Reverse Logistics Network Design and Optimization for Battery Recycling of Waste Electric Vehicle Based on Circular Economy

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ABSTRACT

With the development of energy and environmental benefits and technology, the application of electric vehicles is becoming more and more popular, and it is accompanied by the environmental impact and recycling application of used electric vehicle batteries (WEVB). In order to cope with the "decommissioning tide" of new energy vehicle batteries, the establishment of a sustainable and efficient waste power battery recycling network is a key link. The income and government subsidies of decommissioned battery recycling system are the premise of the sustainable development of the overall link. Further application and optimization involve economic feasibility, environmental impact and battery characteristics. In view of this, the site-path optimization model of decommissioned power battery recycling reverse logistics is established with the maximum total profit as the goal, combining the characteristics of power products and the characteristics of battery supply and demand side changes. The optimal location and route direction are obtained, and sensitivity analysis is carried out to determine the influence of factors such as technological development and market changes. The results show that the increase of regional recycling leads to the increase of total profit, the increase of transportation weight, and the increase of unsaturated facilities, and the decrease of profit growth. Increased market demand leads to reduced transportation, environmental costs and network routing optimization; Battery technology changes bring revenue far higher than the cost, improve the echelon utilization and reduce the enterprise capital recovery cycle and benefit the development of recycling links.

Keywords: location - path planning; Power battery recycling; Sustainable development; Circular economy; Reverse logistics network

1. INTRODUCTION

With the depletion of energy and the prominent environmental problems, all walks of life pay more and more attention to sustainable development. In terms of transport, there are already 90 billion vehicles on the road worldwide, and 96% of its energy use comes from fossil resources[1]. With the opening up of policies and industry research, new energy electric vehicles have developed rapidly, and electric vehicles have reduced exhaust emissions by 92-98% compared with fuel vehicles. Under the high efficiency and environmental benefits, the production and sales of new energy vehicles in China in 2022 will reach 7.058 million and 6.887 million, respectively. This was followed by increased battery demand, with a power battery life of about 8 years[2], but when power loss and capacity decline to 80% of the total capacity, resulting in decommissioning due to dissatisfaction with vehicle requirements. In 2020, the total amount of scrapped EV batteries in China will reach about 200,000 tons, and this figure will rise to about 780,000 tons by 2025[3]. Recycling decommissioned batteries is critical for socio-economic and environmental sustainability, especially for China, the world's largest manufacturer and consumer of lithium-ion batteries[4].

From the existing research, Kastanaki et al.[5] show that future investment in battery remanufacturing, reuse, and recycling infrastructure is necessary to deal with the increasing amount of lithium-ion battery waste. Harper et al.[6] point out that recycling decommissioned used batteries into the original network will reduce material loss, reduce environmental risks and health hazards, and increase economic opportunities. At the same time, storage or scrapping (landfill) will cause additional waste and loss. From the perspective of policy, Gu et al.[7] studied the optimal production strategy of EV manufacturers under government subsidies and battery recycling, and the results showed that battery recycling and government subsidies would improve the expected utility and promote the optimal production. Based on this, it is necessary to build a recycling system for retired batteries.

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In summary, site selection and path optimization are rarely considered comprehensively for decommissioned battery recycling. Both path decision and location decision are key decisions for network optimization, and one party alone will produce sub-optimal results. For the characteristics of decommissioned batteries, can not be ignored is the environmental impact and government subsidies, power battery industry is an important way to achieve decarbonization, government subsidies can improve the gradient utilization rate of power remanufacturing and the enthusiasm of material recycling; Since the main body responsible for the construction of the recycling system at this stage is the automobile production enterprise, and the echelon utilization is in the initial construction stage, the overall profit of the construction of the logistics system is the largest, among which the total income is based on practical factors, considering the extension of remanufacturing life and the different income of the market for retired batteries and materials. Based on this, considering the different levels of income and government subsidies under market demand and the overall logistics network cost including carbon emission, aiming at the maximum total profit of the overall logistics network for power batteries and the development of the overall link, the site-path problem of the reverse logistics network for decommissioned batteries was studied, and the whale optimization algorithm was used to solve it. The layout plan of site selection points and path network for decommissioned battery reuse, remanufacturing and recycling is obtained, and the scheme reference is provided for layout decision makers.

2. PROBLEM DESCRIPTION AND MODEL HYPOTHESIS

Power battery reverse logistics network structure, nodes include regional recycling network, collection and inspection center, metal recycling center, remanufacturing center, material market, second-hand market and processing center, as shown in Figure 1.

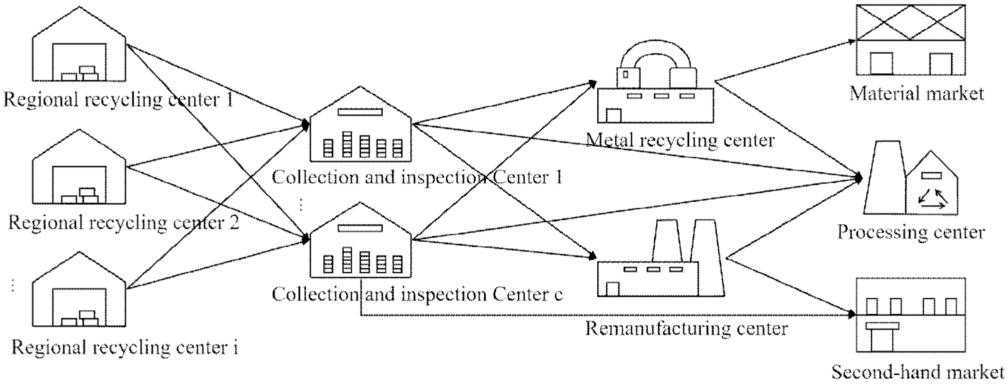

Figure 1. Reverse logistics network structure of decommissioned batteries.

Under the Extended Producer Responsibility system (EPR), relying on 4S stores or dealers and other sales network nodes to form regional recycling outlets, power batteries after meeting a certain number or a period of time, the temporary power batteries will be transported to the collection and inspection center; Starting from the life cycle characteristics of decommissioned power batteries, the optimization analysis of recycling and disassembly, echelon use, reuse, transportation and scrapping disposal processes, specifically for the collection and inspection center to disassemble, test and screen the battery, evaluate its health status (SoH), performance and quality level, according to the testing standards will have the following conditions:

When the battery capacity is greater than 80% and meets the secondary sales standards, the second life (2L) can be generated after processing in the collection and inspection center, and it will flow into the second-hand market to obtain profits; When the battery capacity is 20% to 80%, it can be used in the remanufacturing center for echelon utilization and packaging recycling, and applied in the fields of energy storage system (ESS), urban facilities, low-speed electric vehicles, communication base stations, backup power supplies, etc., so as to obtain profits in the second-hand market. When the battery capacity is less than 20%, recycling, recycling its internal precious metals, can be used in the metal recovery center using fire, hydrometallurgy, electrochemical recovery technology, nickel, cobalt and manganese, etc., applied to the material market. Some parts do not have actual value or actual value is far less than the processing value, will be directly sent to the processing center. Because the battery is a high pollutant, the waste generated in the remanufacturing center and the metal recycling center will be transported to the treatment center for processing.

Specific model assumptions are as follows:

1. The number and time of vehicles in the transport stage of the logistics network are not limited.
2. The potential location and number of collection and inspection centres, metal recycling centres and remanufacturing centres are known.
3. The processing capacity and storage capacity of each facility node are determined and limited.
4. The minimum market demand must be met, and when the combined supply of all facilities exceeds the maximum market demand, the rest is shipped to the processing center.
5. The product flow is only allowed to be transported sequentially between two echelons.

3. MATHEMATICAL EQUATIONS

3.1 Symbol definition

1. Indices

i : Index of regional recycling centers(RCC), $i=1,...,I$; c : Index of collection and inspection centers(CIC), $c=1,...,C$; r : Index of metal recycling centers(MRC), $r=1,...,R$; b : Index of remanufacturing centers(RC), $b=1,...,B$; m : Index of material markets(MC), $m=1,...,M$; l : Index of processing centers(PC), $l=1,...,L$; s : Index of second-hand markets(SM), $s=1,...,S$.

2. Parameters

SC_{cs} : Unit price of reusable batteries; Q_{cs} : Transportation volume of CIC to SM; a_f : The proportion of battery capacity at each stage, $f=1,2,3$; SC_{r1m}, SC_{r2m} : The recovery market prices of cobalt and nickel respectively; θ_1, θ_2 : The proportion of cobalt and nickel in recyclable material batteries; Q_{rm} : Transportation volume of MRC to MC; SC_{bs} : Unit price per extended unit life; RES_b : The remaining life of the battery after the remanufacturing process; W : Prolong the life of remanufactured batteries; U : The existing life of the recovered decommissioned battery and it meets the normal distribution; L : Standard service life of remanufactured batteries; g : Government to decommissioned power battery unit recycling subsidies; $F_{c,r,b}$: The fixed costs of CIC, MRC and RC respectively; YC_f : Recovery cost per unit under different capacity; $YH_{c,r,b,l}$: Unit processing costs for products, modules and materials for CIC, MRC, RC and PC; $PO_{n,l}$: The processing capacity of each facility, $(c,r,b)\in n$; N_n : The maximum processing capacity of each facility; $V_{ic,cs,cr,cl,cb,rm,rl,bs,bl}$: Unit transportation cost between nodes; $D_{ic,cs,cr,cl,cb,rm,rl,bs,bl}$: Transportation distance between nodes; $EF_{c,r,b}$: Carbon emissions from the construction of CIC, MRC and RC; $EH_{c,r,b,l}$: Carbon emission rates per unit of CIC, MRC, RC and PC operations for the production and processing of products, modules and materials; CE : Cost of carbon emissions; $Q_{ic,cs,cr,cl,cb,rm,rl,bs,bl}$: Traffic volume between nodes; $T_{c,b}$: Processing batch interval time; $EV_{ic,cs,cr,cl,cb,rm,rl,bs,bl}$: Carbon emission per unit transportation between nodes; k : Capacity loss coefficient; N_f : The proportion of available battery cells in the total recycled battery; β : Demand rate of MC for battery materials; μ : Demand rate of SM for remanufactured products; $M_{c,p}$: Indicates the maximum storage capacity of each node.

3. Decision variables

x_c : 1 if CIC is opened at potential location c,0 otherwise; x_r : 1 if MRC is set at potential location r,0 otherwise; x_b : 1 if RC is set at potential location b,0 otherwise; $y_{ic,cs,cr,cl,cb,rm,rl,bs,bl}$: 1 if two nodes are connected and transported from the upper node to the lower node, otherwise 0.

3.2 Model construction

Based on the above framework and assumptions, this paper constructs a site-path optimization model of decommissioned battery recycling logistics network to determine the number and location of each node facility, as well as product flow direction and flow route.

$$IV=\sum_c\sum_s SC_{cs}Q_{cs}y_s+\sum_r\sum_m (SC_{r1m}\theta_1 Q_{rm}+SC_{r2m}\theta_2 Q_{rm})y_{rm}+\sum_b\sum_s SC_{bs}RES_b Q_{bs}y_{bs}+\sum_i\sum_c gQ_{ic}y_{ic} \tag{1}$$

$$\begin{aligned}
CV=&\sum_c F_c x_c+\sum_r F_r x_r+\sum_b F_b x_b+\sum_f\sum_i\sum_c YC_f a_f Q_{ic}y_{ic}\\
&+\sum_i\sum_c YH_c Q_{ic}y_{ic}+\sum_c\sum_r YH_r Q_{cr}y_{cr}+\sum_c\sum_b YH_b Q_{cb}y_{cb}+\sum_l\sum_n YH_l PO_l y_{nl}\\
&+\sum_i\sum_c V_{ic}D_{ic}Q_{ic}y_{ic}+\sum_c\sum_s V_{cs}D_{cs}Q_{cs}y_{cs}+\sum_c\sum_r V_{cr}D_{cr}Q_{cr}y_{cr}+\sum_c\sum_l V_{cl}D_{cl}Q_{cl}y_{cl}\\
&+\sum_c\sum_b V_{cb}D_{cb}Q_{cb}y_{cb}+\sum_r\sum_m V_{rm}D_{rm}Q_{rm}y_{rm}+\sum_r\sum_l V_{rl}D_{rl}Q_{rl}y_{rl}+\sum_b\sum_s V_{bs}D_{bs}Q_{bs}y_{bs}\\
&+\sum_b\sum_l V_{bl}D_{bl}Q_{bl}y_{bl}\\
&+CE(\sum_c EF_c x_c+\sum_r EF_r x_r+\sum_b EF_b x_b+\\
&+\sum_i\sum_c EH_c Q_{ic}y_{ic}+\sum_c\sum_r EH_r Q_{cr}y_{cr}+\sum_c\sum_b EH_b Q_{cb}y_{cb}+\sum_l\sum_n EH_l PO_l y_{nl}\\
&+\sum_i\sum_c EV_{ic}D_{ic}Q_{ic}y_{ic}+\sum_c\sum_s EV_{cs}D_{cs}Q_{cs}y_{cs}+\sum_c\sum_r EV_{cr}D_{cr}Q_{cr}y_{cr}+\sum_c\sum_l EV_{cl}D_{cl}Q_{cl}y_{cl}\\
&+\sum_c\sum_b EV_{cb}D_{cb}Q_{cb}y_{cb}+\sum_r\sum_m EV_{rm}D_{rm}Q_{rm}y_{rm}+\sum_r\sum_l EV_{rl}D_{rl}Q_{rl}y_{rl}+\sum_b\sum_s EV_{bs}D_{bs}Q_{bs}y_{bs}\\
&+\sum_b\sum_l EV_{bl}D_{bl}Q_{bl}y_{bl})\\
&+k\sum_c T_c^{0.5}Q_{Ic}+k\sum_b T_b^{0.5}Q_{cb}
\end{aligned} \tag{2}$$

$$Max=IV-CV \tag{3}$$

$$PO_n=\min(N_n,PO_n) \tag{4}$$

$$RES_b=\max(W+U-L,0) \tag{5}$$

$$PO_l=\sum_c Q_{cl}+\sum_b Q_{bl}+\sum_r Q_{rl},\forall l \tag{6}$$

$$\sum_i Q_{ic}=\sum_s Q_{cs}+\sum_r Q_{cr}+\sum_b Q_{cb}+\sum_l Q_{cl},\forall c \tag{7}$$

$$\sum_{z} Q_{cz} = \sum_{i} \sum_{f} a_f N_f Q_{ic}, z = s,r,b, f = 1,2,3, \forall c \tag{8}$$

$$\sum_{l} Q_{cl} = \sum_{i} (1 - \sum_{f} a_f N_f) Q_{ic}, \forall c \tag{9}$$

$$\sum_{c} Q_{cp} = \sum_{m} Q_{pm} + \sum_{r} Q_{pl}, p = r,b, \forall r \tag{10}$$

$$\beta D_{m1} \le \sum_{m} Q_{rm} \le \beta D_{m2}, \forall m \tag{11}$$

$$\mu D_{s1} \le \sum_{b} Q_{bs} \le \mu D_{s2}, \forall s \tag{12}$$

$$\sum_{i} Q_{ic} \le M_c, \forall c \tag{13}$$

$$\sum_{c} Q_{cp} \le M_p, p = r,b, \forall p \tag{14}$$

$$Q_{ic}, Q_{cs}, Q_{cr}, Q_{cl}, Q_{cb}, Q_{rm}, Q_{rl}, Q_{bs}, Q_{bl} \ge 0, \forall i,c,s,r,l,b,s,m \tag{15}$$

$$x_c, x_r, x_b, y_{ic}, y_{cs}, y_{cr}, y_{cb}, y_{cl}, y_{rm}, y_{rl}, y_{bl}, y_{bs} \in [0,1] \tag{16}$$

Equation (1) is total revenue, sales revenue of repeatable modules(RA), sales revenue of precious metals(RB), sales revenue of remanufacturing(RC), and government subsidy(RD); Equation (2) is total cost, fixed cost(FC), recovery cost(YC), processing cost(PC), transportation cost(TC), environmental cost(EC), and battery capacity loss cost(OC); Equation (3) is to maximize the total profit; Equation (4) is the processing capacity of each facility; Equation (5) is the remaining battery life after the remanufacturing process; Equation (6) represents the balance constraint of node processing product flow; Equations (7), (10) represent the balance constraints of node product flow. Equations (8) and (9) are product quantity constraints; Equations (11), (12) represent the need to meet market demand; Equations (13), (14) represents the maximum capacity carrying capacity of a node. Equation (15) is a non-negative constraint. Equation (16) is a binary variable constraint.

4. CASE STUDY

4.1 Basic data

This paper considers 20 RCCS, 8 potential CIC's, 3 potential MRCS, and 3 potential RCS. Details of logistics network parameters are shown in Table 1. The location coordinates of RCC, CIC, MRC, RC, SM, PC, MC and the detailed data of RCC recovery are shown in Table 2.

Table 1. Logistics network related parameters.

Parameter	Value	Parameter	Value	Parameter	Value
SC_{cs}, SC_{bs}	10000, 5000	CE	1000	YH_c	[25,35]
a_f	0.1,0.5,0.4	W, L	6,10	YH_r	[230,250]
SC_{r1m}	19000	g	800	YH_b	[180,195]
SC_{r2m}	10000	U	$N(8,0.5)$	YH_l	[25,50]
θ_1, θ_2	0.5,0.3	k, T_c, T_b	5.25, 64, 36	$EF_{c,r,b}$	[500,700]
F_c	[3500000,4000000]	N_f	0.96,0.92,0.94	$EH_{c,r}$	0.64,6.25

F_r, F_b	[5250000,6450000]	β, μ	0.8, 0.9	$EH_{b,l}$	8.16,1.5
YC_f	7000,4000,2000	N_c	7000	$M_{c,r,b}$	12000, 4000, 6000
$V_{ff'}$	[17,20]	N_r	1800	D_{m1}, D_{m2}	2002,2402.4
$EV_{ff'}$	[0.02,0.03]	N_b	2000	D_{s1}, D_{s2}	3802,4562.4

Table 2. RCC, CIC, MRC, RC, SM, PC, MC position coordinates and RCC recovery amount.

Facility	No.	Coordinate	Amount of recycling(t)	Facility	No.	Coordinate
RCC	1	(12.89,1.28)	808.6	CIC	1	(6.22,0.57)
	2	(7.57,3.94)	411.4		2	(15.87,10.28)
	3	(16.23,12.02)	788.2		3	(8.6,13.7)
	4	(10.66,0.44)	1076.6		4	(3.7,11.94)
	5	(7.01,13.93)	1022		5	(14.1,5.48)
	6	(18.78,10.95)	486.6		6	(2.59,3.93)
	7	(17.52,7.33)	1544.4		7	(8.78,5.03)
	8	(11,8.68)	240.2		8	(5.22,7.2)
	9	(12.45,3.56)	482	MRC	1	(5.16,2.05)
	10	(11.74,6.88)	296.4		2	(8.17,10.82)
	11	(4.15,14.45)	287.2		3	(11.9,1.6)
	12	(6.02,8.2)	229.8	RC	1	(5.24,9.81)
	13	(9.42,7.82)	961		2	(12.06,7.41)
	14	(4.61,3.47)	574		3	(14.22,11.69)
	15	(16.89,7.33)	634.4	SM	1	(4.43,10.73)
	16	(3.9,9.36)	325.2	PC	1	(5.93,13.36)
	17	(4.52,10.19)	522	MC	1	(8.48,10.48)
	18	(3.41,5.93)	1344.8			
	19	(4.55,5.51)	851			
	20	(8.71,14.82)	693			

4.2 Result discussion

Through optimization and calculation, the total profit, total revenue and total cost are 16,377,6215 yuan, 18,4182,517 yuan and 20,406,302.3 yuan respectively. The facility location results and decommissioned battery node traffic distribution corresponding to the case optimal solution are shown in Table 3. The economic distribution of the optimal overall goal and each sub-goal is shown in Table 4.

Table 3. Location of facilities and traffic distribution.

Type of facility	Centers to be opened	Traffic direction of retired battery products
CIC	1,7,8	1-1-1-1
MRC	1,2,3	2-7-3-3
RC	1,2,3	…
		20-7-3-3

Table 4. The distribution of each target amount.

Performance criterion	Value	Performance criterion	Value
RA	13035648(7.08%)	YC	2938320(14.40%)
RB	78078100(42.39%)	PC	2919336.88(14.31%)
RC	82205729.3(44.63%)	TC	4809679.77(23.57%)
RD	10863040(5.90%)	EC	4452779.75(21.82%)
FC	4555049(22.32%)	OC	731136.907(3.58%)

4.3 Sensitivity analysis

(1) Regional recycling volume and market demand impact

Figure 2 show that the increase in regional recycling leads to the increase in the overall regional total profit, and the increase in total cost and total revenue. From the perspective of facilities, with the increase of recycling volume, the number and scale of each facility are expanded, and the utilization rate of each facility is from near saturation at the beginning to insufficient utilization rate after the increase of facilities, which will result in lower profit growth rate. In terms of route selection, with the increase of recovery volume, the principle of proximity of transport routes will be caused by economies of scale. The weight of transport distance under the measurement standard will increase, and the selectivity of transport from CIC to MRC and RC will decrease.

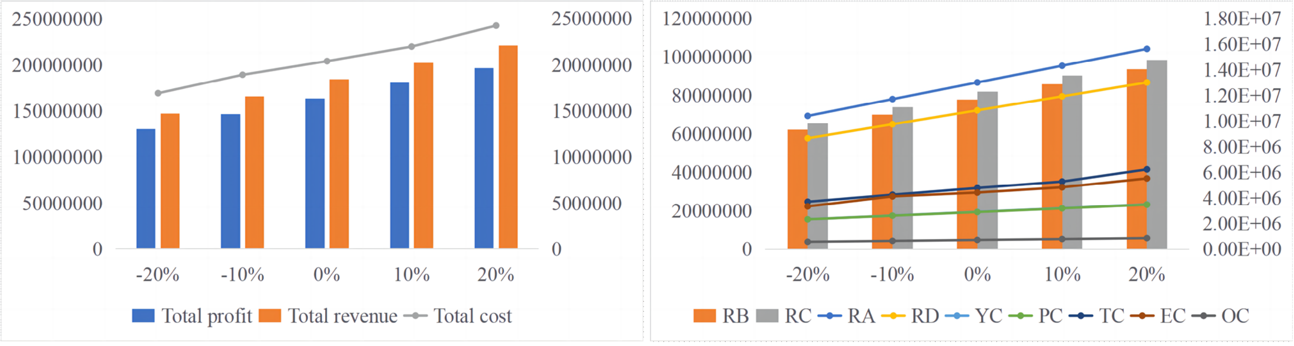

Figure 2. The impact of changes in recycling volume on each index.

Figure 3 shows that with the increase of market demand, total revenue does not change, and total profit shows an increasing trend due to the reduction of total cost. As can be seen from Figure 3, the change of demand has little impact on site selection, mainly on route planning. Therefore, it is also pointed out in Figure 3 that the reduction of total cost comes from the reduction of transportation cost, and at the same time, the change of environmental cost also comes from the optimization of transportation route network. At the same time, Figure 3 also shows that with the increase of market demand, the processing cost fluctuates, but the overall state is increasing. After the demand increases by 10%, the maximum processing limit of the enterprise will make the processing amount stabilize, and the increase amount will surge and then stabilize at a certain range. With the increase in demand, the enterprise will continue to make profits, if it needs to meet the market demand and achieve cost reduction and efficiency, it is necessary to expand the production and operation limits of the enterprise.

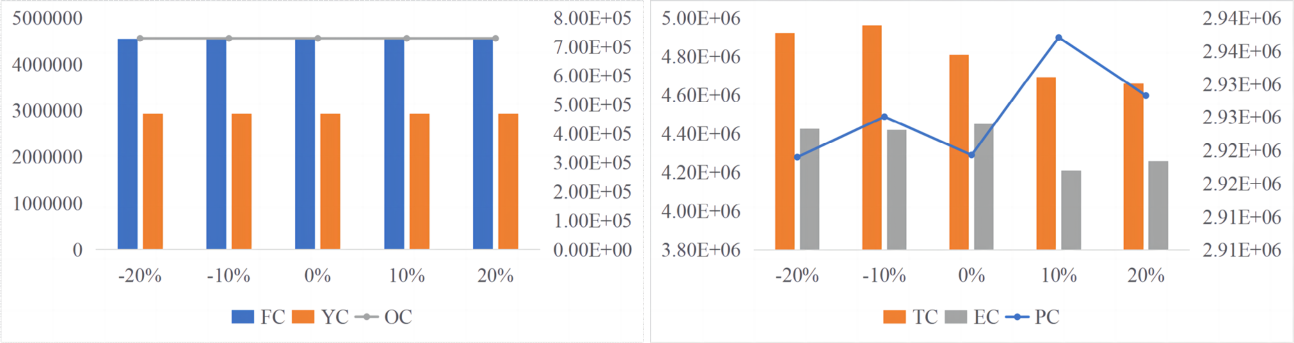

Figure 3. Market demand changes on the impact of indicators.

(2) Quality impact of decommissioned batteries

The development of power battery technology to achieve efficient energy density and safety, bringing higher battery life and safety assurance, so when the battery is retired, the quality level is also iterated. Figure 4 shows that when product quality is improved, the amount of directly recyclable products and remanufactured products increases, and the corresponding revenue growth rate is much higher than the cost growth rate, and the total profit increases. Quality changes have little impact on site selection, but for path planning, with the improvement of product flow quality, recycling channels focus on direct recycling and remanufacturing. Figure 4 shows that when the deterioration rate of market products is too high, its income will be reduced to a certain value, resulting in a bad cycle, that is, the recovery of inferior power batteries, most of which are transported to metal recycling, which will prolong the capital recovery cycle of enterprises. At the same time, enterprises cannot provide economic benefits, consumers will choose to hand over decommissioned batteries to small workshops, etc., and the enterprise recovery link will be more blocked. Government subsidies and metal recycling have not fluctuated, because government subsidies come from the amount of decommissioned battery recycling, and metal recycling accounts for a certain proportion of the overall supply chain. As shown in Figure 4, with the iteration of battery technology, the cost of recycling and transportation decreases, indicating that battery recycling and transportation are more purposeful and the recycling logistics network is more detailed. Corresponding to the increase in processing costs and environmental costs, although decommissioned battery recycling ecology is far less pollution than the dismantling of inefficient materials, but the development of decommissioned battery recycling, it is necessary to pay attention to the green treatment of waste water, waste gas and waste solids generated by enterprise processing.

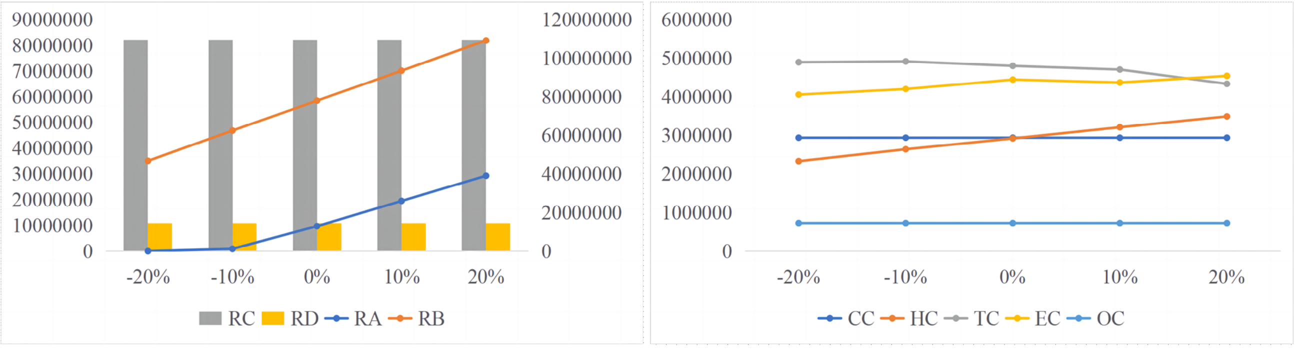

Figure 4. The influence of product quality change on the index.

5. CONCLUSIONS

This paper considers the costs of the 3Rs (recycling, reuse and remanufacturing), policy push, logistics network for power battery recycling, and battery recycling losses in a circular economy. A site-path optimization model of reverse logistics for decommissioned power battery recycling is constructed, which maximizes total profit under revenue (sales revenue of repeatable modules, sales revenue of precious metals, sales revenue of remanufacturing and government subsidies) and cost (construction cost, recovery cost, processing cost, transportation cost, environmental cost and battery capacity loss cost). Combined with the characteristics of power products and the characteristics of battery supply-side and demand-side changes, the influence on reverse logistics network was analyzed. The results show that:

(1) The increase in regional recycling volume increases the total cost, total revenue and total profit, the number and scale of facilities increase but the utilization rate is not saturated, resulting in a decrease in the growth rate of total profit, and the weight of transportation distance greatly increases in route planning.

(2) The increase in market demand brings about the reduction of transportation and environmental costs, which has a great impact on the path selection. The processing cost of battery 3R will stabilize in a certain range after the surge of the maximum processing limit of the enterprise, and the enterprise will continue to make profits, but in order to meet the market demand and achieve cost reduction and efficiency, it is necessary to expand the production and operation limit of the enterprise.

(3) Battery technology change brings revenue far higher than the cost, improves the echelon utilization rate and reduces the enterprise capital recovery cycle, transport on the logistics network is more purposeful, processing costs and environmental costs increase, and we need to pay attention to the green treatment of waste.

In the future, the impact of multi-cycle, technology expansion, inventory and efficiency, and customer satisfaction on the power battery reverse logistics network can be further considered, and more effective algorithm optimization and transportation route constraints can be designed.

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