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Layout and optimization of EV charging infrastructure based on service scope constraints: A case study of Tianjin

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ABSTRACT: The development of electric vehicles (EV) is constrained by factors such as the spatial distribution and planning volume of charging infrastructure. In order to determine the planning volume of charging piles in charging stations and the spatial layout of charging infrastructure service area within the service radius of Tianjin, this paper firstly determines the service area demand based on the service radius, combined with the demand prediction function and the EV ownership, and secondly forms the charging infrastructure service area with the central place theory large spatial layout, and finally determine the planning volume of charging infrastructure through queuing service system. The research results can provide a new theoretical basis for the layout planning of charging infrastructure, and finally put forward the relevant factors and development trends for the optimal layout of charging facilities.

1. INSTRUCTION

The industrialization and large-scale development of EVs and their charging facilities is an important measure to implement China's "double carbon" strategic goal and build a new type of power system. The 14th Five-Year Plan of Modern Energy System proposes to optimize the layout of charging infrastructure and promote the synergistic development of vehicle-pile. Combined with the operation of EV charging infrastructure released by China EV Charging Infrastructure Promotion Alliance, from January to October 2022, the incremental charging infrastructure was 2.09 million units and 5.28 million new energy vehicles were sold, with an incremental pile-vehicle ratio of 1:2.5. The construction of charging infrastructure can basically meet the rapid development of new energy vehicles, but there is still a gap with the vehicle-pile ratio of 1.1 proposed by the National Development and Reform Commission: 1, but there is still a certain gap with the goal of the National Development and Reform Commission.

Shi [1] proposed that the layout orientation of new energy vehicle charging infrastructure needs to be in line with the local government's urban planning, road planning and other policies, and Tianjin clearly pointed out the construction radius of new energy vehicle charging infrastructure in each region in the "Implementation Plan for Accelerating the Construction of New Energy Vehicle Charging Infrastructure in Tianjin (2018-2020)", but did not comprehensively consider the construction radius of each region in the specified radius Based on how to determine the spatial location of charging stations and the construction quantity of charging piles in each region, Zhang [2] proposed that therefore the construction of charging infrastructure is chosen in the easier to build locations during the construction process, which makes it difficult to form a larger spatial layout of the charging infrastructure service area, and Li [3] proposed that the density of new energy vehicle ownership in the region should be determined proportionally to the Marianov [4] et al. introduced the queuing theory model for the first time in the maximum coverage site selection problem, and modeled charging stations as M/M/1 and M/M/m queuing systems in their work. Wang [5] et al. proposed that the queuing theory has the advantage of being able to provide a more accurate portrayal of the number of EVs arriving at charging stations for charging, and can plan reasonable charging station capacity by setting waiting time constraints, queue length constraints The advantage of queuing theory is that it can provide a more accurate picture of the pattern of the number of EVs arriving at charging stations, and can plan a reasonable charging station capacity by setting waiting time constraints, queue length constraints, etc., to better guarantee the charging experience of users.

This paper determines the spatial location of charging infrastructure by combining the central place theory with the service radius of charging infrastructure to achieve full coverage of charging service in the planning area, and at the same time determines the planning quantity of charging piles in the estimated charging stations in the service radius according to the queuing theory and the scale quantity of EVs, so as to improve the matching degree between the layout planning of EV charging infrastructure and EVs and make the service experience of

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customers and the charging facilities This study is beneficial to the development of EV charging facilities. This study is beneficial to the layout and optimization of EV charging facilities, and can provide some theoretical basis for the layout of charging facilities.

2. CHARGING FACILITY PLANNING OBJECTIVES AND SERVICE TARGETS

The object of this paper is the rechargeable EV (PEVS), which is a type of motor vehicle that can be charged by an external power source (e.g., a wall outlet). The battery inside the vehicle provides all or part of the power needed to operate the vehicle. These include battery EVs (BEVs), plug-in hybrid vehicles (PHEVs), modified hybrid vehicles, or conventional internal combustion engine vehicles. Compared with traditional fuel vehicles, new energy vehicles are characterized by low energy consumption, clean energy, low pollution, and low operating costs.

The planning objectives of this paper are the spatial location of charging stations and the number of charging facilities in charging stations. Charging stations are similar to gas stations for fuel cars, in that they concentrate a large number of charging piles in charging stations, and customers go to the charging stations to charge their new energy vehicles. Most of the charging piles in charging stations are DC fast charging piles. Fast charging piles charge faster, but they are also slightly slower than switching stations, and according to statistics, it takes about 30 minutes to charge a typical new energy vehicle to 80% using fast charging piles.

3. EV CHARGING INFRASTRUCTURE LAYOUT AND OPTIMIZATION MODEL

3.1. EV Charging Demand Forecast

There are two main types of demand forecasts for existing charging facilities: one is based on the number of original charging facilities, and the other is based on the EV ownership and charging facility ratios in the target area. Due to the late promotion of EVs in China, the second forecasting method is commonly used at present, such as Hu [6] introduced the forecast of EV ownership based on the forecast of motor vehicle ownership and determined the number of charging facilities based on the vehicle-pile ratio. Ge [7] considered the spatial constraint of charging infrastructure, divided the sub-types of EVs into three scenario pile utilization characteristics of high, medium and low, and estimated the vehicle-pile ratio of different types of EVs, highlighting the difference types of fast charging and slow charging, and finally determined the total demand of charging facilities.

As for the construction of charging infrastructure, Xu [8] pointed out that the planning layout of new energy vehicle charging infrastructure is determined by the charging demand in the region, while the charging demand of new energy vehicles in the region is determined by the ownership of new energy vehicles, the type of new energy vehicle users and the average range of new energy vehicles within the studied region. Morrow [9] suggests that the larger the number of new energy vehicles in the region, the higher the charging demand for new energy vehicles and the higher the number of charging infrastructure requirements for new energy vehicles.

Let the annual EV ownership be L and the average daily charging demand of vehicles be i. The total charging infrastructure demand in the region is

$$P = L \bullet i \tag{1}$$

If there are n charging stations with service radius R in a given area of S, the total number of EVs to be served per day at each charging station, if the geographical factor is not considered, is

$$p = \frac{L \cdot i \cdot \pi \cdot R^2}{S} \tag{2}$$

The prediction process of charging demand is shown in Table 1.

Table 1 Charging Demand Forecast

Number of electric vehicles (units)	Total area of the region (km^2)	Charging station service radius (km)	Number of charging stations in the area (pieces)	Total daily charging demand (units)	The total number of electric vehicles that a single charging station needs to serve daily
L	S	R	$n = \frac{S}{\pi \cdot R^2}$	$P = L \cdot i$	$p = \frac{P}{n}$

3.2. Central Place Theory

The central place theory is based on a square hexagonal grid for spatial layout planning. The center point needs to serve the central service area determined based on the specified radius. If the center service range is established based on circles, at this time, the center point serves the largest area, but the three adjacent circles will have a blank area in the tangent part, and this area is the area that cannot be served by each center point, and if the center point is added in this blank area, it will cause the overlapping of the service area. Huang [10] proposed that full coverage of charging services of new energy vehicle charging infrastructure to the area within the hexagon can be achieved, while each hexagon can be seamlessly connected to each other, so that there is no area that fails to be served in the study area. In this paper, the hexagonal theory of central place theory is used for the layout planning of charging infrastructure, and the center point of each hexagon is the construction point of new energy vehicle charging infrastructure, and the service area of each point is the whole hexagonal area. As shown in Figure 1.

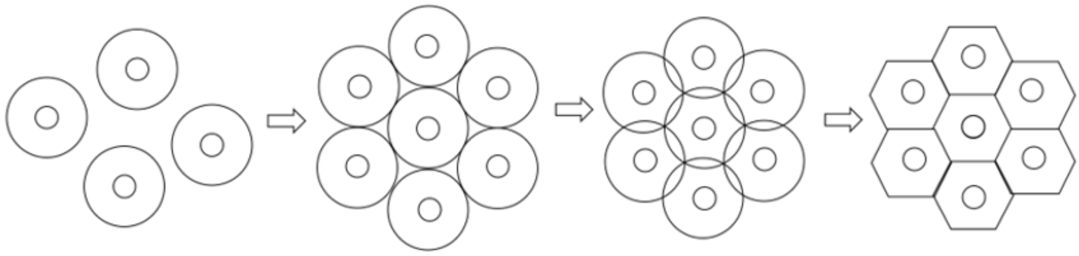

Figure 1 The Formation Process of The Ortho-Hexagonal Region

3.3. M/M/C Model of Queuing Service System

The system has c (c ⩾ 1) charging piles serving independently and in parallel. The customer arrival time interval T in the system obeys the parameter λ Poisson distribution and the customer arrival is independent of each other. The random variables in the system are independent of each other and the service mechanism is first-come Service first, if the system is busy, customers will wait in line, the service time of the charging pile obeys the negative exponential distribution, the average service rate is the same, both are μ.

The equilibrium equation for the probability of state of the system is obtained from the system steady state:

$$\begin{cases} \mu P_1 = \lambda P_0 & (3) \\ (n+1)\mu P_{n+1} + \lambda P_{n-1} = (\lambda + n\mu)P_n \quad 1 \le n \le c & (4) \\ c\mu P_{n+1} + \lambda P_{n-1} = (\lambda + n\mu)P_n \quad n > c & (5) \end{cases}$$

In the system, n represents the number of electric vehicles in the queuing system; Pn is the probability corresponding to the state of n electric vehicles in the system at this time; when nϵ(0,c), it indicates that the charging pile can satisfy the arriving vehicles, There is no need to queue, and there are (cn) idle charging piles at this time; if nϵ(c,+∞), the system has no idle charging piles, and customers need to queue.

When $\sum_{n=0}^{+\infty} P_n = 1$ and only when the help desk service intensity$\rho = \frac{\lambda}{c\mu} < 1$, the system reaches a steady state.

$$P_0 = \left[\sum_{n=0}^{c-1} \frac{1}{n!}\left(\frac{\lambda}{\mu}\right)^n + \frac{1}{c!} \cdot \frac{1}{1-\rho} \cdot \left(\frac{\lambda}{\mu}\right)^c\right]^{-1} \quad (6)$$

$$P_n = \begin{cases} \frac{1}{n!}\left(\frac{\lambda}{\mu}\right)^n P_0 \quad n \le c & (7) \\ \frac{1}{c!\,c^{n-c}} \cdot \left(\frac{\lambda}{\mu}\right)^n P_0 \quad n > c & (8) \end{cases}$$

Then substitute$L_q = \sum_{n=c+1}^{+\infty}(n-c)P_n$ intoP_n to get:

Probability of system idleness:

$$P_0 = \left[\sum_{n=0}^{c-1} \frac{1}{n!}\left(\frac{\lambda}{\mu}\right)^n + \frac{1}{c!} \cdot \frac{1}{1-\rho} \cdot \left(\frac{\lambda}{\mu}\right)^c\right]^{-1} \quad (9)$$

Utilization of charging facilities:

$$\rho_0 = \frac{\lambda}{(c\mu)} \quad (10)$$

Therefore the average number of queues waiting for services in the system:

$$L_q = \sum_{n=c+1}^{+\infty}\left[(n-c)\frac{1}{c!\,c^{n-c}}\left(\frac{\lambda}{\mu}\right)P_0\right] = \frac{(c\rho)^c\rho}{c!\,(1-\rho)^2}P_0 \quad (11)$$

The average number of queues of customers in the system:

$$L_s = L_q + \frac{\lambda}{\mu} \quad (12)$$

Average service time per customer in the system:

$$W_q = \frac{Lq}{\lambda} = \frac{(c\rho)^c\rho}{c!\,(1-\rho)^2\lambda}P_0 \quad (13)$$

Average time spent in the service system per customer in the system:

$$W_s = \frac{L_s}{\lambda} \quad (14)$$

From this, the optimal number of charging posts C in different charging stations with the same service radius can be determined based on the demand.

4. APPLICATION VALIDATION

4.1. Daily Service Vehicle Volume In Tianjin

The Tianjin Municipal Government has clearly pointed out in the "Implementation Plan for Accelerating the Construction of New Energy Vehicle Charging Infrastructure in Tianjin" the construction radius of new energy vehicle charging infrastructure in each region of Tianjin.

The regional information of new energy vehicles in Tianjin is obtained from the relevant government public website of Tianjin, and the process of determining the daily service vehicles of each regional charging station according to the electric vehicle ownership in each district of Tianjin in 2020 and the service radius of each district planned by Tianjin is shown in Table 2.

Table 2 The Number Of Vehicles Served By Charging Stations In Each District Of Tianjin

Area	EV parc (units)	Day-charge demand （$i = 0.6$）	Total area of the region (square kilometers)	Charging station service radius (km)	The total number of EV that a single charging station serves daily
six urban districts	85077	51046.2	180	0.9	721.28
Beichen district	49444	29666.4	478	0.9/3	779.52
Xiqing district	40172	24103.2	570.8	0.9/3	530.37

Jinnan district	20288	12172.8	420.22	0.9/3	363.83
Dongli district	19442	11665.2	477	0.9/3	307.16
Binhai new area	52641	31584.6	2270	0.9/3	174.76
Wuqing district	27356	16413.6	1574	3/5	523.90
Jinghai district	18620	11172	1414.9	3/5	396.69
Baodi district	7971	4782.6	1509.66	3/5	159.16
Jizhou district	7350	4410	1470	3/5	150.72
Ninghe District	4897	2938.2	1031	3/5	143.18

4.2. Optimal Configuration Of Charging Station Capacity

The Poisson's parameter of this charging station is λ=30, and the charging time of EV is 30min, then μ=2. And because the charging service intensity $\rho = \frac{\lambda}{c\mu}$ <1, the number of charging posts should be greater than 15, i.e., the number of charging posts must be 16 to meet the charging service demand. Then the operation index of charging station is shown in Table 3.

Table 3 Charging Station Operation Index

Number of charging piles	Number of customers waiting in the queue(person)	Total number of customers in the system(person)	Waiting time in queue(h)	Time spent in service(h)
16	10.951	25.951	0.365	0.865
17	7.5	22.5	0.25	0.75
18	1.95	16.95	0.065	0.56
19	0.995	15.995	0.066	0.566
20	0.525	15.525	0.035	0.535

The high service intensity of the system will lead to long queuing time, and the low service intensity of the system will result in low system utilization. Through the comprehensive comparison in Table 3, when the number of charging piles is 18, the optimal number is reached, so we choose to use 18 charging piles in this area.

5. CONCLUSION

EV charging infrastructure is one of the key factors to determine whether EVs can enter the market on a large scale. Due to the different development bases and regional traffic conditions in each province and city, the planning basis and supporting construction standards of urban charging facilities also vary, so it must be carefully studied and analyzed and planned according to local conditions and the current development situation of each city. This paper provides some research ideas for the spatial layout of charging infrastructure service areas and the number of charging facilities in each area in terms of charging infrastructure layout methods and charging infrastructure layout optimization models.

With the development of battery storage technology, the research and development of big data technology in the direction of transportation-energy integration and the optimization of operation decision-making mechanism, the charging efficiency and service level of urban charging facilities will be greatly improved, and how to further optimize the construction layout of urban charging facilities needs to be thoroughly studied and discussed.

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