and status of waiting vehicles.

4 TWO-STAGE HEURISTIC ALGORITHM

Paragraphs above analyse how the scale and layout of charging stations for electric vehicles affect the cost of charging companies and car-owners. A sound layout of such stations could minimize the cost of both parties. As regards the optimal layout and scale of charging stations, this paper adopts a two-stage heuristic algorithm to work out a solution. First, define the area for constructing charging stations (S collection), and then define the station's scale based on the area's location and its transportation network. Here are the steps:

Step 1: Set the parameters: the need of charging at different moments in each place, resistance coefficient in different road section, the cost of investment in constructing charging stations in each site.

Step 2: Search for the route with the lowest cost of driving, and make a ranking, $\{s_1, s_2, \cdots \}$

Step 3: Check if the time it takes to arrive at s_1 meets the inequation of $\tau - \tau_p < \upsilon/\eta$, τ_p is the smallest average amount of time for driving. If the inequation isn't met, stop searching and jump to Step 5; if it's met, jump to Step 4.

Step 4: Search for another site s_2, so that driving to s_1 and s_2 as a set will cost the least. Repeat Step 3 to pinpoint the site of minimal investment within the smallest viable collection.

Step 5: Search for other sites where the cost of time for constructing new stations is small than the accrual of the cost of investment.

Step 6: If the accrual is minus 0, make the site the charging station, and repeat Step 5. If the accrual is plus 0, stop searching, as the site is perfect for constructing a charging station, and the scale is perfect.

In the above 6 steps, the first four steps are considered Stage One "**Choose the Site for Charging Stations**",

Step 5 and Step 6 are considered Stage Two "**Define the Optimal Scale of the Charging Station**".

This paper assumes the positive absoluteness of charging an electric vehicle. In fact, Access to car-owners' behavioural patterns calls for massive sampling survey and statistical analysis.

5 EXAMPLE ANALYSIS

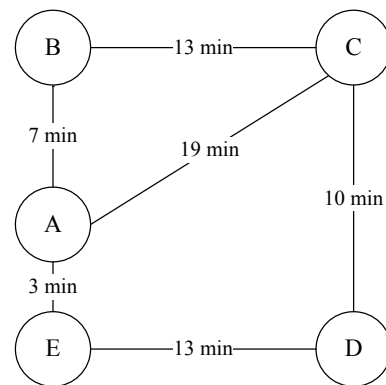Observe and consider the simple network of Figure 2 below.

Figure 2: Network diagram

Set A, B, C, D, E as five sites with different electric capacity, electric vehicle ownership and road transportation. The time of driving varies due to the carrying capacity, traffic flow and road length. For instance, it takes at least 19 minutes to drive from A to C, but 20 minutes to drive from B to C. Suppose that the car-owner is of sound mind, he or she will choose the shortest route. Suppose that the vehicles under study are electrically powered only, charged at a fast and average duration of 10 minutes. The largest amount of time for charging a person can take is 20 minutes, and we have the hard-time-window for charging as [0,20min]. Table 1, combined with above suppositions, leads to Table 2.

Table 1: Basic Data

Site	Cost of Investment in Each Station (in RMB one thousand)	Overall Number of Cars to be Charged
A	2000	4
B	3000	7
C	4000	3
D	2500	6
E	1500	5

It can be seen from Table 2 that the largest amount of time (hard time window) a person can tolerate driving from A, B, E to C, D meets the inequation of $\tau - \tau_p < \upsilon/\eta$. Likewise, the time a person can tolerate driving from C, D to A, B, E exceeds the hard-time-window. To make the layout of future charging

stations meet the need of the hard-time-window, we should set up a charging station at two sites respectively, $i \in \{A, B, E\}, j \in \{C, D\}$. If we compare the total cost of investment in the construction of each charging station, the best solution is to make D and E the site for charging stations, each equipped with six fast charging machines and eleven fast charging machines. This will meet the demand of charging for electric vehicles in areas under study, with the lowest overall cost.

Table 2: Peak demand charging profile and the scale of the charging stations

Site	Time of driving to each location (min)					Station Scale	Cost invested
	A	B	C	D	E		
A	0	7	19	16	3	10	0.26
B	7	0	13	23	10	11	0.41
C	19	13	0	10	22	7	0.34
D	16	23	10	0	13	6	0.18
E	3	10	22	13	0	11	0.25

6 CONCLUSIONS AND ADVICE

The popularization of future electric vehicles is determined by the convenience of charging these vehicles. By modeling and calculation, this paper has come to this conclusion based on some assumptions: the layout of charging stations for electric vehicles is largely determined by the amount of electric power required and the time of charging which may vary from place to place; the scale of charging station is relevant to the number, distribution and time of charging of waiting vehicles at peak hours.

The construction of electric vehicles should be planned based on the charging need of electric vehicles, plus the mode of charging. A sound layout of such stations plays an irreplaceable role in the popularization and development of electric vehicles. The following suggestions are proposed hence.

(1) The government should offer a comprehensive plan, gradually establish the supporting service system for electric vehicles, and formulate policies that bolster the infrastructure of electric vehicles;

(2) The government should set up a specialized plan of infrastructure improvement for electric vehicles, especially facilitating charging at city roads, highways, residential areas and public parking lots;

(3) The government should encourage citizens and entities to participate in the construction and management of these charging stations, explore multiple ways of charging and modes of business;

(4) In the enlargement of electric market needs, the government should endeavor to make the energy-supply network more efficient, thus fueling the popularization of electric vehicles.

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