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Optimization of Reverse Logistics Network for Electric Vehicle Used Battery under Direct Collection Mode of Manufacturer Based on New Energy Low-carbon Background

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Abstract:
As the concept of low-carbon travel gradually takes root in the public's mind, the production and sales of electric vehicles are steadily climbing, and due to the limited service life of electric vehicle power batteries, they will be gradually eliminated and replaced. Enhancing the recycling infrastructure for used electric vehicle batteries and developing a systematic and efficient reverse logistics framework is crucial for advancing the sustainability, cost-effectiveness, and operational efficiency within the electric vehicle sector. This paper firstly analyses the direct collection battery recycling mode of the manufacturer, and on this basis, constructs the optimization model of the reverse logistics network of used batteries, as well as the dual objective optimisation model of total network cost minimisation and carbon emission minimisation. Finally, based on relevant data from C Electric Vehicle Manufacturing Company, an example analysis is carried out to derive its optimal solution for the reverse logistics network of used batteries for electric vehicles in Beijing. The research in this paper has a positive effect on reducing the reverse logistics costs of related enterprises and reducing environmental pollution, thus helping to realize the green ecological development of the electric vehicles industry.

Keywords: electric vehicle used batteries; reverse logistics; mixed integer programming; genetic algorithm; low carbon.

INTRODUCTION

As the standard of living improves, the demand for automobiles increases year by year. Carbon monoxide, hydrocarbons, nitrogen oxides, and particulate matter emitted from the tailpipe of conventional fuel-fired vehicles are the main sources of air pollutants [1, 2]. In order to achieve the goal of "carbon peaking and carbon neutrality", realize green eco-friendly development, promote the low-emission transformation of the automotive industry, vigorously promote new energy vehicles to replace fuel vehicles [3] has been imminent. Based on statistics from the China Association of Automobile Manufacturers (CAAM), at the end of June 2024, new energy vehicle ownership in China amounted to 24.72 million, accounting for 7.18% of the total number of vehicles. And as reported by the International Energy Agency, by 2030, ownership of electric vehicles in China set to reach 80 million. Along with the continuous growth of electric vehicle sales, it is foreseeable that the phase-out of used power batteries will make recycling electric vehicle batteries a difficult problem.[4]. On the one hand, the recycled used power batteries can be used in non-automotive applications such as engineering, machinery, energy storing and two-wheeled vehicles [5]. What's more, valuable metals like lithium, nickel, cobalt, manganese can also be recovered from used power batteries through professional recycling treatment [6, 7]. However, if they are not properly treated, they may damage groundwater sources and soil, causing serious environmental pollution [8].

Currently, part of the research on used power batteries focuses on the economic, environmental and social benefits of recycling used batteries [9, 10]. A further part of the research is focused on the study of models for reverse logistics, including producer recycling models, retailer recycling models and third-party recycling models [11-13]. The research methods in the field of reverse logistics network involve mixed integer planning, genetic algorithm, genetic algorithms [14], heuristic algorithms [15], etc. For example, TADAROS constructed a discrete multi-period reverse logistics mixed integer programming model in Sweden, and solved the recycling problem of used electric car batteries in Sweden by solving the location of each facility in the reverse logistics network [16]. However, there are fewer systematic studies on the network optimization model of electric vehicle used power battery in existing researches. Therefore, we will construct a network optimization model for the reverse logistics of used electric vehicle power battery under the producer direct collection mode from the responsibility of electric vehicle producers in reverse logistics. And under the influence of dual-carbon policy, the model is considered to be optimised to minimise network costs and carbon emissions. The research in this paper can serve as a reference for the recycling of used batteries in related electric vehicle companies, which is important for the sustainable development of the electric vehicle industry.

The remaining sections are structured as follows: section II provides a brief review of the relevant literature, section III describes the constructed reverse physical network model for used batteries in electric vehicles, section IV carries out an empirical analysis using C electric vehicles as an example to validate the validity of the model constructed in this paper, and section V concludes the study.

LITERATURE REVIEW

With the increasing popularity of electric vehicles, national and international scholars have gradually began to focus on the recycling of used power batteries [17,18]. Many scholars' studies have demonstrated the positive effects of recycling waste power batteries, Kim et al. studied the environmental benefits that can be obtained by counting the specific amount of recycled waste power batteries converted into stationary energy storage systems [9]. DeRousseau et al. considered different recycling options for the end-use scenarios for EV batteries in the USA, and proposed that remanufacturing, recycling, and other industrial energy storage applications for waste power batteries [19]. Sloop et al. studied the callback of waste electronics and used lithium battery packs for electric vehicles. A comparative analysis found that in a reverse logistics supply chain, recycling waste from both would create economic benefits for the producer [10]. Arifidin designed a battery management system (BMS) consisting of used power batteries. By determining the battery capacity and categorizing the battery life, the recycled used power batteries are utilized in a power generation storage system or a micro power generation system, which provides a practical solution for the management of waste power batteries [20]. Roberto et al. evaluated the recycling process of used power batteries from 44 commercial recyclers, and proposed a new qualitative model, Strategic Material Weighting and Valuation (SWAVE), to compare the strategic significance and recyclability of different materials of various materials in waste power batteries for electric vehicles [21]. Thus, recycling used electric vehicle batteries is imperative and has significant benefits. In terms of recycling strategy and recycling mode, scholars' research mainly focuses on the evaluation of recycling mode [11, 12], optimal pricing strategy [22-24].

Reverse logistics networks, as an important way to study the recycling of used products, have been researched in the field of recycling and scrapping of electric vehicles or traditional fuel vehicles. Kuşakcı et al. constructed a reverse logistics network for electric vehicles through the use of a mixed integer planning model, and verified the model validity using an example in Istanbul Metropolitan Area [25]. Amin et al. constructed a reverse logistics recycling network for disused vehicles, and validated it with a real example of an electric vehicle recycling company in North America [26].

Nengye et al. designed a sustainable dynamic reverse logistics network model which includes six logistics nodes, and explored the node placement of the reverse logistics network of decommissioned power batteries by solving the model of combinatorial multi-objective optimisation [27]. Jiang used the robust optimization theory method with regret value constraints to construct a reverse logistics network optimization model for end-of-life vehicles in Beijing, and used the recycling work of end-of-life vehicles in Beijing as a case study [28]. Based on the background of mandatory recall of electric vehicles in China, and with the aim of minimization of safety risks and environmental issues and maximization of social responsibility and economic benefits, Hao et al. built a multi-objective, multicycle reverse logistics network model for electric vehicle recall. The results will help EV manufacturers and related industry decision makers understand EV recalls, improve safety and environmental aspects of EV recall processes, and promote the establishment of EV recall reverse logistics network[29].To solve the problem of waste tire recycling within Heilongjiang Province, Wang et al. constructed a reverse logistics network of scrap tires under the recycling mode of third-party enterprises, and adopted the linear mixed integer planning method to determine sites for recycling centers and remanufacturing enterprises respectively [13]. There are also some studies analysing battery recycling for electric vehicles. Based on the background of producing, selling and owning new energy vehicles in China, Hucheng Wang constructed a manufacturer-led decommissioned battery recycling network, and used genetic algorithms based on uncertainty planning theory to minimize the overall cost of the decommissioned battery recycling network within a single cycle [14].Consider the recycling and remanufacturing process of used electric vehicle batteries from a circular economy and environmental protection point of view, Liao et al. developed a fuzzy optimization model of a reverse logistics network under carbon emission constraints to select the location of facilities [30].

The current research on reverse logistics model and used battery recycling is more mature, and reverse logistics network optimisation is a hot research topic, and the network optimization research is generally through the establishment of the introduction of heuristic or intelligent optimization algorithms to solve. Electric vehicles as a new thing, its waste battery recycling research has just started, a lot of research is reference to other reverse logistics research, mainly combined with the characteristics of the supply chain related to electric vehicles for research, for each link of the main body to bear the responsibility to focus on the analysis. In the main body of the link, the producer as the key body of used power battery recycling, if the analysis from the producer-led viewpoint can further optimize recycling network for used electric vehicle batteries in China.

Focusing on this problem, this paper firstly constructs a reverse logistics network optimization model of used power battery for electric vehicles. under the producer direct collection mode with the dual objectives of network cost minimization and carbon emission minimization. And an empirical study is carried out with C Electric Vehicle Company as an example, so as to test the validity of the constructed model.

MODEL CONSTRUCTION

Model Parameters and Assumptions

The power battery of an electric vehicle may need to be replaced after a few years due to longevity issues. At this time, there are three choices for the disposal of used batteries, namely, the recycling mode in which the battery and vehicle manufacturers are involved, the recycling mode in which the manufacturer entrusts disposal to a third party recycler, and the recycling mode in which the manufacturer entrusts disposal to the retailer. The producer direct recycling model is the focus of this paper. Figure 1 shows the closed-loop supply chain process framework of the producer direct recycling model.

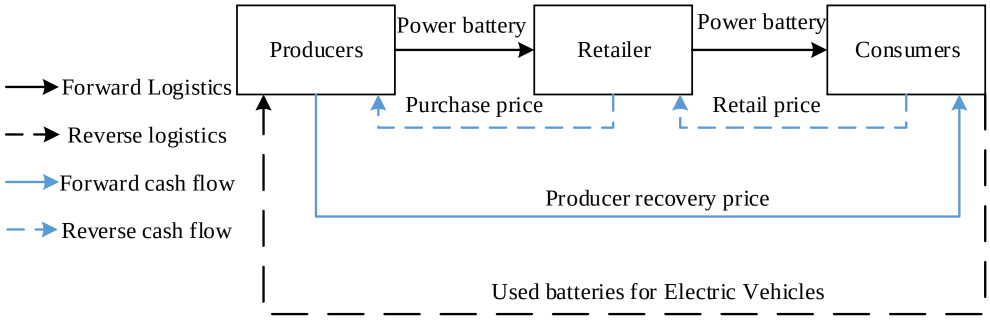

Figure 1. Manufacturer direct recycling of used batteries model

In the reverse logistics under the producer direct mode, the retailer only serves as a transfer station for the producer's reverse logistics, and the manufacturer participates directly in the recycling of used batteries by setting up its own reverse logistics network. The construction of recycling centers, processing centers and other facilities will undoubtedly cause manufacturers to spend a lot of reverse logistics channel construction costs, but manufacturers are most familiar with the battery's lifespan, raw materials and performance characteristics of the most familiar information, recycling can be more professional treatment, the resulting economic benefits are also the greatest. Meanwhile manufacturers can help optimize the performance of their next-generation power batteries by conducting experimental research and analysis on recycled used power batteries.

The composition of the reverse logistics network for EV used power batteries in direct collection mode is as follows:

(1) Recycling service locations

The first step in the flow of used power batteries in the reverse logistics network is from consumers to recycling service locations. Firstly, it is fundamental to plan the address of the recycling service network on the basis of the characteristics of used power batteries and the size of the recycling volume, so as to ensure the convenience of the first step of the flow of used batteries. Simultaneously, in the construction of the recycling network, it is also possible to utilize existing sales centers as recycling service outlets.

(2) Classification and testing centers

Under the mode of direct collection by manufacturers, it is necessary to consider building a new classification and testing center for the pre-processing of used power batteries. As there are many types of used power batteries, the first step of pre-processing is to classify the used power batteries, which can effectively save costs and improve the processing efficiency through informatization equipment. The second step of pre-processing is to test and screen the used power batteries, mainly to test their battery capacity for subsequent processing.

(3) Recycling and processing centers

Recycling and processing centers are at the heart of the reverse logistics network. The recycling center's construction of the is crucial to the processing of used power batteries for electric vehicles. After receiving the used batteries delivered by the classification and testing center, the recycling processing center needs to formulate the processing plan of used batteries according to the classification and testing results.

(4) Waste centers

Waste centers contain the worthless waste portion of waste that has been processed by recycling and treatment centers and has been treated in a harmless manner.

Based on the above analysis, the parameters of the reverse logistics network optimization model for used power battery under the direct collection mode of the manufacturer are explained and illustrated in a unified way. Table 1 gives a summary of the parameters and their meaning.

Table 1. Description of model parameters and meanings

Category	Parameter	Meaning
Recycling model	M	Representing the producer-direct collection mode
Logistics facilities	R	Collection of recycling service locations, $R=\{1,2,\ldots,\ \|R\|\}$. It is known that the location of the recycling service outlet r belong to R
	G	Collection of classification and testing centers for power batteries $G=\{1,2,\ldots,\ \|G\|\}$. Candidate locations for classification and testing centers g belong to G
	H	Collection of recycling and processing centers for power batteries, $H=\{1,2,\ldots,\ \|H\|\}$ .Candidate locations for recycling and processing centers h belong to H
	W	Collection of waste centers for power batteries, $W=\{1,2,\ldots,\ \|W\|\}$. The location of the known waste center w belongs to W
	I_g^M	Maximum classification testing capacity of classification testing center g
	I_h^M	Maximum capacity of recycling processing center h
	D_{rg}	The distance that a power battery is transported from a recycling service location r to a sorting and testing center g
	D_{gh}	The distance of power batteries transported from the sorting and testing center g to the recycling processing center h
	D_{hw}	The distance of power batteries transported from the recycling processing center h to the waste center w
	Q_r^M	Volume of used power batteries recycled at recycling service locations r
	Q_g^M	Disposal of used power batteries at classification and testing center g
	Q_h^M	Volume of used power batteries processed at recycling and processing center h
	Q_{rg}^M	Volume of used power batteries transported to classification and testing center g by recycling service location r
	Q_{gh}^M	Transportation of used power batteries from classification and testing center g to recycling and processing center h
	Q_{hw}^M	Transportation of used power batteries from recycling and processing centers h to waste centers w
Costs	F_r^M	Fixed investment construction costs for new recycling service location r
	F_g^M	Fixed investment construction cost for a new classification and testing center g
	F_h^M	Fixed investment construction cost of a new recycling and processing center h for used power batteries
	C_r^M	Unit recycling cost of recycling service location r for used power batteries
	C_{rr}^M	Unit operating cost of recycling service location r
	C_g^M	Unit cost of treatment of used power batteries by classification and testing center g
	C_h^M	Unit cost of treatment of batteries by recycling and processing center h
	C_w^M	Unit treatment cost of waste center w
	C_d	Unit transportation cost of power battery per distance
The cost of carbon emissions	EF_r^M	Carbon emissions associated with building a new recycling service location r
	EF_g^M	Carbon emissions associated with building a new a new classification and testing center g
	EF_h^M	Carbon emissions associated with building a new a new recycling and processing center h

Category	Parameter	Meaning
	E_r^M	Carbon emissions from used power batteries in the operation unit of recycling service locations
	E_g^M	Carbon emissions from used power batteries in processing units of classification and testing centers
	E_h^M	Carbon emissions from used power batteries of processing units in recycling and processing centers
	E_w^M	Carbon emissions from used power batteries per unit of landfill treatment in the waste center
	E_d	Carbon emissions per unit of transportation distance of used power battery
	φ	Carbon tax, treatment cost per unit of carbon emissions
Decision variables	X_r^M	0-1 variable, whether the r-th location is selected for the recycling service location
	X_g^M	0-1 variable, whether location g is selected for construction of classification and testing center
	X_h^M	0-1 variable, whether to select location h for a recycling and processing center
	X_w^M	0-1 variable, whether to select the w-th location for a waste center
	X_p^M	0-1 variable, whether to select the p-th location as a producer node

The following assumptions are made before constructing the model:

(1) The whole reverse logistics process only considers the logistics network of one recycling cycle separately.

(2) Consumers in each region are set to send all used power batteries to the nearest recycling service outlets after the batteries have reached the end of their working life, either actively or passively, instead of sending them directly to sorting and testing centers, recycling and processing centers, and landfill centers.

(3) The economic costs considered such as unit transportation cost, fixed investment cost and unit operation cost are known. And the recycling service outlets, sorting and testing centers and recycling and processing centers receive used power batteries with fast turnover, without considering the time cost and storage cost.

(4) Carbon emissions per unit of transportation distance and carbon emissions from new construction and operation of network nodes are known.

(5) Recycling service outlets under the producer-direct model are selected at the locations of existing retail stores and do not need to consider the costs and carbon emissions generated by the operation process.

(6) The sorting and testing center and the recycling and processing center have not yet been constructed and will need to be built by selecting from known alternative locations.

(7) Neither the sorting and testing center nor the recycling and processing center have been built yet, and a new one will need to be built by selecting among the known alternative addresses.

(8) The location of the waste center is known, and a selection among the known alternative addresses is required. Only the unit price of waste treatment and the carbon emissions in the treatment process are considered in the operation of the network.

(9) The recycling network has good road conditions and transportation between the node facilities. The transportation cost only considers the shortest transportation distance of the map between each node facility, without considering other influencing factors.

(10) The transportation distance between the node facilities of the recycling network is fixed and known, and the carbon emissions from transportation activities are only related to the distance between the facilities.

(11) There is no inventory capacity in the recycling service network, and all the recycled used power batteries are sent to the classification and testing center; the classification and testing center and the recycling and processing center have the maximum processing capacity limitation, but the waste center does not.

Construction of the Optimization Model

Objective functions

Under the mode of direct participation of manufacturers in recycling, the optimization model of single-cycle EV power battery reverse logistics network is designed to minimize the cost of the reverse logistics network and minimize carbon emissions. Among them, reverse logistics network costs comprise the fixed investment cost of facility construction at each node, the operation and processing cost of power battery at each node, and the transportation cost between nodes. Therefore, the objective function of the power battery reverse logistics network cost is shown in equation (1).

$$\min F_M = F_{M1} + F_{M2} + F_{M3} \tag{1}$$

$$F_{M1} = \sum_{g=1}^{g} F_g^M \cdot X_g^M + \sum_{h=1}^{h} F_h^M \cdot X_h^M \tag{2}$$

$$F_{M2} = \sum_{r=1}^{r} C_r^M \cdot Q_r^M + \sum_{r=1}^{r}\sum_{g=1}^{g} C_g^M \cdot Q_g^M + \sum_{g=1}^{g}\sum_{h=1}^{h} C_h^M \cdot Q_h^M + \sum_{h=1}^{h}\sum_{g=1}^{g} C_w^M \cdot Q_{hw}^M \tag{3}$$

$$F_{M3} = C_d \cdot (\sum_{r=1}^{r}\sum_{g=1}^{g} Q_{rg}^M \cdot D_{rg} + \sum_{g=1}^{g}\sum_{h=1}^{h} Q_{gh}^M \cdot D_{gh} + \sum_{h=1}^{h}\sum_{w=1}^{w} Q_{hw}^M \cdot D_{hw}) \tag{4}$$

In the above equation, F_{M1} is the total cost of fixed investment in the construction of fixed facilities, F_{M2} is the total cost of operation and treatment of waste power batteries at each node, and F_{M3} is the total cost of transporting used batteries among each node.

The objective function of carbon emission from reverse logistics network of used battery is shown in equation (5).

$$\min E_M = E_{M1} + E_{M2} + E_{M3} \tag{5}$$

$$E_{M1} = \sum_{g=1}^{g} EF_g^M \cdot X_g^M + \sum_{h=1}^{h} EF_h^M \cdot X_h^M \tag{6}$$

$$E_{M2} = \sum_{r=1}^{r}\sum_{g=1}^{g} E_g^M \cdot Q_g^M + \sum_{g=1}^{g}\sum_{h=1}^{h} E_h^M \cdot Q_h^M + \sum_{h=1}^{h}\sum_{w=1}^{w} E_w^M \cdot Q_w^M \tag{7}$$

$$E_{M3} = E_d \cdot (\sum_{r=1}^{r}\sum_{g=1}^{g} Q_{rg}^M \cdot D_{rg} + \sum_{g=1}^{g}\sum_{h=1}^{h} Q_{gh}^M \cdot D_{gh} + \sum_{h=1}^{h}\sum_{w=1}^{w} Q_{hw}^M \cdot D_{hw}) \tag{8}$$

In the above equation, E_{M1} total carbon emitted in constructing fixed facilities, E_{M2} is the total carbon emitted from operating and treating used power batteries at each node, and E_{M3} is the total carbon emitted from transporting used batteries between nodes.

Constraints

(1) Network nodes traffic constraints

The amount of used power batteries recycled by the recycling service locations is equal to the amount of used power batteries that they transport to the classification and testing centers:

$$\sum_{r=1}^{r} Q_r^M = \sum_{r=1}^{r}\sum_{g=1}^{g} Q_{rg}^M \cdot X_g^M \tag{9}$$

The amount of used power batteries handled by the classification and testing center is equal to the amount of used power batteries it transports to the recycling and processing center:

$$\sum_{g=1}^{g} Q_g^M = \sum_{g=1}^{g}\sum_{h=1}^{h} Q_{gh}^M \cdot X_h^M \tag{10}$$

The amount of used power batteries handled by the recycling and processing center is less than or equal to the amount of used power batteries it sends to the waste center for transportation:

$$\sum_{h=1}^{h}\sum_{w=1}^{w} Q_{hw}^M \cdot X_w^M \le \sum_{h=1}^{h} Q_h^M \tag{11}$$

(2) Constraints on the number of network nodes

The number of nodes selected for each reverse logistics network is at least 1, but not greater than its maximum number of candidates:

$$1 \le \sum_{g=1}^{g} X_g^M \le G \tag{12}$$

$$1 \le \sum_{h=1}^{h} X_h^M \le H \tag{13}$$

$$1 \le \sum_{w=1}^{w} X_w^M \le W \tag{14}$$

(3) Constraints on the node's processing capacity

Throughout the recycling process, the used power batteries handled by the classification and testing center and the recycling and processing center cannot exceed their respective maximum processing capacity:

$$\sum_{g=1}^{g} Q_g^M \cdot X_g^M \le I_g^M \tag{15}$$

$$\sum_{h=1}^{h} Q_h^M \cdot X_h^M \le I_h^M \tag{16}$$

(4) 0-1 constraints

Ensure that each candidate network node has only two states, selected and unselected, with values of 1 and 0, respectively:

$$X_g^M, X_h^M, X_w^M \in \{0,1\} \tag{17}$$

(5) Non-negative constraints

The network traffic between the nodes satisfies the non-negative constraint:

$$Q_r^M, Q_g^M, Q_h^M, Q_{rg}^M, Q_{gh}^M, Q_{hw}^M \ge 0 \tag{18}$$

EMPIRICAL ANALYSIS

In this chapter, C electric vehicle production company (referred to as Company C) will be selected for empirical analysis. The reverse logistics network optimization model of used power batteries of this company is solved by genetic algorithm. Obtain the results of selecting the number of each reverse logistics network node facility, the location of the node facility, and the specific transportation routes and transportation volume between the node facilities. Thus, the optimal program of the reverse logistics network of electric vehicle used power batteries of Company C is finally determined.

Forecast of Recycling Volume of Used Power Batteries in Company C on the Basis of the Stanford Model

The Stanford model was selected to predict the recycling volume of Company C's used power batteries for electric vehicles in Beijing, taking into account the characteristics of used electric vehicle batteries, the recycling situation of Company C's used power batteries for electric vehicles, the availability of relevant data, and the applicability of the prediction model.

The Stanford model mainly estimates the recycling volume of a product based on the product, the sales volume in a given period, the average service life of the product, and the life distribution ratio. For product i, its service life is M, and the probability of needing recycling disposal after $n_1, n_2, \ldots n_m$ years of operation is $p_1, p_2, \ldots p_k$, respectively, which is then combined with the sales volume of the product in different years to predict the future recycling volume [31, 32].

According to the Stanford model, based on the volume of electric vehicles sold by company C in Beijing from 2015 to 2022, the prediction model of the recycling volume of used power batteries is constructed as equation (19).

$$Q_j = \sum_{k}^{M} S_{j-k} P_k \tag{19}$$

In Eq. (19), Q_j is the recycling amount of used power battery in the j-th year, M is the service life of power battery, S_{j-k} the amount of batteries recycled after k years of use, and P_k is the recycling rate in the k-th year of use.

Through data collection, the sales volume of electric vehicles in Beijing and China from 2015 to 2022 of Company C are obtained as shown in Table 2.

Table 2. Electric vehicles sold by Company C during the calendar year

Year	Sales (vehicles)	
	Sales in Beijing	Sales in China
2015	103	8655
2016	477	22380
2017	5458	61237
2018	2404	86800
2019	1829	37854
2020	1492	27776
2021	2392	106400
2022	4516	271240

Based on the current level of development of domestic power battery technology and the actual situation of recycling used electric vehicle batteries in Company C, it is obtained that the lifetime of power batteries for electric vehicles is generally 6-8 years. According to the Stanford model, the actual lifetime of batteries used in Company C's electric vehicles is divided into 6 different levels, namely 1 year, 3 years, 5 years, 6 years, 7 years and 8 years, and the corresponding probability that the electric waste batteries need to be recycled is p_1, p_3, p_5, p_6, p_7, p_8. From 2015 to 2018, due to the industry and the technological level of the power batteries for electric vehicles produced by Company C limitations, the lifespan of the power battery produced by Company C is only 6 years. After 2018, the lifespan of Company C's power battery reaches 8 years due to the development of technology in the power battery industry and the result of Company C's investment in power battery R&D. It is known that the weight of the power battery used in the electric car offered for sale by Company C is 350 kg. The estimated amount of used power battery required to be recycled for Company C's electric car in Beijing in 2023 is shown in Table 3.

Table 3. Amount of Electric Vehicle Battery Recycling in Beijing, Company C, 2023

Year	Sale volume	Distribution of battery life (%)						Recovery volume	Weight of batteries (tons)	Battery recycling (tons)
		p_1	p_3	p_5	p_6	p_7	p_8			
2015	103	5	19	34	28	—	—	—	0.35	—
2016	477	5	17	35	29	—	—	—	0.35	—
2017	5458	4	16	35	33	—	—	1910.30	0.35	668.61
2018	2404	4	15	38	31	—	—	913.52	0.35	319.73
2019	1829	4	14	16	25	17	12	219.48	0.35	76.82
2020	1492	3	13	16	26	18	14	119.36	0.35	41.78
2021	2392	3	11	15	27	18	16	119.60	0.35	41.86
2022	4516	3	10	15	27	18	17	135.48	0.35	47.42
2023	—	—	—	—	—	—	—	—	—	1196.21

Data Acquisition and Analysis

Reverse logistics network nodes data

Beijing, where Company C is located, is the capital of China and has a total of 16 jurisdictions. Statistics from the Ministry of Industry and Information Technology show that Company C has set up a total of 9 used battery recycling service locations for new energy vehicles in 9 jurisdictions in Beijing, including Chaoyang, Haidian, Fengtai, Shunyi, Daxing, Tongzhou, Fangshan, Yanqing, and Pinggu, etc. These 9 recycling service outlets will serve as the first-level nodes in the Company C's reverse logistics network of used power batteries for electric vehicles, whereby the consumers will send used power batteries to these 9 recycling service outlets directly, and the recycling service outlets will then transport used power batteries to the sorting and testing center. Consumers will send their used power batteries directly to these nine recycling service outlets, which will then transport the used power batteries to the classification and testing center. The Classification and Testing Center is mainly responsible for the temporary storage of used batteries shipped from the recycling service locations, and the classification of used batteries by type and the testing of remaining battery capacity. According to the company's current situation, and with reference to the existing used power battery classification and testing institutions in Beijing, it is determined that the candidate classification and testing centers are located in Changping, Haidian, Tongzhou, Shunyi and Daxing, with a total of five candidate classification and testing centers. According to the company's current situation, and with reference to the existing used power battery classification and testing institutions in Beijing, the locations of the candidate classification and testing centers are located in Changping, Haidian, Tongzhou, Shunyi and Daxing, with a total of five candidate classification and testing centers. There are three candidate recycling and processing centers. With reference to the location of Company C's manufacturing and R&D centers and the location of used power battery laddering enterprises in the Ministry of Industry and Information Technology's list of enterprises in the "Industry Specification Conditions for Comprehensive Utilization of Waste Power Batteries for New Energy Vehicles", candidate recycling and processing centers will be constructed in three jurisdictions, namely, Fangshan, Daxing, and Shunyi, respectively. Considering the locations of waste metal landfills in Beijing, existing waste landfills in three jurisdictions, Mentougou, Daxing and Shunyi, were selected as known candidate waste center locations.

The fixed investment cost of building facilities of the reverse logistics network nodes is often related to its maximum operation scale, the advanced degree of technical equipment, labor cost and geographic location and other factors. The operation and processing costs of each facility node mainly consider the operation and handling costs of the classification and testing center and the recycling and processing center, as well as the cost of the commissioned waste landfill as a waste center to process the waste power batteries of electric vehicles. Referring to the latest research of Bao Jufang and Jiang Sheng [33] on the recycling network of retired automobile batteries, and combining with the actual situation of Company C, the relevant data of the nodes of the reverse logistics network of used power batteries for electric vehicles are determined. Meanwhile power battery recyclers said that the recycling price of used batteries for electric vehicles has soared to about CHY 30,000 per ton in 2023, and this article takes this as a reference to determine the recycling price of used power batteries as RMB 30,000.

The detailed parameters of the classification and testing center, the recycling and processing center, and the waste center are shown in Table 4.

Table 4. Recycling network nodes parameters

Network nodes	No.	Investment cost (ten thousand yuan)	Operating cost (yuan/ton)	Treatment capacity (tons/year)
Classification and testing centers (g)	g_1 (Changping)	500	9200	500
	g_2 (Haidian)	520	9250	500
	g_3 (Tongzhou)	500	9200	500
	g_4 (Shunyi)	480	9180	500
	g_5 (Daxing)	500	9200	500
Recycling and processing centers (h)	h_1 (Fangshan)	1800	18000	1000
	h_2 (Daxing)	1800	18000	1000
	h_3 (Shunyi)	1780	17950	1000
Waste Center (w)	w_1 (Mentougou)	—	1945	—
	w_2 (Daxing)	—	1945	—
	w_3 (Shunyi)	—	1945	—

Reverse logistics network flow data

According to existing studies, the recycling volume of used electric vehicle batteries in each region is positively correlated with the ownership. Therefore, this paper considers that the proportion of Company C's recycling volume of used power batteries in each jurisdiction of Beijing is equal to its proportion of electric vehicle ownership in each jurisdiction of Beijing. Collecting the electric vehicle holdings of Company C in each district of Beijing in 2022, the detailed data are shown in Table 5.

Table 5. Electric Vehicle Ownership of Company C in Beijing Districts in 2022

Administrative region	Retention	Retention percentage	Administrative region	Retention	Retention percentage
Chaoyang	2690	17.23%	Shunyi	798	5.11
Haidian	2452	15.71%	Fangshan	783	5.02
Fengtai	1447	9.27%	Shijingshan	398	2.55
Dongcheng	1391	8.91%	Miyun	311	1.99
Xicheng	1261	8.07%	Huairou	292	1.87
Changping	1080	6.92%	Pinggu	285	1.83

Daxing	1018	6.52%	Yanqing	203	1.30
Tongzhou	1005	6.44%	Mentougou	198	1.27

In this paper, it is assumed that the recycling service outlets will recycle the used power batteries in the hands of consumers in their vicinity, and at the same time, consumers will go to the recycling service outlets closest to them to recycle the used power batteries. Consumers in Dongcheng District will send their used power batteries to the recycling service outlets in Chaoyang District; consumers in Changping and Mentougou Districts will send their used power batteries to the recycling service outlets in Haidian District; consumers in Xicheng and Shijingshan Districts will send their used power batteries to the recycling service outlets in Fengtai District; and consumers in Miyun and Huairou Districts will send their used power batteries to Shunyi recycling service outlet and Yanqing recycling service outlet respectively. The consumers in Miyun and Huairou districts sent used power batteries to Shunyi and Yanqing respectively. Therefore, the recycling volume of each recycling service center can be derived as shown in Table 6.

Table 6. Company C's recycling volume at Beijing recycling centers

Recycling service locations	Administrative region	Volume of used power batteries recycled (tons)	Percentage (%)
r_1	Chaoyang	312.69	26.14
r_2	Haidian	285.89	23.90
r_3	Fengtai	237.93	19.89
r_4	Shunyi	84.93	7.10
r_5	Daxing	77.99	6.52
r_6	Tongzhou	77.04	6.44
r_7	Fangshan	60.05	5.02
r_8	Yanqing	37.92	3.17
r_9	Pinggu	21.89	1.83

According to the reverse logistics network model under the producer direct collection mode, the sorting and testing center only carries out battery classification and residual capacity detection processing for used power batteries, without considering the wastage rate of used batteries in the recycling service outlets and sorting and testing centers, and the recovered used power batteries are only subjected to the gradient utilization and specialized processing in the recycling and processing center. Since current waste battery recycling and treatment technologies can recover 92% of the battery material, this paper assumes that the waste material transported to the waste center is 8% of the total amount recovered.

Transportation distances and rates

The distance between the nodes facilities of the reverse logistics network for used power batteries is calculated by using the shortest transport route, and the specific distance data are shown below.

(1) Distance between recycling service locations and classification and testing centers

The distance between each recycling service location of Company C and the classification and testing center is presented in Table 7.

(2) Distance between classification and testing centers and recycling and processing centers

The distance between each classification and testing center and the recycling and processing center of Company C is shown in Table 8.

Table 7. The distance between recycling service locations and classification and testing centers

g / r	g_1 (Changping)	g_2 (Haidian)	g_3 (Tongzhou)	g_4 (Shunyi)	g_5 (Daxing)
r_1 (Chaoyang)	66.9	34.2	19.1	54.8	24.9
r_2 (Haidian)	33.9	3.7	41.4	42.4	36.9
r_3 (Fengtai)	58.2	27.9	41.6	71.8	29.6
r_4 (Shunyi)	49.3	37.7	40.1	12.4	66.1

r_5 (Daxing)	65.2	28.6	19	67	10.3
r_6 (Tongzhou)	60.1	37.6	28.1	28.8	48.3
r_7 (Fangshan)	75.4	45	45.6	92.5	22.4
r_8 (Yanqing)	50.3	71.5	130.9	86.6	113.1
r_9 (Pinggu)	80	80.1	87.2	39.9	104.4

Table 8. The distance between classification and testing centers and recycling and processing centers

g \ h	h_1 (Fangshan)	h_2 (Daxing)	h_3 (Shunyi)
g_1 (Changping)	93.2	65	43.2
g_2 (Haidian)	68.2	39.1	40
g_3 (Tongzhou)	47.3	5.8	44.1
g_4 (Shunyi)	104.1	47.2	9.2
g_5 (Daxing)	25.3	25.7	66.1

(3) Distance between recycling and processing centers and waste centers

The distance between each recycling and processing center and the waste center of Company C is shown in Table 9.

Table 9. The distance between recycling and processing centers and the waste centers

h \ w	w_1 (Mentougou)	w_2 (Daxing)	w_3 (Shunyi)
h_1 (Fangshan)	36.7	28.9	96.2
h_2 (Daxing)	53.5	26.5	48.5
h_3 (Shunyi)	69.4	71.5	17.8

The transportation range of Company C's waste power batteries in the reverse logistics network is within Beijing, and the weight of each transportation is generally not more than 3 tons. Therefore, when Company C chooses the transportation mode of waste power batteries, based on the actual situation of transportation range and transportation weight, it chooses road freight transportation mode, which can effectively save the transportation cost. According to Xu [34] related to the analysis of road freight prices, this paper determines that the unit cost of road freight for transporting waste power batteries in Company C is 0.4 yuan/ton kilometer.

Carbon emissions and carbon tax

Referring to the existing research results [35, 36], we measured the carbon emissions per unit construction of the classification and testing center and the recycling and processing center in the reverse logistics network to be 1.5 tons and 5 tons, respectively. Referring to the existing studies [37, 38], the carbon emissions per unit of treatment for the classification and testing center, the recycling and processing center, and the waste center in the reverse logistics network were determined to be 300kg, 750kg, and 50kg, respectively. According to the study of Yang Jun [39], the carbon emission of Beijing road freight transport unit was determined to be 3.27 tons/ton-km. According to the findings of the China Carbon Price Survey Report 2021, the national carbon market's average trading price is expected to be 49 yuan/ton in 2022, and is expected to reach 87 yuan/ton in 2025, with an average annual growth rate of carbon trading price of about 21%.Based on this, this paper assumes that the carbon tax in 2023 is consistent with the carbon market trading price, so it predicts that the carbon tax φ = 59.29 yuan/ton in 2023.

Discussion

Results of model solving

When solving the model using the genetic algorithm, the initial population size is set to 300, the probability of crossover is 0.7, and the probability of variance is 0.1. MATLAB software is used to write the corresponding program for the optimization model. The program is based on the genetic algorithm. Substitute the relevant data obtained in the previous section into the algorithm program, and obtain the convergence curve of the genetic algorithm population see Figure 2.

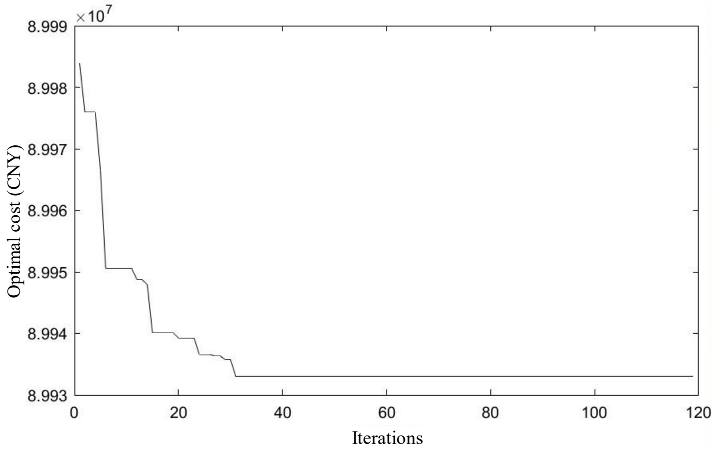

Figure 2. Iterative convergence curve of Genetic Algorithm population

It can be seen that as the number of iterations increases, the fitness value of the optimal cost of the reverse logistics network maintains an overall decreasing trend. And when iterated about 30 times, the fitness value reaches the optimal state, and the optimal total cost of the network is obtained at this time. Based on the genetic algorithm for reverse logistics network optimization model solving, the results of site selection decision, transport flow of node facilities and network optimal cost are obtained as follows.

(1) Optimal choice of variables for site selection decisions

The results of the site selection decision scheme for each new center are shown in Table 10. According to the solution results of the genetic algorithm, the final decision is to build new classification and testing centers in Tongzhou, Shunyi and Daxing districts, and new recycling and processing centers in Daxing and Shunyi districts, and Daxing and Shunyi districts are selected as alternative waste centers.

Table 10. Network Optimal Site Selection Program

	New classification and testing center					New recycling and processing center			Alternative waste center		
Nodes	g_1	g_2	g_3	g_4	g_5	h_1	h_2	h_3	w_1	w_2	w_3
Administrative region	Changping	Haidian	Tongzhou	Shunyi	Daxing	Fangshan	Daxing	Shunyi	Mentougou	Daxing	Shunyi
Selection results	0	0	1	1	1	0	1	1	0	1	1

(2) Transportation options from recycling service locations to classification and testing centers

The optimal transportation scheme from the recycling service outlets to each classification and testing center is shown in Table 11. It can be seen that the used batteries of the four recycling service locations of Chaoyang, Daxing, Fangshan and Pinggu will be transported to Tongzhou Classification and Testing Center. The waste batteries of the four recycling service locations in Haidian, Shunyi, Tongzhou and Yanqing will be transported to Shunyi Classification and Testing Center. Used batteries from Fengtai recycling service locations will be transported to Daxing Classification and Testing Center.

(3) Transportation options from classification and testing centers to recycling and processing centers

The transportation scheme from each classification and testing center to the recycling and processing center is listed in Table 12. Used batteries from Daxing Classification and Testing Center will be transported to Daxing Recycling and Treatment Center. Used batteries from Tongzhou and Shunyi Classification and Testing Center will be transported to Shunyi Recycling and Treatment Center.

Table 11. Optimal transportation solutions from recycling service locations to classification and testing centers

g / r	g_1 (Changping)	g_2 (Haidian)	g_3 (Tongzhou)	g_4 (Shunyi)	g_5 (Daxing)
r_1 (Chaoyang)	0	0	1	0	0
r_2 (Haidian)	0	0	0	1	0

r_3 (Fengtai)	0	0	0	0	1
r_4 (Shunyi)	0	0	0	1	0
r_5 (Daxing)	0	0	1	0	0
r_6 (Tongzhou)	0	0	0	1	0
r_7 (Fangshan)	0	0	1	0	0
r_8 (Yanqing)	0	0	0	1	0
r_9 (Pinggu)	0	0	1	0	0

Table 12. Optimal transportation solutions from classification and testing centers to recycling and processing centers

g \ h	h_1 (Fangshan)	h_2 (Daxing)	h_3 (Shunyi)
g_1 (Changping)	0	0	0
g_2 (Haidian)	0	0	0
g_3 (Tongzhou)	0	0	1
g_4 (Shunyi)	0	0	1
g_5 (Daxing)	0	1	0

(4) Transportation options from recycling processing centers to waste centers

The optimal transportation scheme from each recycling center to the waste center is shown in Table 13. Used batteries from the Daxing recycle center will be transported to the Daxing waste center, and used batteries from the Shunyi recycle center will be transported to the Shunyi waste center.

Table 13. Optimal Transportation from Recycling Processing Centers to Waste Centers

h \ w	w_1 (Mentougou)	w_2 (Daxing)	w_3 (Shunyi)
h_1 (Fangshan)	0	0	0
h_2 (Daxing)	0	1	0
h_3 (Shunyi)	0	0	1

(5) Transportation flow from recycling service centers to sorting and testing centers

Table 14 shows the optimum transport volume from each recycling service location to the classification and testing center. It can be seen that the optimal transport volume from Chaoyang, Daxing, Fangshan and Pinggu recycling service centers to Tongzhou classification and testing center is 312.69 tons, 77.99 tons, 60.05 tons and 21.89 tons respectively, and the total amount of used batteries received by Tongzhou classification and testing center is 472.62 tons.

(6) Flow direction from classification and testing centers to recycling and processing centers

The optimal transportation volume from each classification and testing center to each recycling and processing center is listed in Table 15. You can notice thatt the optimal transportation volume from Tongzhou and Shunyi Classification and Testing Center to Shunyi Recycling and Processing Center is 472.62 tons and 485.78 tons respectively, and the total amount of used batteries received by Shunyi Recycling and Processing Center is 958.4 tons.

Table 14. Optimal transport volume from recycling service locations to classification and testing centers

r \ g	g_1 (Changping)	g_2 (Haidian)	g_3 (Tongzhou)	g_4 (Shunyi)	g_5 (Daxing)
r_1 (Chaoyang)	0	0	312.69	0	0
r_2 (Haidian)	0	0	0	285.89	0
r_3 (Fengtai)	0	0	0	0	237.93
r_4 (Shunyi)	0	0	0	84.93	0

r_5 (Daxing)	0	0	77.99	0	0
r_6 (Tongzhou)	0	0	0	77.04	0
r_7 (Fangshan)	0	0	60.05	0	0
r_8 (Yanqing)	0	0	0	37.92	0
r_9 (Pinggu)	0	0	21.89	0	0

Table 15. Optimal transportation from classification and testing centers to recycling and processing centers

g \ h	h_1 (Fangshan)	h_2 (Daxing)	h_3 (Shunyi)
g_1 (Changping)	0	0	0
g_2 (Haidian)	0	0	0
g_3 (Tongzhou)	0	0	472.62
g_4 (Shunyi)	0	0	485.78
g_5 (Daxing)	0	237.93	0

(7) Flow direction from recycling and processing centers to waste centers

The optimal transportation volume from each recycling and processing center to each waste center is shown in Table 16. The total weight of used batteries transported from Daxing Recycling and Processing Center to Daxing Waste Center is 237.93 tons, and the total weight of used batteries transported from Shunyi Recycling and Processing Center to Shunyi Waste Center is 958.4 tons.

Table 16. Optimal transportation from recycling and processing centers to waste centers

h \ w	w_1 (Mentougou)	w_2 (Daxing)	w_3 (Shunyi)
h_1 (Fangshan)	0	0	0
h_2 (Daxing)	0	237.93	0
h_3 (Shunyi)	0	0	958.40

(8) Carbon emissions optimization

The optimal carbon emission scheme of the reverse logistics network of used power batteries for electric vehicles is listed in Table 17. The optimal carbon emissions of facility construction, operation treatment and transportation process are 14.5, 1260.93 and 30.28 tons respectively. It can be seen that it is mainly the operation process that generates a large amount of carbon emissions in the whole logistics network.

Table 17. Optimal carbon emissions schemes for reverse logistics networks of used power batteries

Composition of Carbon Emissions	Carbon emissions (tons)
Carbon emissions from facility construction	14.50
Carbon Emissions from Operation and Processing	1260.93
Carbon emissions from transportation	30.28
Total Carbon Emissions	1205.71

(9) Optimal cost solution for reverse logistics networks

The optimal cost scheme of the reverse logistics network for used power batteries is shown in Table 18. The logistics network costs consist of battery recycling cost, facility construction cost, operation and treatment cost, and transportation cost, with the lowest transportation cost being 37,045.07 yuan. Among the carbon emission costs, the carbon emission cost during transportation and handling is the largest. The total cost of the whole reverse logistics network is about 89.93 million yuan.

Table 18. Optimal cost solution for reverse logistics network of used power battery

Cost Components	Classification	Cost (yuan)
Logistics network costs	Battery recycling costs	35886300
	Facility construction costs	21260000

Cost Components	Classification	Cost (yuan)
	Operation disposal cost	32672289.35
	Transportation costs	37045.07
Carbon emission costs	Facility construction carbon cost	859.81
	Operation and disposal carbon cost	74760.64
	Transportation carbon cost	1795.46
Total costs	—	89933050.33

From the above results, we can know the optimal solution for the selection of the location of the reverse logistics network for used power batteries of Company C in Beijing, as well as the optimal solution for the transportation volume, carbon emissions, and total network cost among the nodes and facilities of the reverse logistics network, in which the site selection of the reverse logistics network and the flow selection of the facility nodes are shown in Figure 3.

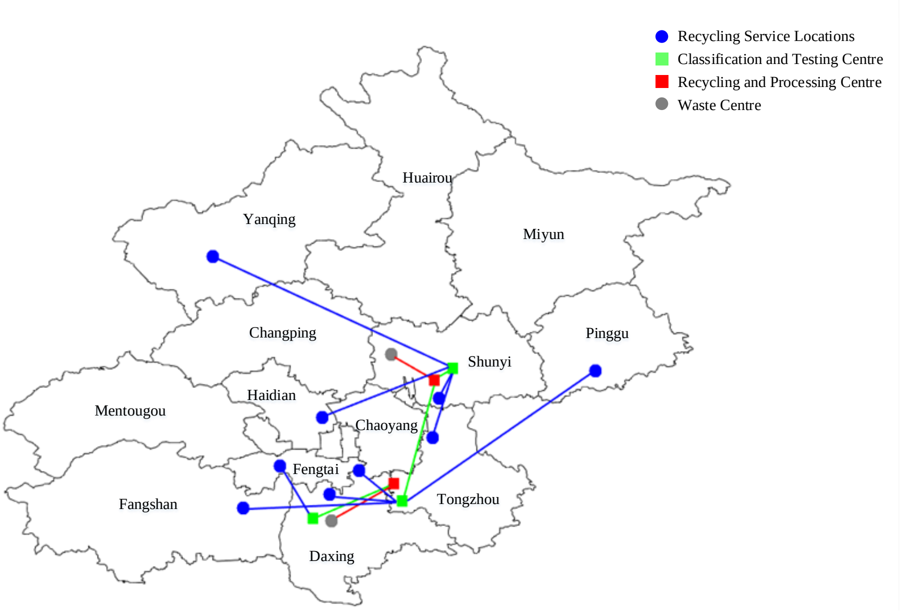

Figure 3. Company C's electric vehicle power battery reverse logistics network site selection and flow direction selection

Sensitivity Analysis

(1) Sensitivity analysis of operating costs

In this section, the change of operation processing cost of node h_3 is selected to explore its impact on the logistics network, and the results of the implementation through MATLAB are shown in Table 19. From the analysis of the operation results, when the operation processing cost of h_3 increases, the site selection scheme and the flow selection scheme between the facilities of the logistics nodes are not affected, and the total network costs remain unchanged. When the operation and processing cost of h_3 decreases, the total cost of the reverse logistics network decreases. However, selecting node h_3 as the recycling processing center, the siting of each node increases the transportation distance resulting in a doubling of the total carbon emissions.

Table 19. Variation of the optimal solution for different operating costs

Operational treatment costs (yuan)	Site selection results	Total cost (yuan)	Total carbon emissions (tons)
17500	(1,3,4), (1,3), (2,3)	89530313.29	61.98
18000	(3,4,5), (2,3), (2,3)	89933050.33	30.28
18500	(3,4,5), (2,3), (2,3)	89933050.33	30.28

In this section, the change of the construction investment cost of node g_5 is selected to explore its influence on the logistics network, and the results of the implementation through MATLAB are shown in Table 20. From the analysis of the operation results, when the construction investment cost of the g_5 node facility increases by 5 million yuan, there are changes in the location of the reverse logistics network and the flow rate between facilities at logistics hubs, and the total cost and the total carbon emissions increase slightly. When the operation processing cost of g_5 decreases by 5 million yuan, the reverse logistics network's cost also decreases by 5 million yuan, and the siting of the reverse logistics network and the flow between logistics node facilities remain unchanged.

Table 20. Variation of the optimal program for different construction costs

Construction investment costs (10000 yuan)	Site selection results	Total cost (yuan)	Total carbon emissions (tons)
450	(3,4,5), (2,3), (2,3)	89883050.33	30.28
500	(3,4,5), (2,3), (2,3)	89933050.33	30.28
550	(1,3,4), (2,3), (2,3)	89937745.49	31.25

(3) Sensitivity analysis of transportation costs

In section "Transportation distances and rates" above, the road freight logistics cost is set to be yuan 0.4 yuan/ton-kilometer, and this paper considers the impact when the road freight logistics cost changes within the range of yuan 0.1-1 yuan/ton-kilometer. Since the transportation cost accounts for a small proportion of the total network costs, the change of freight logistics cost in the range of 0.1-1 yuan/ton-kilometer only has an impact on the overall transport costs of the network, and has no impact on the logistics site selection and traffic flow direction. The change of total cost under different transportation cost is shown in Figure 4.

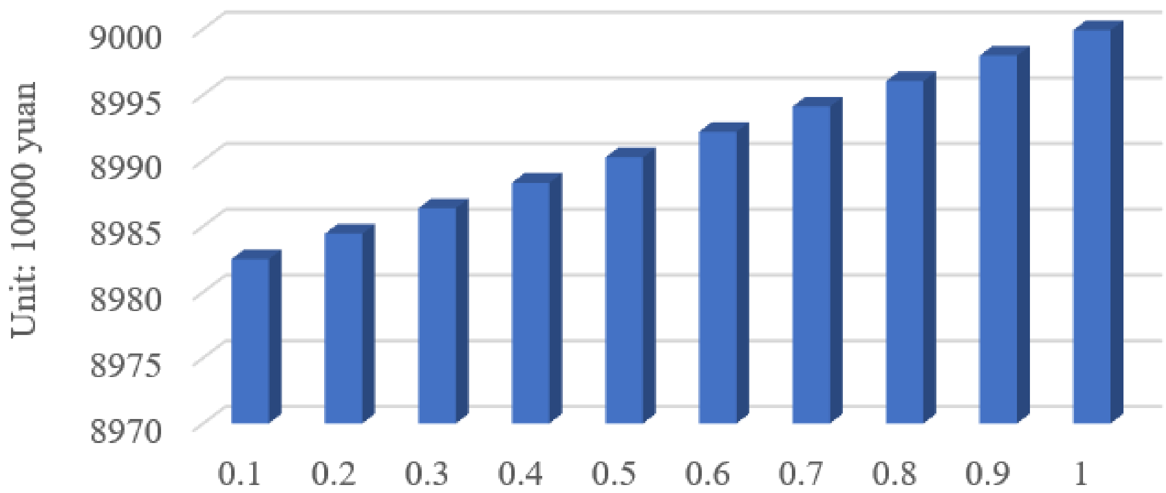

Figure 4. Variation in total costs with different transportation costs

(4) Sensitivity analysis of the cost of carbon emissions

The carbon tax of this paper is RMB 59.29/ton, and this section is still based on the 21% growth rate to compare and analyze the potential impact of carbon tax changes in 2023-2025, and the results are presented in Table 21. We can find that the growth rate of carbon tax in 2023-2025 has no impact on the location of reverse logistics network and the flow of used power batteries in each node, and the total carbon emissions remains unchanged because the cost of carbon emission is a small part of the reverse logistics network's total cost.

Table 21. Variation in the cost of carbon emissions under different carbon taxes

year	Carbon tax (yuan/ton)	Total carbon emissions (tons)	The cost of carbon emissions (yuan)
2023	59.29	30.28	77415.91
2024	71.74	30.28	93672.08
2025	87.00	30.28	113597.31

CONCLUSION

In the past few years, the scale of electric vehicles in China has shown a trend of rapid growth, but due to the limited service life of electric vehicle power batteries, resulting in the number of used batteries is increasing day by day. Therefore, this paper aims at the problems of imperfect recycling system and high recycling cost of used power batteries for electric vehicles, designs a profit model under the direct recovery mode of manufacturers based on closed-loop supply chain, and constructs a reverse logistics network optimization model of used power batteries for electric vehicles with the goal of minimizing costs and carbon emissions. Finally, an empirical analysis was carried out on the example of C Electric Vehicle Company. The optimal solution for siting the reverse logistics network of Company C's used power battery for electric vehicles in Beijing was obtained. That is, Tongzhou, Shunyi and Daxing as sorting and testing centers, Daxing and Shunyi as recycling and processing centers, and Shunyi and Daxing as candidate waste centers, as well as optimal solutions for transport volumes, carbon emission and the total network cost between the node facilities of the reverse logistics network.

This paper studies the optimization of the reverse logistics network of used power battery under the manufacturer's direct collection mode, which can provide reference for the relevant enterprises to undertake the recycling work of used power battery, and help the development and advancement of the recycling system of used power battery, which is of certain practical significance. In addition, this paper in the process of example analysis of the transportation price to do a simplified treatment, in fact, the transportation cost and logistics vehicle models, geographic location, traffic conditions and other factors. Therefore, a more detailed consideration of transportation cost can be considered in future research.

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