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Research on Optimization of Power Battery Recycling Logistics Network

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Abstract

With the popularity and development of electric vehicles, the demand for power batteries has increased significantly. Power battery recycling requires a complex and efficient logistics network to ensure that used batteries can be safely and cost-effectively transported to recycling centers and properly processed. This paper constructs a dual-objective mathematical model that minimizes the number of recycling centers and minimizes the logistics cost from the service center to the recycling center, and designs the power battery disassembly and recycling process and the recycling logistics network, and finally uses a genetic algorithm to solve it. Finally, this article takes STZF Company as an example to verify the effectiveness of this method. The verification results show that the logistics intensity of the optimized power battery recycling logistics network has been reduced by 36.2%. The method proposed in this article can provide certain reference for power battery recycling logistics network planning.

Keywords: power battery, recycling logistics, logistics network.

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1. Introduction

With the rapid development of new energy vehicles in China, the number of new energy vehicles has reached an astonishing 18.21 million units (2023)[1][2]. A power battery is a battery specially used to store and provide electrical energy to drive electric vehicles. China's new energy vehicles mainly use power batteries as drive batteries. These batteries are usually high-capacity, high-performance batteries that can provide enough power to support the operation of electric vehicles[3][4]. A large number of scrapped power batteries have brought serious environmental problems, such as heavy metal pollution, ecological environment damage and human health hazards. [5-7]. Optimizing the recycling logistics network of power batteries can better collect and transport used batteries and increase the recycling rate. High recycling rates mean more batteries are recovered and reused, reducing reliance on disposal sites while mitigating the need for new resources and environmental damage. Through the optimization of the logistics network, the transportation costs, processing costs and labor costs of the recycling process can be reduced. This helps build a more competitive battery recycling industry and promotes its sustainable development. Therefore, the optimization research of power battery recycling logistics network is of great significance for achieving sustainable development goals, reducing environmental impact, improving resource utilization efficiency and promoting industrial development.

There are many research students on recycling logistics network and the results are rich. Desticioglu B[8] studied the construction of a recycling logistics network with stochastic demand, using the CCP method to solve it, and achieved good results. Gao ZH[9] studied multi-objective problems such as fixed cost of vehicle transportation, transportation cost, carbon emission cost during driving and time penalty cost of reverse logistics. Pereira N[10] studied the management model of reverse logistics of electronic products and methods of protecting the environment. Roudbari ES[11] A has conducted multi-faceted research on product reuse, remanufacturing, recycling and refurbishment of uncertain recycling logistics networks. Singh M[12] A took the recycling of medical waste as the research object to establish a recycling logistics model and achieved good results. Abdissa G[13] conducted research on the recycling logistics of mineral water bottles to avoid

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environmental problems caused by white waste pollution. The above-mentioned scholars have made rich research results on recycling logistics, but there are few studies on recycling logistics for power batteries.

As the market for electric new energy vehicles becomes larger and larger, power batteries are gradually entering the scrap cycle. In order to prevent environmental problems caused by scrapping of power batteries, it is necessary to optimize the logistics network and design a sustainable low-cost recycling logistics network.

The rest of the article is organized as follows: Section 1 presents research pertaining to the contribution of Power battery and logistics network. Section 2 presents the recycling logistics network design. Section 3 presents mathematical model building. Section 4 presents case application. Finally, Section 5 presents the conclusion.

2. Power battery recycling logistics network design

2.1. Power battery disassembly process

China's power batteries are mainly lithium batteries. Lithium batteries mainly include lithium, copper, iron, manganese and other materials. Among the materials that can be used, the economic significance of iron and manganese is relatively small, so the recyclable metals with economic value are lithium, copper, etc. The detailed lithium battery recycling process is shown in Figure 1.

2.2. Recycling logistics network design

The scrapped power battery recycling network starts from consumers, passes through after-sales service centers, to recycling testing centers, and finally to power battery manufacturers or scrap metal processing plants. Since the working locations of the after-sales service center and scrap metal processing plant remain unchanged, the most important factor affecting the cost of the reverse logistics network is the location of the recycling testing center. This article designs and decomposes the reverse logistics process to obtain a schematic diagram of the reverse logistics node of the power battery, as shown in Figure 2.

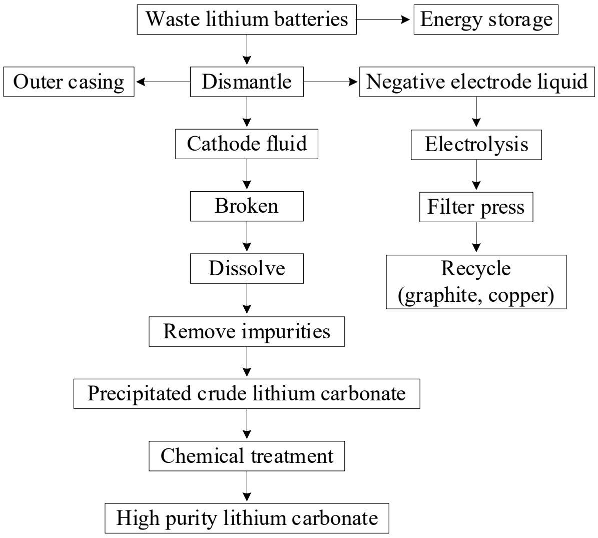

Figure 1. Lithium battery disassembly and recycling process

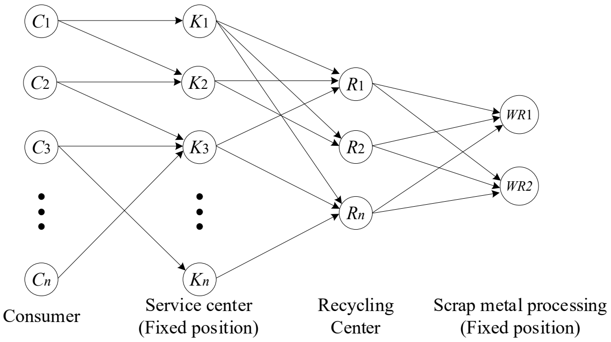

Figure 2. Schematic diagram of reverse logistics nodes for power batteries

- After-sales service center

The main functions of the after-sales service center are electric vehicle testing, repair, fault analysis and maintenance. As the first link of the system, the after-sales service center functions to recycle scrapped power batteries. Consumers will send retired power batteries that have reached the end of their life to after-sales service. The service center has a fixed location.

- Recycling Testing Center

The second link is the recycling and testing center, which is responsible for receiving retired power batteries collected from the after-sales service center, and testing, decomposing and temporarily storing a large number of retired power batteries. After disassembly and testing, the power batteries can reach the next stage. After meeting the requirements, enter the next step.

- Processing center

The key task in the processing corresponding to the construction of the logistics network is to conduct professional analysis of retired power batteries with recycling and reuse functions, and then process the analyzed power batteries to promote the use of retired power batteries in echelons, thereby effectively improving the industry's Electric energy resource utilization.

- Scrap metal processing plant

The scrap metal treatment plant mainly decomposes scrap batteries, recycles the scrap metal in the batteries, manufactures related electronic products, and then harmlessly disposes the scrap power batteries that cannot be recycled.

3. Power battery recycling logistics model

3.1. Mathematical conformity

The mathematical correspondence means as follows:

N represents the number of recycling testing centers.

H represents the number of optional recycling testing centers.

h indicates that the h-th service center can be used as an alternative recycling center.

α_h is to determine whether the hth alternative recycling and testing center can be used as the optimal recycling and testing center.

D_{mi} represents the maximum transportation distance from m to i

S_{mi} represents the distance from the i-th alternative recycling testing center to the m-th after-sales service center

ρ_{mi} indicates whether the used power batteries at the K-th recycling point are received by the i-th recycling inspection center. C represents the total cost of transportation;

Q_i represents the recycling volume of the i-th after-sales service center;

P represents the transportation cost per unit mass of the product.

3.2. Mathematical model building

The reverse logistics mathematical model of power batteries is a dual-objective mathematical model. The first objective is to minimize the number of recycling center objective functions, and the second objective is to minimize the logistics cost from the after-sales service center to the recycling center. The constructed mathematical model is shown below.

The minimum objective function for the number of recycling centers is shown in Equation (1).

$$N = \min\left(\sum_{h=1}^{H} \alpha_h\right) \tag{1}$$

The constraints of formula (1) are as shown in formula (2), formula (3) and formula (4).

$$S_{mi} * \rho_{mi} \leq D_{mi} \tag{2}$$

$$\alpha_h = \begin{cases} 1 & h \text{ service center is selected} \\ 0 & h \text{ service center is not selected} \end{cases} \tag{3}$$

$$\rho_{mi} = \begin{cases} 1 & m \text{ is received by } i \\ 0 & m \text{ is not received by } i \end{cases} \tag{4}$$

The minimum objective function of the logistics cost from the after-sales service center to the recycling center is shown in Equation (5).

$$C = \min \sum_{h=1}^{H} Q_i S_{mi} P \tag{5}$$

The constraints of equation (5) are as shown in equation (6) and equation (7).

$$\sum_{i=1}^{I} \rho_{mi} = I \tag{6}$$

$$\sum_{h=1}^{H} \alpha_h = N \tag{7}$$

$$\overline{f} = \frac{qn}{m} \tag{8}$$

Equation (6) represents the selection of recycling testing centers from pre-selected after-sales service centers to ensure that the number of recycling testing centers is minimized, and the minimum value is N; Formula (7) represents the selected recycling testing center that can be included in Recycle retired power batteries from all after-sales service centers within the area. Formula (8) represents the average logistics intensity, which is one of the indicators for evaluating logistics networks.

4. Case application

4.1. Case introduction

STZF mainly conducts comprehensive recycling of lithium batteries. The recycled lithium batteries are used to produce electronic grade cobalt oxide, industrial grade cobalt oxide, cobalt hydroxide, cobalt sulfate, electrolytic copper and other products. In recent years, with the promotion and development of the electric vehicle industry in China, electric vehicles have entered a period of rapid development. Rapid development will inevitably lead to the retirement of a large number of power batteries. If these used power batteries are not properly processed, they will inevitably be destroyed. Land and water resources are polluted. In order to cooperate with relevant national policies and regulations, STZF actively encourages energy reuse and is committed to the recovery and recycling of lithium-ion power batteries.

4.2. Data

- Power battery usage and scrapping

STZF's power battery usage and scrapped batteries are shown in Table 1.

Table 1. Power battery usage and scrap volume

Year	Usage (tons)	Scrap (tons)
2015	198.5	5.8
2016	437.5	23.1
2017	856.3	57.1
2018	1055.1	163.6
2019	4013.6	391.6
2020	9036.3	663.8
2021	16787.9	1132.2

- Logistics network node coordinates

The node coordinates of STZF's logistics network are shown in Table 2.

Table 2. Logistics network node coordinates

Service center	Coordinate	Service center	Coordinate
K1	(1542, 3512)	K16	(3715, 1238)
K2	(749, 1315)	K17	(3218, 2179)
K3	(3077, 2844)	K18	(4061, 2370)
K4	(2612, 1499)	K19	(3780, 2012)
K5	(1644, 1505)	K20	(3676, 2578)
K6	(3336, 1556)	K21	(4029, 2838)
K7	(1238, 1439)	K22	(1963, 2932)
K8	(4206, 1044)	K23	(3429, 1908)
K9	(4312, 790)	K24	(1507, 2306)
K10	(4386, 570)	K25	(1394, 2643)
K11	(4407, 960)	K26	(2439, 3201)
K12	(2592, 1676)	K27	(2565, 3240)
K13	(2878, 1651)	K28	(3140, 3550)
K14	(891, 2256)	K29	(2545, 2357)
K15	(1332, 695)	K30	(2778, 2826)

- Recycling ability

The recycling capabilities of STZF's 30 scrap metal treatment plants are shown in Table 3.

Table 3. Recycling capacity of scrap metal processing plants

Service center	Recycling capacity (tons)	Service center	Recycling capacity (tons)
K1	261	K16	372
K2	493	K17	340
K3	285	K18	573
K4	593	K19	370
K5	594	K20	350
K6	390	K21	573
K7	417	K22	392
K8	284	K23	373
K9	492	K24	310
K10	242	K25	162
K11	390	K26	492
K12	560	K27	219
K13	341	K28	178
K14	532	K29	392
K15	168	K30	491

- Transportation cost

The after-sales service center of STZF company directly transports to the scrap metal processing plant. The transportation costs of 30 after-sales service centers to the scrap metal processing plant are shown in Table 4.

Table 4. Unit transportation cost (tons/km/yuan)

Service center	Cost	Service center	Cost
K1	0.65	K16	0.91
K2	0.75	K17	0.51
K3	0.73	K18	0.73
K4	0.87	K19	0.84
K5	0.97	K20	0.83
K6	0.68	K21	0.97
K7	0.79	K22	0.62
K8	0.53	K23	0.76
K9	0.74	K24	0.88
K10	0.87	K25	0.99
K11	0.58	K26	0.52
K12	0.69	K27	0.45
K13	0.74	K28	0.79
K14	0.83	K29	0.82
K15	0.85	K30	0.68

4.3. Calculation example solution

The genetic algorithm has good results in solving the logistics transportation network. Therefore, this paper uses the genetic algorithm in the literature[14][15] to solve the problem. The population size of the genetic algorithm is 100, the crossover probability is 0.5, the mutation probability is 0.4, and the number of iterations is 100. The genetic algorithm was run in MATLAB 2019a software. As a result, the population converged to the optimal solution after 39 iterations. The iterative convergence curve is shown in Figure 3. The recycling and testing center network location plan is shown in Figure 4.

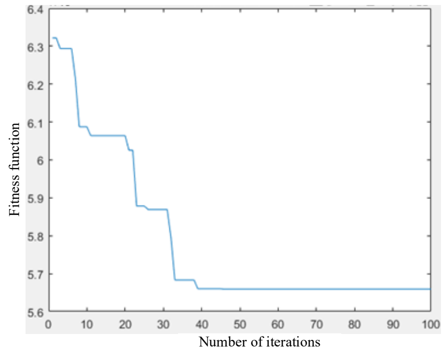

Figure 3. Genetic algorithm iteration process

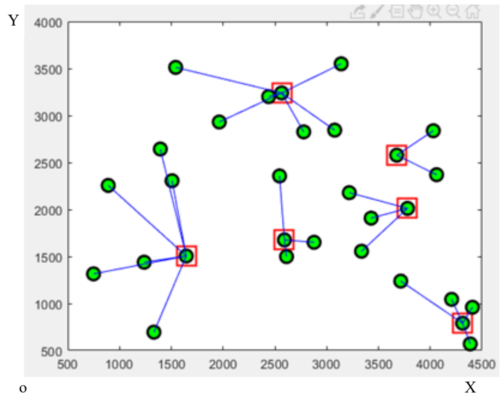

Figure 4. Recycling center network location plan

There are a total of 6 recycling testing centers derived from the genetic algorithm, and their corresponding coordinates are shown in Table 5. The recycling capacity of the recycling testing center can be predicted based on the recycling capacity of the corresponding region.

Table 5. Coordinates of recycling centers and their recycling capabilities

Recycling center	Service center	Coordinate	recycling capability(tons)
R1	K5	(1644, 1505)	2800
R2	K9	(4312, 190)	2000
R3	K12	(2592, 1676)	2100
R4	K19	(3780, 2012)	1800
R5	K20	(3676, 2578)	1700
R6	K27	(2565, 3240)	2500

According to the logistics intensity formula (8), it can be calculated that the average logistics intensity before improvement is 26673.17 tons/year, and the logistics intensity after improvement is 17007.02 tons/year, and the logistics intensity is reduced by 36.2%.

5. Conclusion

This study takes the recycling logistics of power batteries as the research object, constructs a mathematical model, designs the recycling logistics network, and uses STZF Company as a case to verify the method. The final verification results show that the logistics intensity of the optimized power battery recycling logistics network has been reduced by 36.2%. The method proposed in this paper can provide some reference for the planning of power battery recycling logistics network.

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