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A New Model for Optimal Deployment of Electric Vehicle Charging and Battery Swapping Stations

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Abstract

It is recognized widely that the electric vehicle is of vast potential as an environment-friendly traffic tool. And the construction of the charging and battery swap stations is of critical importance for popularizing it. However, the deployment of the charging station is far from mature even though the construction is being undertaken in some cities. In order to reduce the cost and land use, many researchers and practitioners advocate an oil-electricity union, i.e., we can build the charging and battery swap stations at the existing gas stations. This paper proposes a new location model based on the set cover model taking the existing traditional gas station network as the candidate sites to determine the distribution of the charging and battery swap stations. A numerical experiment is presented to illustrate and verify the proposed model. Our model can help governments to promote the development of the electric vehicle.

Keywords: *Electric vehicles; traditional gas station; charging station; spatial load forecasting model*

1. Introduction

It has become a consensus that we must reduce carbon emissions to mitigate global warming. Low carbon development has become the national development strategy in many countries. At the same time, greenhouse gas emissions, particularly carbon dioxide, are increasing as energy consumption within the transportation sector is expanding. In China, the sales of cars have reached the top since 2010. It can be assumed that the number of cars will remain growing in the long run in China. It has been a serious threat to our energy security since 85% of the country's gasoline is consumed by cars and as the oil relatively resource-poor country, our dependence on foreign oil has been more than 50% in 2009. Development of new energy vehicles has become an important strategy to cope with climate change and energy crisis. Electric vehicle, known for their advantage as local, emission free, energy-conserving, has become the future trend.

Electric vehicle is new energy car driven wholly or partly by power-driven motor as a dynamic system. In accordance with the current technology, there are three types: pure battery electric vehicle, hybrid plug-in electric vehicle and fuel cell vehicle. The known charging patterns include ordinary charging, rapid charging and battery replacement. The ordinary charging method is applicable to equipment at home, shopping malls, parking lot and other public places, like along the street, supermarkets and office buildings for its long

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waiting hours. The battery swapping is convenient. The swapping machine in the service station will replace the batteries running out of power with fully charged battery pack and the process is generally within 10minutes.Rapid charging intends to charge deeply in a short period of time. Therefore, it mainly serves for the long-distance travel or vehicles in need of recharging in short time. According to the customers' preference analysis, the driving range and the concerns about the supporting facilities are the most important factors that influence their buying choice. To popularize the electric vehicles, we should consider the construction of charging and battery swapping facilities as precondition except for the high price and unresolved technical bottleneck.

In reality, the deployment of the charging stations offering the rapid charging service is our priority. Their existence will alleviate the common users' concerns about the recharging process in the travel and will greatly facilitate the spread of electric vehicles and decrease the carbon emissions, achieving the purpose of energy-saving. Up to now, quite a few cities begin to construct the charging station while lacking a mature system for the planning and deployment. The construction of highly efficient energy supply net is a precondition for the commercialization and industrialization of the electric vehicle. Therefore, the research of the deployment of electric vehicle stations has great practical significance.

In order to reduce the cost and land use, many researchers and practitioners advocate an oil-electricity union, i.e., one can build the charging and battery swap stations at the existing gas stations. In this paper, we will propose the idea of considering traditional gas stations as candidate sites and present a new model based on the set cover model to choose the suitable ones. It takes advantage of the existing gas stations network and makes the early decision process convenient. We also conduct a numerical experiment to verify our model and algorithm.

The rest paper is organized as follows.The review of the literature related will be discussed in Section 2. The principles of the location and the problem definition will be described in Section 3. A numerical experimentis conducted to test and verify the model in Section4 and Section 5 will provide the conclusions and further directions.

2. Literature Review

The literature on the location of the charging and battery swapping station is sparse. In 2007, with the electric vehicle being put into practical use, the research about this area has got attentions. Li, Weige, Jiang [2] introduced the design and the operation concept of the vehicle charge-station on the basis of the operation mode of the electric vehicle for the 2008 Olympic Games.Morrow, Karner, Francfort [3] analyzed the infrastructure requirements for plug in hybrid electric vehicles (PHEV) and provided an estimate of the infrastructure costs associated with PHEV deployment. Gao, Huo, Luo [4] provided a comprehensive analysis of the present situation on the development of electric vehicles and some principles and basic steps for the distribution of electric vehicle charging stations, and used the model of combination analysis of qualitative and quantitative. Sweda, Klabjan [6] presented an agent-based decision support system for identifying patterns in residential EV ownership and driving activities to enable strategic deployment of new charging infrastructure. Wang, Liu, Lu, *et al.* [7] introduced the distribution model of charging facilities in terms of these real backgrounds. This model captures the influence of important factors which depends on users' choice behavior. Zhang, Liu, Niu, *et al.* [8] compared the difference between traditional gasoline car and electric vehicle and put forward planning models of electric vehicle charging facilities considering different economic levels.

Liu Z, Wen F, Ledwich G [13] present a new method to handle uncertainties in the optimal siting and sizing of DGs under the chance constrained programming (CCP) framework. They firstly develop a mathematical model of CCP with the minimization of the cost as the objective, security limitations as constraints, and the siting and sizing of DGs as optimization variables and then employ a Monte Carlo simulation-embedded genetic-algorithm-based approach to solve the developed CCP model. Singh M, Panigrahi BK, Abhyankar A R, *et al.* [15] propose an optimization problem to determine relay coordination under maximum penetration level of distributed generation by optimally selecting location, parameters and size of distributed generation. The proposed optimization problem is implemented on IEEE 15 node radial system.

Apart from these, the researchers also analyzed and discussed about the location of the charging stations from different perspectives. Wang, Li [16] followed the concept of set cover for proposing a refueling-station-location model using a mixed integer programming method based on vehicle-routing logics. The results show that range is crucial in reducing the facility-location costs, and therefore is an important issue in the development of alternative-fuel-vehicle technology. Wang, Wang [17] proposed another hybrid model with dual objectives to economically site refueling stations to simultaneously serve intercity and intra-city travel. This model can be applied to plan a network of refueling stations for the emerging and/or monopolistic automotive market of alternative fuel vehicles. Ip A, Fong S, Liu E [19] focus on planning BEV charging locations to be installed in urbanized areas where they are usually characterized by dense traffic concentrations, restricted street spaces and other complex factors such as the distribution of power grids. Wang, Huang, Zhang, *et al.* [20] presented a multi-objective planning model which is comprehensive for the layout of electric vehicle charging station taking in account factors including electric vehicles sustainable development, characters of charging station, characters of charging consumers, distribution of the charging demand, the power grid and factors of municipal planning. Wang, Liu, Han et al [21] introduced a distribution model of EV charging station. They introduced the attractive factor of charging stations and the area-different factor. Wang, Liu, Cui *et al.* [22] establisheda location model of charging stationsbased on electricity consumption along the roads among cities and present a quantitative model of charging stationsbased on the conversion of oil sales in a certain area..

Two basic objectives for the location problem are to minimize the cost, including the construction cost, the integrated cost and so on, and to minimize the users' loss. Lingfeng K, Zifa L, Huan Z [23] presented an optimization cost model of locating and sizing of charging station for electric vehicle. The model simulates the number of electric vehicle based on the distribution of residents and determines the weight of candidate address by using of Analytic Hierarchy Process (AHP). Li, Li, Yong *et al.* [24] forecasted the total amount and distribution of electric vehicles and proposed the charging station minimal cost model of the year on the basis of the conservation theory of regional traffic flow. Ren, Shi, Zhang *et al.* [25] used a dynamic traffic network method to build a multi-objective optimization model with a hard time window constrains to obtain the optimal distribution and scale of electric vehicles' charging stations. In this model, the minimum of capital cost and charging cost is treated as the optimization objective, and a two-phase heuristic algorithm is proposed to solve this model. Jia, Hu, Song *et al.* [26] introduced an optimization process with the objective of the model minimizing the integrated cost of charging stations and consumers. Liu, Wen, Ledwich [27] first identified the optimal sites of EV charging stations by a two-step screening method with environmental factors and service radius of EV charging stations considered. Then, a mathematical model for the optimal sizing of EV charging stations is developed with the minimization of total cost associated with EV charging stations to be planned as the objective function and solved by a modified primal-dual interior point algorithm.

Ge, Feng, Liu [28] proposed a method of locating and sizing of charging station for electric vehicle based on grid partition. This method aims at minimizing the users' loss on the way to the charging station, zoning the planning area with grid partition method, and choosing the best location of each partition in genetic algorithm on the consideration of traffic density and charging station's capacity constraints. Chen, Kockelman, Khan *et al.* [29] used parking information from over 30,000 personal-trip records in the Puget Sound Regional Council’s 2006 household travel survey to determine public parking locations and durations. The algorithm minimizes EV users’ station access costs while penalizing unmet demand. Shao-yun G E, Liang F, Hong L I U, *et al.* [30] presented a planning model which considers the road network structure, vehicle flow information and capacity constraints. The model selects the station sites and plug-in locations with the objective of minimizing the sum of users’ wastage cost on the way to the charging station and the investments of station lines, realizes the auto-partition of station service areas by the weighted Voronoi diagram, and also optimally allocates the station capacities based on the queuing theory. Feng, Ge, Liu [31] presented a novel method for electric vehicle charging station planning based on weighted Voronoi diagram. The users' minimum loss on the way to the charging station is chosen as the objective function for locating the charging station. While Feng L, Ge S, Liu H, *et al.* [32] construct a planning model of charging stations on the trunk road. The maximum expectation of electric vehicles coming to stations for recharge from the trunk road is chosen as the objective function for locating the charging station.

From all above, we can conclude that the research about the location of the charging stations for electric vehicles has attracted attention in recent years. Although these papers have proposed the basic concepts, the factors that affect the planning of the charging stations and built different mathematical models, the environmental cost and the usage of existing traditional gas station network were less to be considered and made use of. Therefore, an optimization model for rapid charging stations considering those factors was proposed in this paper.

3. The Model

When deciding the candidate sites for the charging and battery swapping stations offering rapid charging and swap service, the principles according to the guiding regulations should be taken into consideration: (1) The overall planning should be compatible with the local regional and urban plan and in line with the requirements of environmental protection and fire safety; (2) The sites should be easy to obtain the power supply and close to the terminal and take advantage of the transportation, fire protection, water supply and drainage and flood control and other public facilities nearby; (3) Stations within the city limits should be close to the city roads and away from the intersection of the city roads, heavy traffic, potentially dangerous places, dusty, corrosive gas and intense vibration or high temperatures [33].

Besides, the construction of the charging stations should meet a series demand from power supply, monitoring system and security. The traditional gas stations have metalmost all these necessary demanding requirements. It provides us with the possibility that the traditional gas stations can be taken as the candidate sites which maybe transformed into charging stations. This scheme saves a lot of efforts and takes advantage of the existing network in the city.

The problem is described as follows. On the gas stations network, the government should decide how many the charging or battery swapping stations should be built, where they locate, and which grades they are. The cost of transformation of each candidate site depends on its scale and conditions. The objective is to minimize the cost of rebuilding.

Considering the green and low carbon emission background of this promotion, the objective is to choose the appropriate candidate sites that each customer will exhaust the least emissions on the way. Since we also consider the cost of transformation, it is not appropriate to add the carbon emissions directly into the objective function. Here we assign a unit cost to present the environmental cost produced by the customer's charging behavior. Generally, this unit cost varies depending on the engine type, terrain driven and the driver tendencies. In this situation, we assume it is a measurable constant representing the mileage and the environmental cost.

Here are the hypotheses of this model:

1: The candidate sites for the charging stations are chosen from all the gas stations in the planning area.

2:Each demanding point represents a small area and the demand means the total number of electric vehicles in need of charging.

3: All the users in each demanding point can only accept the service in one charging station in a fixed period of time.

4: The environmental cost has a simple linear relationship with the distance, which is the Euclidean distance.

The notation used in this paper is as follows.

p : The fixed number of electric vehicle charging stations in the planning area

$P=\{p\}$: The set of origin-destination paths selected on the network

V_p : The set of nodes belongings to a path p

I : The set of demand points

J : The set of candidate sites

D_i : The demand at node i

m : The grade of the charging station

F_{jm} : The transformation cost of the grade m charging station at candidate j

C_m : The service capacity of the grade m charging station

d_{ij} : The distance between demanding point i to candidate site j

$$x_{jm}=\begin{cases}1, & \text{if we choose the candidate site } j \text{ and transform it into grade } m \text{ charging station}\\ 0, & \text{otherwise}\end{cases}$$

$$y_{ij}=\begin{cases}1, & \text{if demand point } i \text{ is covered by a charging or battery swapping station located at } j\\ 0, & \text{otherwise}\end{cases}$$

Then based on the objective function and constraints, the problem is formulated mathematically as follows:

$$\min \sum_j \sum_m F_{jm} x_{jm} \quad (1)$$

$$s.t. \ \sum_j \sum_m x_{jm} y_{ij} \geq 1, \forall i \in I \quad (2)$$

$$y_{ij} \leq \sum_m x_{jm}, \quad \forall i \in I, j \in J \quad (3)$$

$$\sum_i D_i y_{ij} \leq \sum_m C_m x_{jm}, \forall j \in J \quad (4)$$

$$\sum_m x_{jm} \leq 1, \forall j \in J \quad (5)$$

$$x_{jm} \in \{0,1\}, \forall j \in J, m \in M \quad (6)$$

$$y_{ij} \in \{0,1\}, \forall i \in I, j \in J \quad (7)$$

The objective function (1) is to minimize the transformation cost. Constraint (2) states that each demand point should be covered by at least one charging station. Constraint (3) means that the service can be offered only if the charging station is located in this candidate site. Constraint (4) restricts the service capacity of the charging station. Constraint (5) means one candidate site can only be transformed into one grade charging station. Finally, constraints (6) and (7) are the integrality constraint.

4. Numerical Experiment

Based on the model proposed above, the first step is to choose the set of suitable candidate sites. Upon the idea that has been discussed and verified, we eliminate the unsatisfied ones from the whole set of gas stations and then get the set of candidate sites J. The selection criteria can partly refer to the principles of the location discussed. Then we collect the relative data to determine the parameter P.

In this study, the model with multi-level location problems is pure integer linear problem (PILP). Here we use LINGO to solve this model. LINGO provides a completely integrated package that includes a powerful language for expressing optimization models, a full-featured environment for building and editing problems. Take a city as example. First we divide the city into different districts based on the administrative area. Then acquire the total planning number of charging stations issued in the government plan and the specific number P of charging stations in each area through the spatial forecasting model. Mark each residential area in each divided district as the demanding points and get the distance between the demanding points i and candidate sites j through the specific planning map. In the simulation experiment these demanding points and distances will be generated randomly.

Generate 20 demanding points and 10 candidate sites randomly from 50×50 coordinate plane. The objective is to choose $P = 7$ charging stations. The distribution of the demanding points and the candidate sites are in the Table 1and 2. The demanding number in each demanding point is between [20, 40]. According to the issued “Technical specifications of electric vehicle power supply and protection”, there are four levels of the charging stations. We assign a rational service capacity and transformation cost to each level presented in Table 3. For the environmental cost, we assign a constant $\lambda = 1$.

Table 1. Demanding points coordinates and corresponding demand

NO.	*X*	*Y*	*Demand*
1	22.85	46.69	32
2	39.65	24.16	38
3	8.27	44.58	30
4	5.51	22.87	23
5	21.39	26.64	35
6	29.47	11.42	35
7	21.07	45.94	32
8	31.25	27.36	25
9	40.83	46.14	31
10	32.62	25.76	32
11	18.54	34.74	21
12	2.3	26.66	38
13	10.52	33.74	32
14	2.5	26.01	33
15	33.33	19.69	28
16	25.58	39.38	24
17	40.08	40.5	26
18	23.11	32.12	40
19	9.25	17.48	27
20	12.71	18.3	30

Table 2. Candidate sites coordinates

NO.	*X*	*Y*
1	32.00	6.00
2	39.00	8.00
3	35.00	45.00
4	10.00	41.00
5	33.00	42.00
6	12.00	24.00
7	44.00	1.00
8	34.00	25.00
9	34.00	14.00
10	25.00	34.00

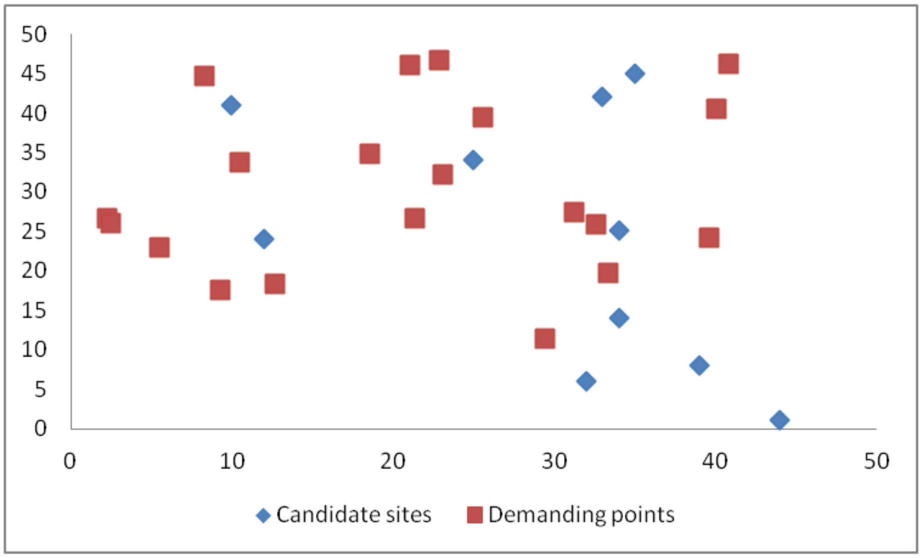

Figure 1. The layout of the demanding points and candidate sites

Table 3. Stations level and corresponding service capacity and transformation cost

Stations Level	Service Capacity	Transformation Cost
1	350	350
2	250	230
3	110	100
4	70	50

Run the algorithm on LINGO 12 and get the results shown in Table 4, then the best solution is 3,4,5,6,8,9,10, and the total cost is 4966.4.

Table 4. The results

grade	sites{demanding points(demand)}
level 2	6{4(23),12(38),14(33),19(27),20(30)}
	8{2(38),8(25),10(32),15(28)}
	10{5(35),11(21),16(24),18(40)}
level 3	4{3(30),7(32),13(32)}
level 4	3{9(31),17(26)}
	5{1(32)}
	9{6(35)}

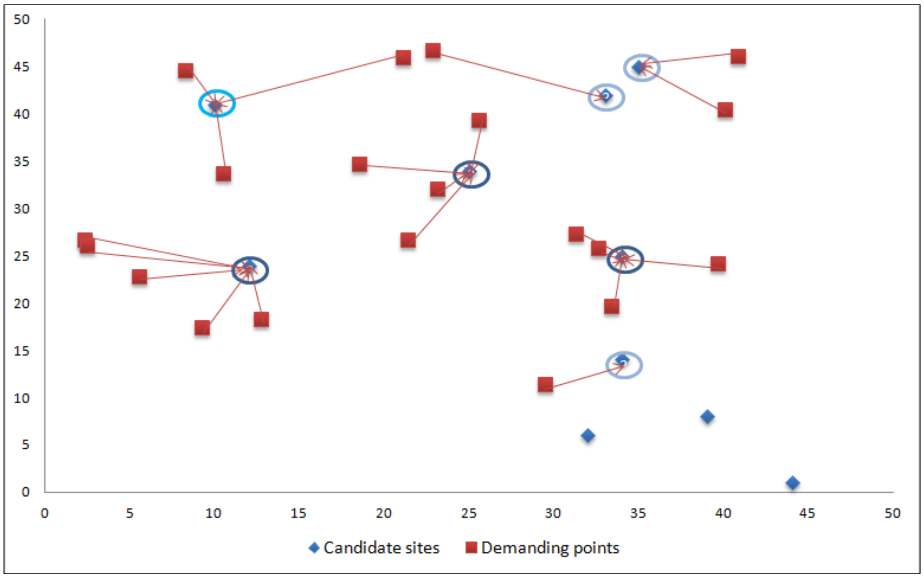

Figure 2. The allocation of the demanding points and transformed candidate sites

According to the results, selecting a different candidate site to rebuild the charging stations decides the distribution of the demand and the grade of the transformed charging stations. This method is practical and helpful for the government when making decisions about the deployment of the charging stations.

5. Conclusions

In this paper, a novel idea of choosing the suitable charging stations has been proposed and practiced here. We talked about the feasibility of the method and put forward the criteria when employing this approach. By this way we can greatly reduce the complexity when facing the location problem without any reference and experience. The traditional gas stations meet most of the conditions that a charging station should satisfy which enable the construction process needs only some refurnishing and rebuilding. The corresponding part of the transformation process can be partly and mostly completed in accordance with the relevant technical standards which involve equipping the charging apparatus proportional to the stations' area and scale. This method helps the government to make decisions while reducing huge initial construction expense.

Besides, the distribution of the planning charging stations is further discussed by dividing the planning area in which the resident loads is used to determine the practical amount of the planning charging stations. The number of the charging stations is commonly viewed as the objective function while in this research we assume the total amount of the charging stations in the planning is determined and can be acquired through the regulations or relative documents issued by the government planning department. After all, the number and the developing speed of the charging station should consist with the whole city planning and technical development. On the basis of the relative documents, here introduces the spatial load forecasting model to determine the specific amount in each divided district. This method gives full consideration to the power system based on which allocate the number of planning charging stations, which is well-founded and reliable.

The optimization model constructed here introduces the objective function of minimizing the total cost of deployment of the charging stations, including the transformation cost and the environmental cost which means the carbon emission exhausted along the way. Here we translate it into an environmental cost through the mileage related to the location problem. Then we use the LINGO to solve the minimization process and get the operation results. The results have proven practical and helpful for government to solve this problem. When used in the practical situation, we can just input the relative parameters to get the results, providing the final decisions reference observation.

This article provides a convenient and economic way for the government to make decisions and use the method taking the supported electricity industry into account. The vigorous development of electric vehicle industry attracts a huge investment and brings more business opportunities which deserve further study.

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