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Location optimization of electric vehicle charging stations: Based on cost model and genetic algorithm

Guangyou Zhou [a], Zhiwei Zhu [a], Sumei Luo [b, *]

[a] School of Economics, Fudan University, Shanghai, 200433, China
[b] School of Finance, Shanghai University of Finance and Economics, Shanghai, 200433, China

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ABSTRACT

Nowadays, the development of new energy science has gradually entered a good situation, and accordingly, electric vehicles have been recognized by people all over the world and rapidly popularized in various countries. However, the rapid growth of electric vehicles has caused a series of problems, such as insufficient number of charging stations, uneven distribution, and high cost, which are becoming increasingly serious. In order to solve the above problems, this paper takes Ireland as an example for research. Based on the collection of relevant information, this paper first tries to build a social total cost model, and calculates the total operating cost of charging stations under various distribution conditions. In this model, the total social cost is subdivided into comprehensive economic cost and environmental cost. Economic costs include construction costs and fees, while environmental costs include electricity consumption and carbon dioxide emissions. Secondly, this paper established a charging station location optimization model based on genetic algorithm, which simplified the Irish territory into a rectangle with a length of 350 km and a width of 200 km, subdivided it into small squares, and adjusted the correlation coefficient to meet the charging demand. This solution solves the minimization problem of operating cost under the constraints of depreciation period of charging station, power consumption per unit distance of charging station and vehicle charging probability. Finally, in order to determine the factors that may have a significant impact on the total cost of charging stations, we conducted sensitivity analysis and found that the total cost is very sensitive to the number of charging stations and the possibility of EV charging per day.

1. Introduction

In today's society, it is remarkable that the development and popularization of new energy have been widely concerned by the world. Therefore, as a representative of the development and application of new energy, new energy electric vehicles are favored and recognized by the majority of consumers. With the increasing number of new energy electric vehicles, the demand for charging stations for new energy vehicles is also increasing. The maximum rationalization of the distribution of charging stations can effectively meet the charging needs of electric vehicles. Therefore, it has become an important research topic to determine the optimal distribution of EV charging stations in this paper. This research has attracted extensive attention of scholars, including sitting charging stations of taxis [1–3], buses [4], and private EVs. There are also many research scholars from economic cost, user demand This paper analyzes the factors affecting the distribution of charging stations from different angles such as environmental benefits [5–9], and puts forward the optimal distribution model and algorithm of electric vehicle charging stations [10–14].

At present, the allocation of charging stations is small even if the EV market in many countries is huge and full of potential, disorganized and lack of planning, which will have a serious impact on the EV market in the long run. Therefore, determining the optimal distribution of EV charging stations based on regional and market factors has an important guiding role in the development of the EV market.

The number and location distribution of charging stations is an important factor affecting the development of the electric vehicle industry, which is related to various economic and social factors. It also affects the operation of the electric car business itself. In conclusion, the analysis and study of the maximum rationalization

* Corresponding author.
E-mail address: luosumei@shufe.edu.cn (S. Luo).

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of the number and location distribution of charging stations is of great guiding significance to the popularization of electric vehicles.

Therefore, this paper chooses Ireland as the research object. Through the construction of electric vehicle charging station location model, and the construction of charging station distribution optimization calculation model. On this basis, this paper takes the five major cities in Ireland as the research object to collect relevant data, so as to establish a siting model and distribution optimization model of charging stations based on reality, simulate the optimal distribution results of charging stations, and conduct sensitivity analysis.

The innovation of this paper is mainly reflected in the following aspects: (1) the research perspective is novel. From the perspective of total social cost, the optimal charging station distribution model based on total social cost is constructed to provide a theoretical basis for simulating the optimal charging station distribution; (2) Using the recognized genetic algorithm with obvious advantages, the optimal layout of charging station is iterated and simulated; (3) In parameter setting, the model no longer uses the traditional Euclidean distance, but introduces the road bending coefficient to calculate the distance between the electric vehicle and the charging station, so that the model results are more consistent with the actual demand; (4) By introducing the coefficient, the demand for charging stations in the five major cities of Ireland is considered to better simulate the actual distribution of EV charging demand in each city, so as to determine the optimal distribution location of charging stations.

The rest of this paper mainly includes: Section 2, literature review, literature review from the influencing factors of charging station layout, the construction of optimal model and model algorithm; Section 3, data selection and processing, this part explains the data source and processing process; In section 4, model construction and solution, the optimal distribution model of charging stations based on total social cost is constructed and solved by genetic algorithm. Section 5, example simulation and analysis, this part takes Ireland as an example to simulate the optimal charging station layout and conduct sensitivity analysis. Section 6, conclusions and prospects, summarizes the whole paper and puts forward prospects for future research.

2. Literature review

The research on the location of electric vehicle charging stations can be divided into the following three categories: one is to study factors influencing the location of the charging station, the other is to build a model for optimal location, and the third is the algorithm associated with the model.

2.1. Influencing factors

There are many factors that affect the number and location of charging stations, and the location of charging stations is influenced by many factors, including economic problems of operators, charging satisfaction of drivers, power loss of vehicles, traffic congestion of transportation system and safety of power grid [6]. Falvo et al. Considering the electricity consumption of both electric vehicles and subways, in order to use existing power plants as much as possible to save energy [15]. Guo et al. Using the fuzzy TOPSIS method to determine the location of the charging station based on environmental, economic, and social standards [16]. Asamer et al. Calculated the charging demand based on the taxi data, and determines the location of the charging station based on many factors such as environmental conditions, electricity, and laws [1]. Luo et al. Studied the impact of transportation costs and transportation networks on the location of charging stations [17]. Zhu et al. Studied the impact of user costs and charging station costs on the number and location of charging stations. Studied the influence of consumer preferences and total charging demand on the location of charging stations [5]. Sun et al. Divided residents into short distance and long-distance categories according to their travel characteristics, so as to determine the number and location of charging stations [18].

Although electric vehicles have good environmental and economic benefits, the location of charging infrastructure needs to be determined to meet the needs of electric vehicle users. Based on this, they proposed a method to determine the optimal location selection of EV charging stations based on a multi-objective method. Pareto Frontier method is used to support the optimal location decision process of charging stations. The results show that the best charging station location for EV penetration in the medium term can also adapt to long-term planning, and EV charging demand is high [8]. In addition, some studies have fully considered the impact of user behavior uncertainty on charging station location [9]. Pan et al. considers the influence of EV drivers' charging choice behavior on charging station layout [7], Dong et al. clearly considers the strategic behavior of EV users and its influence on RCS planning efficiency [19], and the impact of EV load uncertainty on the optimization planning of EV charging stations [20].

2.2. Model construction

In order to study the optimal distribution and number of charging stations, scholars have proposed many models.

Frade et al. studied the locations of charging stations in the Portuguese capital and uses a maximal covering model to determine the number and capacity of charging stations [21]. He et al. analyzed the driving distance and charging demand of the car, and established a double-layer mathematical model to solve the best position of the charging station [22]. With the goal of maximizing vehicle mileage, Shahraki et al. proposed an optimization model based on vehicle driving patterns, and uses real data to determine the location and scale of the charging station [23]. Wu et al. used stochastic flow capturing location model (SFXLM) to optimize the location and number of charging stations [24]. Tu et al. considered time and space constraints to maximize the service level of ET and charging stations for modeling, and studies the location of charging station [25]. Luo et al. used a second-order planning model to study the allocation of electric vehicle charging stations [26]. He et al. established a two-level planning model based on the distance traveled by the car to determine the best location of the charging station [27]. Liu et al. modeled from battery characteristics and used multi-objective biogeography-based optimization (M-BBO) approaches to investigate the optimal strategy to meet the requirements of different charging applications [28]. Mehrjerdi et al. Modeled and optimized the charging network from the power and capacity of charging facilities and energy storage battery systems [29]. Roni et al. Used data such as vehicle driving time, queue waiting time, and charging time for modeling, and analyzes the impact of the number of charging stations and coverage on time [30]. Lin et al. Established a multi-stage planning model for the location and scale of charging stations based on the operating characteristics and charging modes of electric buses [31]. Bouguerra et al. Comprehensively considered the driving range, various restrictions in reality, investment costs and user convenience, and established a weighted model to determine the location and scale of the charging station [32]. He et al. Considering the cost of batteries, charging stations, and energy storage systems, and establishes a mixed integer linear programming model to determine the deployment of charging stations and the design of batteries and energy storage systems [4]. Davidov et al. Started modeling from the minimization of charging station layout cost, and studies the influence of mileage and service quality on charging station layout and total cost. From the perspective of minimizing the annual social cost [33].

Previous studies mainly focused on using optimization models to deal with EVCS site selection that only considers quantitative factors. Hosseini and Sarder proposed a Bayesian Network (BN) model that considers both quantitative and qualitative (subjective) factors [34]. Zhou et al. combined geographic information system (GIS) and multi-criteria decision method (MCDM) for modeling to determine the location of photovoltaic charging stations (PVCS) [35]. Chen et al. Used a two-layer mathematical model to determine the location and scale of the charging station by minimizing the travel path and charging waiting time [36]. Luo et al. proposed a location model for electric vehicle charging stations, taking into account the impact of reservation service, idle rate during off-peak periods, and waiting time during peak periods on improving resource utilization and reducing total costs [37]. Zeng et al. proposed an innovative station-level optimization framework to run the optimal charging station pricing policy and charging plan. The model combines human behavior and clearly and effectively captures the charging decision-making process of drivers [9].

2.3. Model solving algorithm

In addition to building models, scholars have also used various algorithms to solve the configuration problem of charging stations. Sadeghi-Barzani et al. used MINLP optimization method and genetic algorithm to determine the best location and scale of the charging station [10]. Zhang et al. proposed a novel decentralized valley-filling charging strategy, which designs a pricing scheme through cost minimization and is compatible with device-level multi-objective charging optimization algorithms [38]. Arslan et al. used the Benders decomposition algorithm to study the location of hybrid electric vehicle charging stations from the perspective of maximizing mileage and minimizing transportation costs [11]. Dong et al. used the SNN clustering algorithm to study the planning method of charging stations on circular expressways. From the perspective of minimizing the total cost [39]. Zhu et al. studied the selection of the location of the charging station and the number of chargers based on the genetic algorithm [40]. Xiang et al. a new solution is proposed to integrate EVs and optimize the location and size of charging stations, taking into account the interaction between the power and transportation industries [41]. Brandstaetter et al. used two-stage stochastic optimization theory and heuristic algorithm to solve the problem of charging station layout [42]. Awasthi et al. combined genetic algorithm and particle swarm optimization algorithm to determine the location and scale of charging facilities in a city in India [43]. Wang et al. used an improved genetic algorithm to analyze the charging station planning problem given budget constraints and charging station service capabilities [44]. Chen et al. divided the charging facilities into charging stations and battery replacement stations, and used multi-objective particle swarm optimization methods to determine the ratio and distribution of the two [45]. Akbari et al. considered the constraints of the charging station's power, charging time, and travel distance, and used genetic algorithms to optimize the location of the charging station [46].

Zhang et al. used the k-means cluster analysis method to analyze the dynamic distribution of charging stations. From the perspective of CO2 emissions and power limitation [47]. Liu et al. used particle swarm optimization to study the location of bus charging stations [48]. Straka et al. used the k-means clustering method, combined with Dutch charging data to analyze, and studied the charging behavior of users, which can help improve charging station planning and charging technology [49]. Wu et al. combined approximate dynamic programming (ADP) and evolutionary algorithm (EA) to determine the best charging start time for each electric vehicle, thereby reducing the operating cost of electric vehicle charging stations and assigning charging locations [50]. Csiszár et al. adopted the method based on hexagons and greedy algorithm, introduced weighted multi-criteria method to evaluate regional segments, and allocated charging stations within regional segments [12]. Huang et al. From the perspective of maximizing the profit of the charging station, used a genetic algorithm to determine the location of the charging station [13]. Li et al. proposed an EV charging station deployment strategy based on particle swarm optimization algorithm to better determine the positioning of charging stations and the number of charging piles. This strategy is based on the non-uniform distribution of vehicles on the city scene map, and also considers the distribution of vehicles at different times, so that the strategy is more reasonable. A large number of simulation results further show that this strategy is significantly better than k-means algorithm in urban environment [14]. Li et al. takes microgrid composed of power distribution such as wind power photovoltaic (PV), EVCs and energy storage system (ESS) as the research object. The uncertainties of EV charging demand and distributed renewable energy output are considered. A robust optimization model of distributed energy charging station location based on the combination of road network and power grid was proposed [51].

To sum up, a large number of literatures have paid attention to the optimal layout of charging stations, which shows that the research of charging stations has attracted extensive attention. Previous studies have mainly focused on various influencing factors of charging station layout, the construction of optimal charging station model, and the proposed different model solving algorithms, and have made important contributions in these aspects. The relevant research results are also the basis of further research in this paper. At the same time, most of the existing literature studies from the aspects of charging station technology, user needs and behavior, environmental benefits and so on, and also reflects the diversity of optimization methods. However, the optimal layout of charging stations is rarely studied from the comprehensive perspective of total social cost, and mature and recognized genetic algorithms are used to solve the model. Also, typical charging station cases like Ireland are seldom studied. Therefore, from the perspective of total social cost, this paper constructs an optimal distribution model of charging stations based on total social cost, and iterates and simulates the optimal layout of charging stations using a relatively recognized genetic algorithm with obvious advantages. At the same time, in parameter setting, the model in this paper no longer uses the traditional Euclidean distance, but calculates the distance between the electric vehicle and the charging station by introducing the road bending coefficient, so that the model results are more in line with the actual demand. Finally, this paper takes Ireland as an example and considers the demand for charging stations in the five major cities of Ireland by introducing coefficients to simulate the actual distribution of EV charging demand in each city, so as to determine the optimal distribution location of charging stations.

3. Model construction and solution

3.1. Construction of total social cost model

In order to reasonably quantify the total social cost, we built a total cost model based on various social costs: We defined the location as the location of the charging station, which is different from the proportion distributed in the three regions. The process of building this model is divided into two parts: the first part is to build the total social cost model; The second part is to optimize the quantitative model.

We constructed a model to quantify the total social cost. The total social cost includes economic costs and environmental costs F3. Economic costs can be further divided into building cost F1 and charging costs F2. The building cost consists of fixed investments and operating costs. They both depend on the scale of charging stations, reflected by the number of chargers in a station.

Thus, we can get the formula as follows:

$$F_1 = \sum_{j\in J} Cj\left[T\left(N_j\right)\frac{r_0\ (1+r_0)^{n_{year}}}{(1+r_0)^{n_{year}}-1}+Y\left(N_j\right)\right] \tag{1}$$

The charging cost consists of the expenses of getting to charging stations and the electricity expenses. The former refers to the time and power consumption on the roads to the charging station, while the latter refers to the electricity fee people pay when using chargers.

$$F_2 = 365\left[\omega\sum_{j\in J}\sum_{i\varepsilon I}X_{ij}n_i\lambda d_{ij}+k\sum_{i\varepsilon I}n_i\right. \tag{2}$$

The environment cost is carbon emission on the way to charging stations. It can be expressed as the following formula.

$$F_3 = e_{CO2}\sum_{j\varepsilon J_{CS}}\sum_{i\varepsilon J_{CN_i}}C_j p n_i \lambda_{ij} d_{ij} \tag{3}$$

$$e_{CO2} = e_{elec}E_{1km}\Big/\eta_{chrg} \tag{4}$$

Thus, we can get the expression of total social cost as follows:

$$F_{total} = F_1 + F_2 + F_3 \tag{5}$$

Objective Function:

$$MinF_{total} \tag{6}$$

Constraints:

$$G_j(X) = \text{ j } = 1,2,\ldots \text{ n}\sum_{i=1}^{m}n_iX_{ij} \le A_j \tag{7}$$

$$G_i(X) = \text{ i } = 1,2,\ldots \text{ m}\sum_{j=1}^{n}X_{ij} = 1 \tag{8}$$

$$\lambda d_{ij}X_{ij} \le D \tag{9}$$

Constraint condition (7) indicates that the total demand for charging vehicles at j can not exceed the total power supply j can provide. Constraint (8) indicates that vehicle i must choose a charging station for charging. Constraint condition (9) indicates that the distance between vehicle i and the charging station j cannot exceed the maximum driving distance.

Therefore, we build a quantitative model that can effectively measure the total social cost, and then we can calculate the total social cost required under different circumstances according to the changes of various parameters.

Based on the optimization model of total social cost and its constraint conditions, this paper selects various cost factors that affect total social cost. It mainly considers the economic cost composed of construction cost and charging cost, and the construction cost composed of fixed investment and operating cost.

In addition, there are substation location selection, the number of charging car washes, the number of charging stations, substation distance, the charging demand at the first intersection, the probability of charging every day, etc. In addition, we also set the combination of several parameters through MATLAB software, the genetic algorithm under different parameters of the objective function value and the number of charging piles comparison selection, to determine the genetic algorithm of the model of other parameters, such as genetic algorithm population size, crossover probability, mutation probability, maximum algebra. Therefore, we mainly refer to these factors to configure parameters.

Meanings of parameters as follows (Table 1):

3.2. Optimize by genetic algorithm

Genetic algorithm (GA) is a global search optimization method that imitates biological evolution in nature. According to the principle of survival of the fittest and survival of the fittest in biological evolution, the optimal solution function value is finally obtained through coding and continuous evolution. In GA algorithm, selection, crossover and mutation are the three operations. Crossover operation is the main way for genetic algorithm to produce offspring, and the information exchange between parent individuals is realized through crossover, which is also the main generation form of new individuals. In general, the core content of genetic algorithm mainly includes five parts: initial population setting, parameter coding, fitness function design, genetic operation design and control parameter setting.

Genetic algorithms usually follow the following basic ideas: first, the initial population is randomly generated and non-dominant classification is carried out. Then the next generation population is obtained through genetic algorithm selection, crossover and variation, and it is used as the first-generation population. Secondly, starting with the second generation, the parental population merges with the offspring population, and the fast-non-inferior frontier classification was carried out. At the same time, the focusing distance of each non-inferior individual was calculated. According to the focusing distance between individuals and the order of the non-inferior individual, the appropriate individual was selected to form a new parental population. Finally, a new generation of offspring population is generated through the same operations such as selection, crossover and mutation in the genetic algorithm, until the conditions for the end of the program are

Table 1
Meanings of parameters.

Parameter	Meaning
Cj	whether to build a charging station at the position of j
Xij	vehicle i chooses to go to charging station j for charging service
Nj	the number of chargers to be built in site j
T(Nj)	the investment function of fixed cost
Y(Nj)	the annual operating cost of site j
r_0	the discount rate
n_{year}	the depreciation period of charging stations
w	the power consumption per unit distance to charging stations
n_i	the number of cars requiring charging every day at point i
λ	non-linear coefficient about roads
d_{ij}	the space linear distance between the point i to site j
k	the average electricity cost of a electric car currently
e_{co2}	carbon emission
e_{elec}	greenhouse gas (GHG) factor
e_{1km}	the power consumption by a car running 1 km
η_{chrg}	the charging efficiency
p	the probability of charging per car per day
A_j	charging station j can provide the maximum charging capacity
D	the maximum distance an electric car can travel

satisfied. The process of genetic algorithm is shown in Fig. 1.

It can be seen that genetic algorithm, as an optimization algorithm, has the following obvious advantages compared with other algorithms: first, genetic algorithm takes the coding of decision variables as the operation object, and can directly operate structural objects such as sets, sequences, matrices, trees and graphs. This method not only helps to simulate the process of biological genes, chromosomes and genetic evolution, but also facilitates the application of genetic operators. Moreover, genetic algorithm has a wide range of applications, such as automatic function control, number optimization, production scheduling, image processing, machine learning, data mining and other fields. Second, the genetic algorithm directly uses the value of the objective function as the search information. It only uses the fitness function value to measure the individual's good degree, and does not involve the process of differentiating the value of the objective function. Because in reality, many objective functions are difficult to obtain derivatives, or even there is no derivative. Therefore, this reflects the high superiority of genetic algorithm. Third, genetic algorithm has the characteristics of group search. Its search process starts from an initial population P (0) with multiple individuals, which can not only effectively avoid searching points that do not need to be searched, but also because the traditional single point search method is easy to fall into the extreme point of a local single peak when searching the search space of multi-modal distribution, but the population search characteristics of genetic algorithm can avoid

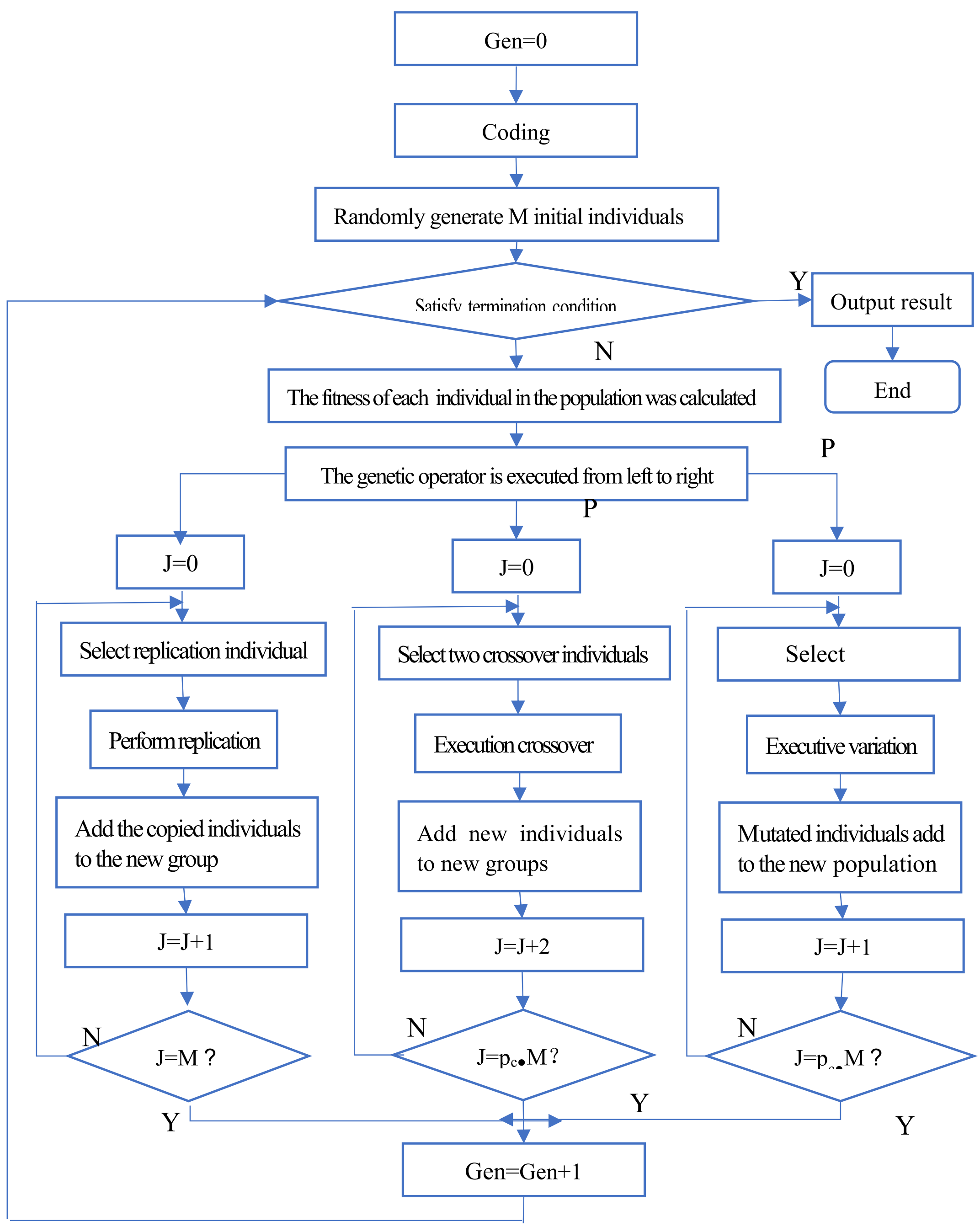

Fig. 1. Process of GA.

such problems, Therefore, it fully embodies the advantages of parallelization and global search of genetic algorithm. Fourth, genetic algorithm is based on probability rules rather than deterministic rules. This makes the search more flexible and can reduce the influence of parameters on its search effect as much as possible. Fifthly, genetic algorithm also has strong scalability and is very easy to be mixed with other technologies.

However, its disadvantages can not be ignored. Genetic algorithm may be irregular and inaccurate in coding. Because a single genetic algorithm coding can not fully express the constraints of the optimization problem, it is necessary to consider the use of threshold value for the infeasible solution, which increases the workload and solving time. Compared with other optimization algorithms, the efficiency of genetic algorithm is usually lower and the problem of premature convergence may occur.

Although there are many optimization technologies and algorithms at present, Genetic Algorithm (GA) has the advantages of strong global search ability and is widely used in complex problems such as planning. In addition, GA binary coding method is suitable for charging station planning problems with known candidate sites. Therefore, a genetic algorithm is selected in this paper to solve the location optimization model of electric vehicle charging station based on total social cost proposed in this paper.

The charging pile layout planning problem studied in this paper involves many variables such as social total cost, the number of charging piles, electric vehicles and parking spaces. Among them, the total cost includes economic cost and environmental cost. Economic cost can be further divided into construction cost F1 and charging cost F2. Construction costs are made up of fixed investment and operating costs, both of which depend on the size of the charging station, which is reflected in the number of charging piles in the station. Charging costs include fees to charging stations and electricity. The former refers to the time spent on the road to the charging station and the power consumed, while the latter refers to the electricity people pay when using the charger. The environmental cost of going to a charging station is carbon emissions. Therefore, the model is complex and the traditional optimization algorithm is difficult to solve, so this paper uses the genetic algorithm toolbox based on MATLAB. Based on the global search for a large population of charging pile layout scheme, the optimal charging pile layout schemes under certain conditions is obtained to achieve the goal of lowest generalized cost of charging pile system.

4. Data selection and processing

The geographic information data of Ireland used in this paper came from the Environmental System Research Institute (SRI). Basic information on electric vehicles comes from the Sustainable Energy Authority of Ireland (SEAI). Other relevant data are from the Central Statistics Office (Ireland, CSO) and Wikipedia.

After the data is recorded, some data is abnormal, and the data is preprocessed as follows: Delete the same data. Delete data with too many missing values. For the data with individual missing values, Lagrange interpolation is used to eliminate the missing values. Standardize the units and formats of various types of data.

At the same time, in order to ensure standardized research, we also make the following assumptions to exclude the interference of other factors on the research:(1) each electric vehicle drives alone. (2) Users of electric cars will optimize their power usage. That is, after the battery runs out, they will start charging. (3) Users will choose the best charging location. That is, users prefer the location without waiting time. (4) Charging stations are in the optimal distribution, which means that the locations of charging stations can always provide the best service capacity. (5) Charging demand is proportional to driving distance. (6) The probability of travel distance obeys Rayleigh distribution f(s). (7) The charge demand in the city is satisfied by destination chargers and the charge demand on the roads is met by superchargers. (8) The charging station is not hierarchical, which means that the number of charger at all charging stations is equal to the average of 6.4.

5. Example simulation and analysis

5.1. Example selection

Under the background of limited supply of fossil fuels and decreasing emissions harmful to the environment, the Irish government has responded from two aspects. First, increase the proportion of renewable energy power generation and reduce the use of fossil energy, so as to optimize the energy structure. Second, the government will increase the use of electric vehicles by formulating strong support policies. Due to Ireland's unique geographical advantages, a large amount of renewable energy (especially wind energy) can be used to produce electricity, and its clean and efficient transportation network can provide power for renewable energy. Among them, the electricity supply board (ESB) is the largest energy supplier in Ireland. It mainly aims at the automobile plan (ESB, 2014) and vigorously develops the national electric vehicle infrastructure to meet the demand for electric vehicles in Ireland to the greatest extent. The ultimate goal is to reach 250,000 electric vehicles by 2020.

Nearly 1000 public charging points had been installed in Ireland by the end of 2013, and the infrastructure is being expanded and improved. In Ireland, every town with a population of more than 1500 will have at least one charging point for electric car users. And 50 quick-charging points have been installed on highways between major cities across the country. These infrastructures were developed by European Commission research and infrastructure funding and direct investment in the ESB. In addition, the Irish government is allowing the first 2000 citizens to use electric vehicles to use home charging stations for free. Ireland has already reached its target of 10% electric vehicles. According to Ireland's national census data, the potential for electric vehicles to replace conventional cars is huge in the vast majority of Ireland, based on the current range and possible commuting distances.

According to ESB, Ireland's leading electricity provider, there are already more than 1000 electric vehicle charging stations in Ireland, but only 600 electric vehicles are registered. Only when that number reaches 2400 will charging stations become profitable. The Irish government has been taking policy measures to promote electric vehicles, such as introducing a €5000 initial purchase grant and a €120 annual road tax credit. It plans to have one million electric vehicles on the road by 2030. However, there is still a long way to go to achieve this goal.

According to Shang et al. [52], the timeline for promoting the development of electric vehicles in Ireland is shown in Table 2.

This paper will take Ireland as the research object. There are two reasons. First of all, Ireland is a developed country, and its car ownership will remain basically unchanged in the future. However, the development of electric vehicles in Ireland is still in the early stage, and its market has great development potential in the future. Secondly, due to Ireland's unique geographical advantages, wind energy, as a renewable energy, can be used to establish an efficient and clean transportation network and provide sufficient electric energy for various industries, thus greatly reducing the cost of developing the electric vehicle industry. Finally, the Irish government has attached great importance to the development of electric vehicles and has introduced many preferential policies to support the development of electric vehicle projects. For the above reasons,

Table 2
Development time of electric vehicles in Ireland.

Category	Number of destinations charging stations	Number of supercharged charging stations
10% electric	Completed in 2021 (4 years in total)	Completed in 2018 (1 year in total)
30% electric	Completed in 2074 (57 years in total)	Completed in 2029 (12 years in total)
50% electric	Completed in 2123 (106 years in total)	Completed in 2049 (32 years in total)
100% electric	Completed in 2248 (231 years in total)	Completed in 2090 (73 years in total)

Ireland can become a model for the transformation and development of electric vehicles.

5.2. Example simulation

First, we simplify the Ireland land area into a rectangle with a length of 350 km and a width of 200 km. Then we fragment it into small squares and there are charging needs at every intersection point.

We establish a coordinate system with the lower left corner of the rectangle as the origin. However, not every point is equivalent, considering Ireland has five main cities as transportation hubs. If we make five 20-kilometerraidus circles with these five cities as the center, respectively, then those points covered by the area should be placed more charging stations in response to more requirements. Therefore, we define ρ as demand coefficient. It can be expressed as follows:

$$p = \begin{cases} \dfrac{1}{d_0 - d_i} & d_i \le 20 \\ 1 \quad d_i \ge 20 \end{cases} \tag{10}$$

where d_0 is threshold, and di is the distance between the point and the corresponding central city. Below is a schematic view (Fig. 2).

We generate 670 points randomly in the rectangle area $(0 \le Y \le 350, 0 \le X \le 200)$ and then replace X_{ij} in equation(x) with their coordinates. After that, we multiply the cost by the demand coefficient we defined before and get the adjusted cost to travel from point A to charging station B. The total cost in the first round can be expressed as. Remembering that our purpose is too minimum the total cost in several rounds, we use Genetic Algorithm to optimize. When the algorithm is terminated, we can get coordinates of 670 points. The distribution of these points is exactly the optimal outcome. Back to reality, we project 670 points to the map of Ireland by making horizontal and vertical coordinates correspond to latitude and longitude. The result is shown in Fig. 3.

As can be seen from Fig. 3, the geographical distribution of charging stations in Ireland is all over the country, but the concentration degree is different, mainly concentrated in Dublin, Athenry, Thuries, New Ross, Cork and other five major cities. This shows that key cities with large urban scale, large population, convenient transportation and developed economy, such as ports, have a large demand for charging stations. This basically conforms to the characteristics of charging station layout. Therefore, the Irish simulation results are to a large extent applicable to the economically developed port cities of each country.

In terms of regional location, Ireland is located in the south central part of the Irish island in Western Europe, bordering the Atlantic Ocean in the west, Northern Ireland in the northeast and Britain across the Irish Sea in the East. From the perspective of landform, Ireland island is 475 km long from north to South and 275 km wide from east to west. The whole island covers an area of 84,000 square kilometers. The central part of Ireland is a plain with many lakes and swamps, with an average altitude of about 100 m. The north, northwest and South are plateaus and mountains. In the middle are hills and plains, and most of the coastal areas are highlands. Therefore, the simulation results of Ireland can be applied to islands with small areas and complex terrain, such as Sri Lanka, Madagascar, Malaysia, Indonesia, the Philippines, New Zealand, Japan, South Korea, Cuba, Florida of the United States, as well as some island cities in countries or regions such as Taiwan Island and Hainan Island of China.

In terms of traffic, in addition to developed aviation and sea transportation, inland transportation in Ireland is mainly by road and railway. The total length of the highway is 96,000 km. The vast majority of international trade in goods is carried by sea. Dublin, Shannon and Cork have major ports and international airports. Ireland has a very developed road network, crisscrossed by roads. This facilitates the mass use of electric vehicles as a means of transportation, but also puts forward higher requirements for the layout of charging stations. Therefore, the simulation results of Ireland in this paper can not only provide reference for the optimal layout of charging stations in Ireland, but also for the layout of charging stations in countries with developed road networks.

Finally, from the perspective of economic development, Ireland is an economically developed country with high per capita income and strong consumption power. It has been dependent on cars for a long time and has large car ownership, which also provides conditions for the massive use of electric vehicles. Therefore, the

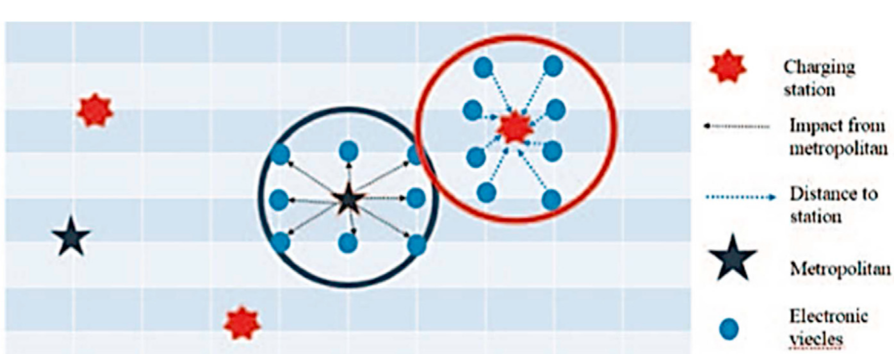

Fig. 2. A schematic view.

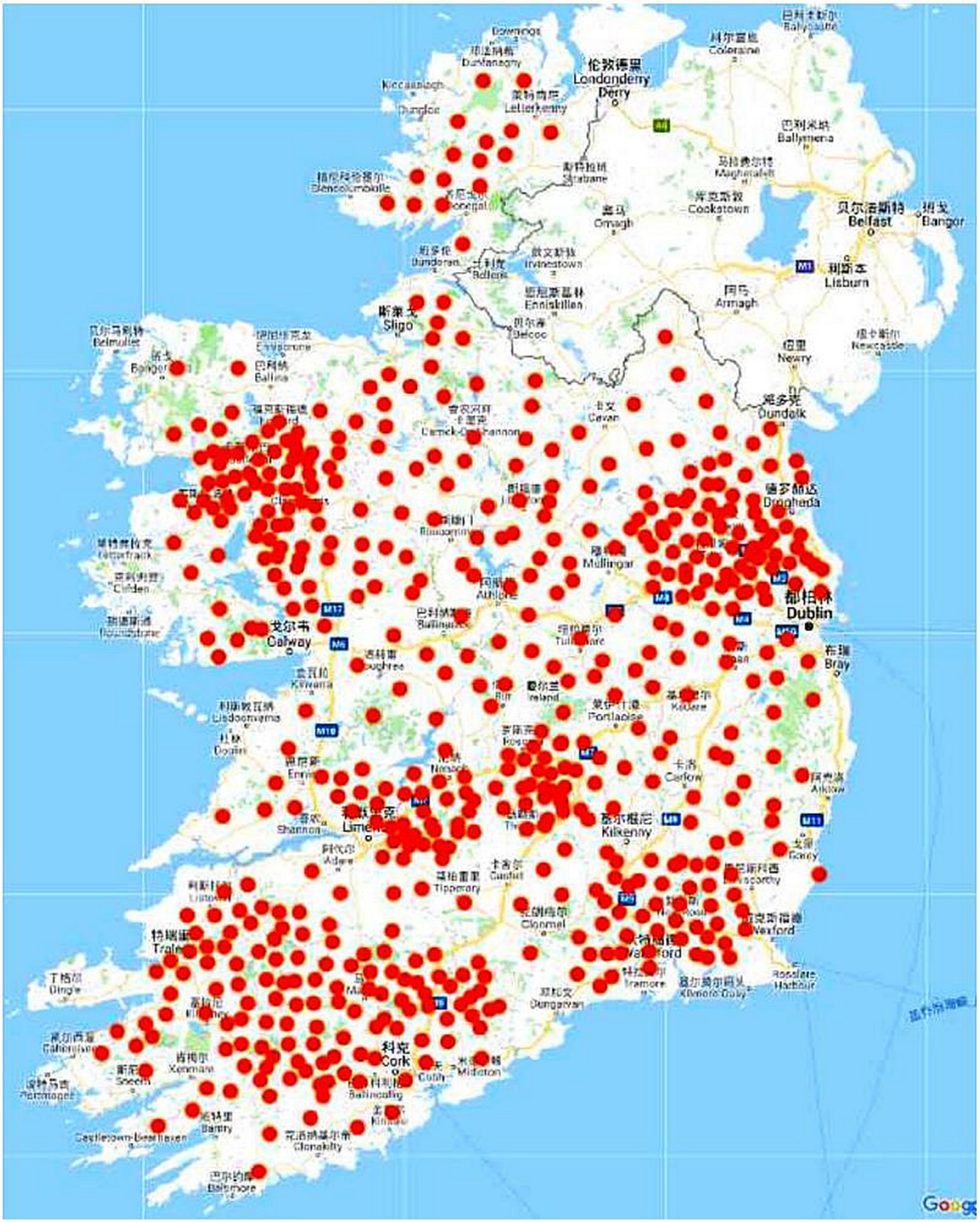

Fig. 3. Optimal distribution of charging stations.

simulation results of the optimal layout of charging stations in Ireland have great reference value for the construction of charging stations in countries with developed economy, high per capita income and large car ownership.

In short, this paper selects Ireland as an example and simulates the optimal distribution of charging stations, which can not only provide reference for the layout of charging stations in Ireland, but also provide reference for other countries or regions in the world in many aspects. Therefore, this example has strong applicability. This also shows the importance of this study from another angle.

5.3. Sensitivity analysis

To figure out key factors that shape our model, we make a sensitivity test. We extract 3 important parameters, the number of charging stations, the demand to charge at every intersection point and the probability of charging each day. The test is done via simulation.

We do sensitivity analysis on the charging vehicle flow. When the charging vehicle flow increases by 5%, the total construction cost of the charging station will increase by 8%. When the charging vehicle flow decreases by 5%, the total construction cost of the charging station will decrease by 4%. The simulation results are shown in Table .3 and Fig. 4. Therefore, the charging vehicle flow is not a sensitive factor to the cost.

We also do sensitivity analysis on the charging probability. When the charging probability changes by 5%, the total cost of charging station construction will change by 11%. Therefore, the

Table 3
Sensitivity analysis of electric vehicles.

Electric vehicles	Change of number	Total social cost	Change of cost
67	5%	1,967,216,017	8.00%
60	0%	1,852,037,265	0%
57	−5%	1,773,852,596	4.00%

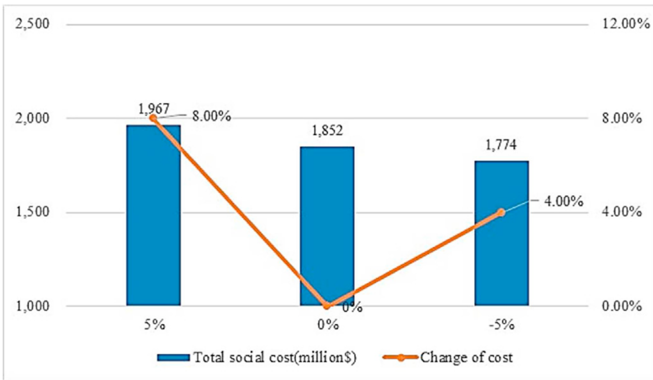

Fig. 4. Sensitivity analysis (change of the number of electric vehicles).

Table 4
Sensitivity analysis of charging probability.

Probability of charging	Change of number	Total social cost	Change of cost
0.105	5%	2,091,100,356	11.00%
0.1	0%	1,852,037,265	0%
0.095	−5%	1,629,792,793	12.00%

charging probability is a sensitive factor to cost. The simulation results are shown in Table .4 and Fig. 5.

We find that the percentage change of total social cost is larger than the percentage change of the three factors. Therefore, we draw the conclusion that the total social cost is sensitive to the number of charging stations, demand to charge at intersection points and probability of charging each day, which implies that the three factors are exactly key factors to shape our model.

We find that the total social cost changes more in response to changes in charging stations and charging probability. Therefore, we draw the conclusion that the total social cost is sensitive to the number of charging stations and probability of charging each day, which implies that the two factors are exactly key factors to shape our model. However, it is not so sensitive to demand to charge at intersection points.

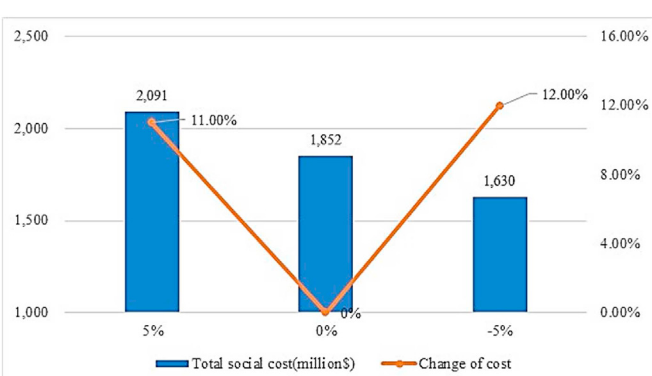

Fig. 5. Sensitivity Analysis (the probability of charging each day).

6. Conclusion and prospect

This paper studies the algorithm to simulate the optimal distribution of charging stations in a specific environment. In order to minimize the construction cost of charging stations, we constructed a total social cost model covering economic and environmental costs. Economic costs include construction costs and operating costs, while environmental costs are the cost of carbon dioxide emissions. The constraints of the model are the maximum charging supply that can be provided by each charging station, the charging options for each vehicle, and the charging distance. And according to the above constraints, this paper takes Ireland as the research object, and establishes a genetic algorithm model. Finally, the optimal distribution locations of 670 charging stations were simulated. On this basis, in order to explore the factors that have a significant impact on the total cost of charging station construction, we conducted sensitivity analysis on possible relevant factors. The results show that the distribution of charging stations is very sensitive to the number of charging stations, the charging demand of intersections and the probability of daily charging. The total social cost is positively correlated with the number of charging stations and the probability of charging.

The main contributions of this paper are as follows: First, from the perspective of total social cost, the optimal distribution model of charging stations based on total social cost is constructed to provide a theoretical basis for simulating the optimal distribution of charging stations. Secondly, the optimal charging station layout is iterated and simulated using the recognized genetic algorithm with obvious advantages. Thirdly, in parameter setting, the model no longer uses the traditional Euclidean distance, but introduces the road bending coefficient to calculate the distance between the electric vehicle and the charging station, so that the model results are more in line with the actual demand. Finally, by introducing the coefficient, the demand for charging stations in the five major cities of Ireland is considered to better simulate the actual distribution of EV charging demand in each city, so as to determine the optimal distribution location of charging stations.

The results have important implications for policy makers in Ireland and other countries in terms of understanding the charging behaviour of potential EV users, particularly when they prefer to charge. Such information can help guide decision makers in smart charging policies and also help provide monetary or other incentives that might be useful for grid load management. The results also help to provide information on the possible potential of renewable energy sources to meet EV demand, based on projected future growth scenarios. One limitation of this work is the scale of the trial, which is an expensive and resource-intensive monitoring feature needed to capture user behavior in a real-world environment.

Although the conclusion of the study on Ireland is of universal significance to a large extent, there are significant differences in the moderate economic development, population size and political stability of each country, and these factors are the main factors determining the scale and layout of charging stations. Therefore, studies on different types of countries need to be carried out in the future to promote the growth of electric vehicles and optimize the layout of charging stations. For example, in countries with developed economy and a small population (such as Singapore), which has the most developed economy and the smallest population, the government can realize the electrification of motor vehicles in a relatively short time by investing in charging stations. In countries with a developed economy and a large population (such as Australia), it may take a long time to promote EV nationwide and optimize the layout of charging stations due to Australia's developed economy, large population and large land area. However, countries with less developed economy and larger population or developed economy and political instability, such as China, have less developed economy, large population and large land area. Indonesia has an underdeveloped economy and a large population. Saudi Arabia is economically prosperous but politically unstable. It will take longer for these countries to electrify their motor vehicles. Therefore, the government needs to increase investment in order to achieve the expected goal in a reasonable time.

Credit author statement

Guangyou Zhou is responsible for the overall design of the paper and literature review writing; Zhiwei Zhu is responsible for Original Draft, data collection and collation, modeling, and analysis; Sumei Luo is responsible for review and editing, chart making and analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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