Research on Optimal Layout Strategy of Electric Vehicle Charging Network by Considering Land Resource and Policy Constraints

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Abstract. With the increasing demand of people for transportation, the number of automobiles in cities continues to increase, which leads to haze weather, PM2.5 pollution and other environmental problems. In order to reduce fossil energy consumption and carbon emissions, the development of energy-saving and environmentally friendly transportation tools has become the focus of attention. In this paper, the electric vehicle industry has developed rapidly, the sales market has begun to take shape, and the Chinese government has given policy support such as purchase subsidies. However, the layout of charging network of regional electric vehicles represented by residential areas is not perfect, which leads to the low satisfaction of users’ charging demand, the insufficient utilization of resources and the high cost of charging station network. In this paper, a single objective non-linear programming model for minimizing the cost of investment, operation and maintenance of charging stations with resource and policy constraints is established. In the optimization of the model, combined with the advantages of particle swarm optimization and genetic algorithm, the hybrid algorithm of particle swarm optimization and genetic algorithm is selected to obtain the optimal solution of the model. Taking a residential area of 10.5 km² as an example, the optimized charging station and its service scope are obtained, the location and capacity of charging station are determined, and the accuracy and validity of the model are verified.

1. Introduction
The development of electric vehicle industry plays an important role in solving the problem of insufficient energy supply and environmental deterioration, and it is also an important way to implement the national policy of "environmental protection". Facing the development opportunities of electric vehicles, China has formulated and implemented systematic policies to actively promote the development of the electric vehicle industry. In 2014, some policies were promulgated, such as exemption from purchase tax, licensing concessions, charging price subsidies and incentives for charging infrastructure construction. Since 2014, the government has promulgated specific incentive standards for charging infrastructure construction. The policy has shifted from purchasing subsidies to accelerating charging infrastructure construction and enhancing charging convenience of electric
vehicles. The improvement of charging infrastructure has stimulated consumers’ demand for electric vehicles. Sales of electric vehicles have risen rapidly and the market of electric vehicles has officially started. Reasonable charging station location and capacity can improve the charging convenience of electric vehicle owners. According to reference[1], in the positioning and capacity of electric vehicle charging station, policy support is the most important factor in actual production and application, and the scheme violating policy will not be allowed to be implemented.

In the reference[2], the continuous Markov chain model is used to study how to increase the peak load of the system. At the same time, an orderly charging control method is developed to maximize the benefits of the grid under the condition of limited power supply, and the charging behavior is controllable. In reference[3], Markov chain is used to describe a variety of vehicle habits with three states to determine the specific charging requirements at each time. To achieve charging pile planning with small operating cost as the goal. In reference[4], service demand partitions are compared by comparing service radius. The location of vehicle recycling sites is optimized by using a large coverage model[5]. The location of charging station in planning area is determined by grid method, and the concepts of load rate control coefficient and charging load intensive area are put forward. Then the planning model of charging station and the profit model of charging station are established[6]. Chaotic particle swarm optimization algorithm is applied to optimize the layout of charging station[7]. An optimization method of charging station location and capacity is proposed with full consideration of factors such as road network structure, traffic information and user path loss. The weighted Voronoi diagram is used to realize automatic division of service scope of charging station, and then the optimal scheme is selected from various planning schemes with the goal of minimizing social cost[8]. It is believed that the relevant national support policies directly promote the market-oriented development of the electric vehicle industry, and industrial policies are conducive to guiding, protecting and promoting the early development of emerging industries[9]. It advocates that industrial policy is the sum of a series of policies, involving all links and departments of the industrial chain, and has an important impact on the development of the industry. To sum up, the research on policy mainly stays at the qualitative analysis level. The policy is classified by the theory of industrial chain. Through the comparative analysis with the development experience of foreign electric vehicles, the current situation and problems of domestic electric vehicles development are analyzed, the advantages and disadvantages of the policy are evaluated, and the application example analysis of the electric vehicle industry policy is lacking. The existing research on layout optimization is based on some algorithm theory to obtain the theoretical optimal solution, without systematically considering the constraints of policy and data in practical application.

In this paper, a single-objective non-linear programming model for minimizing the cost of investment, operation and maintenance of charging stations considering resource and policy constraints is established and solved, which can provide a reference for the layout planning of charging stations.

2. Mathematical Model of Regional Distribution of Electric Vehicle Charging Station
Firstly, in the selected area, the charging demand area is divided. Secondly, the objective function is constructed to minimize the total cost. Finally, the specific location and total capacity of the charging station are determined by the optimization method. Because there are special parking lots and fixed routes for service vehicles such as environmental hygiene electric vehicles and electric buses, charging stations are selected in a relatively small range and usually adopt a fixed mode. However, electric taxis, electric private cars and other passenger cars have a wide range of driving, strong mobility and no fixed mode. In view of this situation, we can establish a charging demand area and simplify the problem. The object of this study is mainly for electric taxis and private cars.

2.1. Distribution of Charging Demand Zones
The method of partitioning is to divide the electric vehicle with charging demand into several charging zones randomly. The geometric center of each charging zone approximates the charging demand zone,
and establishes the optimization function of investment cost, operation cost and maintenance cost to determine the specific location and total capacity of charging station.

2.1.1. Feasibility
In a certain period of time, the central position of charging demand area and the number of electric vehicles are unchanged, so that the electric vehicle with charging demand can be regarded as the load point at the center of gravity of this area. In addition, in order to unify and coordinate power supply and bring into play the maximum economic benefits of both suppliers and consumers, the charging station will guide users who need to charge to the nearest charging station to charge, so that users who need to charge will be fixed at a certain place to charge, which makes the customers who need to serve at the charging station relatively stable, reflecting the practical significance of charging demand community.

In addition, according to the principle of conservation of traffic flow in a region, when the number of electric vehicles in and out of a region is the same, the number of electric vehicles in the region is certain. Therefore, the number of charging services that a charging station needs to provide can refer to the number of electric vehicles in a certain area, scientifically determine the number of vehicles that need to be charged in a certain period of time, so as to provide more planned service to customers.

2.1.2. Principle of division
In order to make the division of charging demand zones scientific and reasonable, various factors should be fully considered. This paper mainly follows the following points:

1) Considering policy factors, the layout scheme should receive policy subsidies as far as possible.
2) Considering the constraints of rational use of resources, such as the high cost of land acquisition in the central area, charging stations should not be located in the central area of the city, so the central area should be excluded when dividing, charging demand area should be more in the areas with dense electric vehicles than in the sparse areas;
3) Considering the range of electric vehicles, the distance between charging demand zones should not be too far, and should be controlled within a reasonable distance.

2.2. Establishment of Mathematical Model
Scientific, reasonable and feasible charging service network can not only promote the marketization of electric vehicles, but also take into account the requirements of rational utilization of resources. It can not only meet the charging demand of electric vehicles, bring convenience to users of electric vehicles, but also reduce the waste of resources[10]. Considering the basic principles and influencing factors of charging station layout planning, a charging station layout planning model for electric vehicle with minimal charging cost is established. The mathematical model is described as follows: Considering the basic principles and influencing factors, the layout planning model of charging station for electric vehicle is established on the basis of minimizing charging cost. Its mathematical model is described as follows:

\[
\min A = A_1 + A_2 + A_3
\]

\[
A_1 = \sum_{j=1}^{m} k_j C_j \left[ \frac{a(1+a)^n}{(1+a)^n-1} \right]
\]

\[
A_2 = \sum_{j=1}^{m} C_j (1+\epsilon)
\]

\[
Z_3 = B_0 M x T \sum_{j=1}^{m} \sum_{i=1}^{d_j} b_{i,j} c_{i,j} n_{i,j} P_i
\]

In the formula: \(A_1\) represents the fixed cost of investment in the construction of charging stations; \(A_2\) represents the cost of operation and maintenance of charging stations; \(A_3\) represents the charging cost of charging users. \(m\) denotes the number of charging stations to be built; \(C_j\) denotes the construction cost
of charging stations; a denotes the discount rate; n denotes the investment recovery period; \( k_i \) denotes the variable if \( k_i=1 \) denotes that the \( j^{th} \) candidate station is selected, otherwise \( k_i=0 \); epsilon denotes the conversion coefficient; \( B_0 \) denotes the loss cost per unit vehicle distance; \( M_x \) denotes the number of days per year; \( T_f \) denotes the average daily charging times per charging user. The distance between the collection center of \( C_{ij} \) charging demand community \( i \) and candidate station \( j \); \( \eta_{ij} \) expresses the road condition coefficient; \( P_i \) expresses the quantity of electric vehicles in charging cell \( i \). \( I_j \) represents the collection of charging users from charging cell \( i \) to charging station \( j \).

\[
T_f = \frac{l_1}{h}
\]  

Among them: \( l_1 \) represents the power consumption of electric vehicles for 100 kilometers; \( l_2 \) represents the average daily travel distance of electric vehicles; \( h \) represents the capacity of electric vehicle batteries.

\[
\sum_{j=1}^{m} b_{ij} = 1
\]  

Among them: \( b_{ij} \) is 0-1 variable, which restricts the charging users in charge demand community \( i \) to charge at the first charging station at a certain time. \( b_{ij}=1 \) represents the charging user in the charging demand area \( i \) to charge at the charging station \( j \). \( b_{ij}=0 \) means that the charging user in the charging demand community \( i \) can not charge at the charging station \( j \).

### 2.3. constraint condition

Considering the actual situation, such as reasonable utilization of data and compliance with relevant policy requirements, the following constraints should be added to the charging station layout planning model.

#### 2.3.1. Resource constraint

It is mainly reflected in the charging capacity constraints of charging stations. If the capacity allocation is not reasonable, the charging stations will not meet the charging demand or excessive capacity will occur.

\[
K_j = \frac{PT_j \sum_{i=1}^{l} b_{ij} P_i}{T_f \eta_{ij}(S_j) \cos \phi_i}
\]

\[
\sum_{i=1}^{l} \leq K_j (K_j \cos \phi)
\]

In the formula: \( K_j \) denotes the distribution capacity of the \( j^{th} \) charging station; \( P \) denotes the charging power of a single electric vehicle; \( T_f \) denotes the charging time of the \( i^{th} \) charging mode per day; \( \eta \) denotes the charging efficiency; \( f \) denotes the required coefficient of the charger; \( t(S_j) \) denotes the loading rate of the charging station; \( \cos \phi \) denotes the power factor of the charging station.

#### 2.3.2. Policy Restraint

Taking Beijing Electric Vehicle Charging Infrastructure Special Plan (2016-2020) and Beijing Electric Vehicle Social Public Charging Facility Operation Assessment and Incentive Interim Measures as examples, the policy requires that the average service radius of public charging network within the Sixth Ring Road is 5 kilometers. Policy constraints are mainly reflected in the service radius constraints of charging stations. Layout schemes that do not meet the policy requirements will not be allowed.

\[
C_q \leq R
\]
In formula: service radius constraint of charging station is expressed by $R$.

Joint formulas (1), (5), (6) and (9) are used to construct the mathematical model for optimal planning of charging station layout. There are many variables in the model, including discrete variables of charging users and integer variables of charging station demand. Traditional optimization algorithm is difficult to solve such a complex problem. This paper chooses genetic algorithm to solve it.

3. Particle swarm optimization genetic hybrid algorithm

In this paper, a hybrid algorithm of particle swarm optimization (PSO) and genetic algorithm (GA) is proposed, because both PSO and GA operate on a group of individuals to reflect the parallelism of the algorithm, and both of them are judged by the value of fitness function, and the encoding method is also based on binary live real number encoding. The essence of particle swarm optimization is to improve the diversity and ergodicity of the population, enhance the global convergence and search speed of the algorithm by adding chaotic variables in particle initialization, aiming at the shortcomings of particle swarm optimization algorithm, such as easy dependence on initial values, easy to fall into local optimum, slow convergence speed and poor accuracy. So the two algorithms can complement each other by combining their advantages and complement each other. Finally, the feasibility of the algorithm is verified by simulation.

3.1. Particle Swarm Genetic Hybrid Algorithms:

In this paper, the particle swarm genetic hybrid algorithm (PSO-GA) is used to initialize the population, and the population size is set to $N$. First, the population is evolved into a certain algebraic $M$ by the particle swarm optimization algorithm. Then, according to the fitness function value, the $N-M_k$ individuals whose fitness function value is better than the mean value of the fitness function value of the population are extracted directly, and then they enter the next generation, and the remaining $(N-M_k)$ individuals are left to $(N-M_k)$ On the basis of individual, GA evolution is carried out to produce $(N-M_k)$ individuals. The remaining $(N-M_k)$ individuals and $(N-M_k)$ individuals of GA evolution are combined to select the first half $(N-M_k)$ individuals. Finally, the individuals directly proposed by PSO evolution and $(N-M_k)$ individuals derived from GA evolution are combined to form a new population $N$, and the next evolution is continued.

3.2. Specific steps to implement PSO genetic hybrid algorithm

Step1: Initialize population parameters such as all $N$ individual positions and velocities in particle swarm optimization, total algebra Grace of hybrid algorithm evolution, two learning factors $y_1$, $y_2$, maximum velocity $V_{max}$ in particle swarm optimization, and particle swarm evolution algebra $M_1$; parameter cross probability $P_c$ and mutation probability $P_b$ in genetic algorithm;

Step2: Initialize the population in the solution space and randomly generate $N$ particles.

Step3: Calculate the fitness function value according to the pre-determined fitness function.

Step4: Total algebraic count $S=1$;

Step5: Judge whether $S$ is less than Grace or not. If $S$ is less than Grace, go ahead and turn to Step15 instead.

Step6: PSO evolutionary algebraic count $m=1$;

Step7: Judge whether $M$ is less than $M$ or not. If $m$ is less than $M$, continue the next step and turn to Step10 instead.

Step8: Update the velocity and position of the particle swarm according to the formula.

Step9: $M=m+1$;

Step10: Ranking $N$ individuals according to fitness function, and calculating the mean value of fitness function of each particle, the fitness is proposed directly by $M_k$ individuals due to the mean value.

Step11: Evolution of the remaining $N-M_k$ individuals with GA.

Step12: Two groups of $N-M_k$ individuals were merged, and the better $N-M_k$ individuals were selected according to the fitness function value.
Step13: The $M_i$ individuals directly proposed by PSO evolution and the $N-M_i$ individuals evolved by GA will form a new particle swarm.

Step14: $k=K+1$, to Step5;

Step15: Output of the optimal solution and the optimal fitness function value.

In order to make better use of advantages and avoid disadvantages, a new algorithm combining particle swarm optimization and genetic algorithm is adopted in this paper. The principle and implementation process of this algorithm are also introduced. This hybrid algorithm is slightly better than particle swarm optimization in terms of success rate and average fitness. And it is obviously stronger than genetic algorithm. The global convergence and search speed of the algorithm are enhanced.

4. Case study

A Development Zone in Shenzhen covers an area of 10.5 km². By 2020, the population density was 13,000 people/km², and the per capita car ownership was 10%, of which electric vehicles accounted for 30%.

### Table 1. Number and location of electric vehicles

| Serial number | Coordinate/km | Quantity | Serial number | Coordinate/km | Quantity |
|---------------|---------------|----------|---------------|---------------|----------|
| 1             | 1.73          | 3.8      | 126           | 1.27          | 1.7      | 69       |
| 2             | 1.94          | 3.4      | 100           | 1.47          | 1.26     | 107      |
| 3             | 2.08          | 2.99     | 80            | -0.13         | 2.86     | 92       |
| 4             | 2.3           | 2.4      | 117           | 0.07          | 2.42     | 79       |
| 5             | 2.71          | 1.91     | 130           | 0.26          | 2.06     | 62       |
| 6             | 1.11          | 3.5      | 122           | 0.53          | 1.52     | 140      |
| 7             | 1.21          | 2.99     | 75            | 0.84          | 0.96     | 107      |
| 8             | 1.43          | 2.64     | 75            | -0.75         | 2.55     | 122      |
| 9             | 1.69          | 2.13     | 135           | -0.41         | 1.96     | 218      |
| 10            | 2.09          | 1.58     | 130           | -0.07         | 1.22     | 186      |
| 11            | 0.5           | 3.16     | 95            | 0.24          | 0.53     | 241      |
| 12            | 0.74          | 2.72     | 89            | -0.13         | 2.3      | 75       |
| 13            | 0.9           | 2.37     | 81            | 0.96          | 1.71     | 117      |
| 14            | 1.1           | 2.02     | 70            | -0.57         | 1.01     | 100      |

Assuming that 90% of all users choose fast charging, charging time $T=2$, charging power $P=150$ kW.

Assuming that 10% of all users choose normal charging, charging time $T=6$, charging power $P=20$ kW, and all vehicles charge once every two days.

### Table 2. Parameter table

| Name               | Parameter | Name               | Parameter |
|--------------------|-----------|--------------------|-----------|
| cosφ               | 0.9       | population size    | 50        |
| Payback period     | 20        | Selection probability | 0.2     |
| discount rate      | 0.1       | Crossover probability | 0.8      |
| Operating Cost     | 0.2       | Mutation probability | 0.01     |
| Discount Coefficient |         |                     |           |
| Parameter                         | Value         |
|----------------------------------|---------------|
| Road tortuosity coefficient      | 1.3           |
| Load rate                        | 0.75          |
| Reentry coefficient              | 1.5           |
| Comprehensive Power Consumption per Kilometer for Electric Vehicles kWh/km | 0.15          |
| Unit Loss Coefficient of Electric Vehicle | 1.3           |
| Average Daily Distance /km       | 200           |
| Demand Coefficient of Charger    | 0.7           |
| Battery Energy of Electric Vehicle/kWh | 60            |
| Charging efficiency              | 0.9           |
| Simultaneous Rate of Charging Station | 0.7         |
| Charging radius /km              | 1.2           |
| Maximum number of iterations     | 100           |

4.1. Optimized results

The unit capacity cost consists of transformer unit capacity, charging facility unit capacity cost and other equipment unit capacity cost. According to the data in reference[5], the unit capacity cost $C=678¥/kWh$ is calculated.

The number of charging stations in the planning area is calculated by the following formula:

$$n = \left\lceil \frac{Pb}{24f_s\eta Se(s)\cos \phi} \right\rceil + 1 \quad (10)$$

Among them, the total number of electric vehicles in the B-planning area. And calculated, $n=6$. The schematic diagram before planning is shown in Figure 1, which divides the whole planning into 28 charging demand zones. Each red dot represents the center of mass of one charging demand zone. Users in charging demand zones are approximately considered to be at the red dot. The overall distribution of charging demand zones is more uniform, and there are no more concentrated phenomena. If the addressing results are stable, the feasibility of the addressing model can be illustrated.

![Figure 1. The layout of charging demand districts](image1)

Firstly, $n=6$ is optimized, and the results are shown in Figure 2.

![Figure 2. Plan in the planning area when $n=6$](image2)
The distribution capacity and coordinates of six charging stations are shown in Table 3.

| The number of charging station | The capacity of charging station | The coordinates of charging station |
|-------------------------------|---------------------------------|-------------------------------------|
| 1                             | 17579                           | 17219, 3.5230                       |
| 2                             | 30499                           | -0.3839, 2.0801                     |
| 3                             | 17504                           | -0.0699, 1.2301                     |
| 4                             | 28189                           | 1.9867, 1.7987                      |
| 5                             | 14301                           | 0.8910, 2.6694                      |
| 6                             | 19930                           | 0.9040, 2.6715                      |

As shown in the figure, the six circles represent six charging stations. The charging demand area covered by No.1 charging station is 1, 2, 3 and 6, the area covered by No.2 charging station is 17, 18, 19, 22, 23 and 26, the area covered by No.3 charging station is 20, 24 and 28, the area covered by No.4 charging station is 4, 5, 9, 10, 15 and 16, and the area covered by No.5 charging station is 21. The smallest target function is $2.6885 \times 10^7$, that is, the smallest annual average cost is $2.6885 \times 10^7$ rmb/year.

The graph below shows the relationship between the cost and the number of evolutions when $n=6$. It can be seen from the graph that the hybrid algorithm combines particle swarm optimization and genetic algorithm. When the number of iterations reaches about 25 times, the stable solution has been obtained, basically no change, and the convergence speed is very fast.

From Figure 3, it can be seen that the layout of Number 1, 2, 4 and 6 charging stations is reasonable. They are located in the center of several charging demand zones, which can not only meet the charging demand, but also make rational use of the device. But the planning of No.3 and No.5 charging stations is unreasonable. Among them, No.3 charging station covers only 3 charging demand zones of No.20, No.24 and No.28, and the utilization rate is low. For these three almost linear zones, in order to reduce the charging cost of drivers, the location of charging station almost coincides with that of No.24 charging station, which reduces the total charging cost. But invisibly, drivers in charge demand districts of No.20 and No.28 have a sense of inequality, which reduces their satisfaction with service. The No.5 charging station covers only 21 and 25 charging demand zones, and the utilization rate is lower. There is also a problem that the charging station overlaps with No.25 charging demand zones.

There are many factors to be considered in the planning of charging station. The situation that the charging station covers fewer charging demand zones will lead to the following drawbacks:

(1) Waste of peripheral facilities;
(2) Improving the difficulty of municipal transportation planning;
(3) Reducing the stability of power grid;
(4) Increase the cost of land use.
Because of the above disadvantages, the scheme of \( n = 5 \) is not practical. Considering that the location of No.3 and No.5 charging stations in \( n = 6 \) is adjacent and close to each other, if only one charging station is set up in the district center of Number 20, 21, 24, 25 and 28 charging demand, many problems mentioned above can be solved.

4.2. Planning Area Construction Results of Five Charging Stations

The \( m = 5 \) is optimized, and the results are shown in Figure 4. The capacity and coordinate table of the charging station are shown in Table 4.

| The number of charging station | The coordinates of charging station | The capacity of charging station |
|-------------------------------|----------------------------------|---------------------------------|
| 1                             | 1.9368, 1.8392                   | 28271                           |
| 2                             | 0.8856, 2.6631                   | 19930                           |
| 3                             | -0.3687, 1.9989                  | 31436                           |
| 4                             | 1.7198, 3.5507                   | 17587                           |
| 5                             | 0.2669, 1.1266                   | 31805                           |

Because of the procedure, the charging station number in the result of \( n = 5 \) is different from that in the case of \( m = 6 \). In the result of \( n = 5 \), the charging demand area covered by No.1 charging station is 4, 5, 9, 10, 15 and 16 charging demand area covered by No.2 charging station is 7, 8, 11, 12, 13 and 14 charging demand area covered by No.3 charging station is 17, 18, 19, 22, 23 and 26 charging demand area covered by No.3 charging station. The charging demand area covered by station is 1, 2, 3, 6 and 5 is 20, 21, 24, 25 and 28. Through calculation, the minimum value of objective function \( F_{\min\text{-cost}} = G^l + G^o + G^c \) is \( 2.696969 \times 10^7 \), that is, the minimum annual average cost is \( 2.6885 \times 10^7 \) rmb/year.

Figure 4. Plan in the planning area when \( n = 5 \)

Figure 5. The cost and evolution number when \( n = 5 \)
The graph of the relationship between cost and number of evolutions when \( n=5 \) is shown in Fig 5. From the graph, we can see that the algorithm of \( n=5 \) can still get more stable solutions when the number of iterations reaches 25 or so, and it has no change basically, and the convergence speed is very fast. For the same example, two different kinds of programming can achieve such fast and stable convergence, so it is feasible to solve the objective function by using this new particle swarm optimization genetic hybrid algorithm.

5. Conclusion
This paper comprehensively considers the constraints of resources and policies in charging station layout planning. The objective function of minimizing investment cost, operation and maintenance cost is established by using single objective non-linear programming. Combining the advantages of particle swarm optimization and genetic algorithm, the hybrid algorithm of particle swarm optimization and genetic algorithm is selected to obtain the optimal solution of the model. The optimized charging station and its service range are obtained through case analysis. According to the data analysis of \( n=5 \) and \( n=6 \), the No.5 charging station in the case of \( n=5 \) covers 20, 21, 24, 25 and 28 districts perfectly, which solves all kinds of problems in the case of \( n=6 \). Meanwhile, the annual average cost of \( n=5 \) is 0.31% higher than the annual average cost of \( n=6 \). The location and capacity of the charging station obtained verify the accuracy and validity of the model.

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