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Research on Power Battery Closed-loop Supply Chain Recycling Strategy Considering Service Level

Yuxin Zhang [1], Xiaonan Lei [1], Bokai Zheng [1], Dongdong Yan [2]

[1] Chongqing No. 2 Foreign Language School, Chongqing 400000, China

[2] Chongqing University of Posts and Telecommunications, Chongqing 400000, China

Abstract

Against the backdrop of the rapid development of the new energy vehicle industry, the recycling of waste power batteries has gradually become a research hotspot. The service level of recycling enterprises and the energy density of power batteries are key factors influencing the recycling efficiency and overall profit of the closed-loop supply chain. Taking the closed-loop supply chain of power batteries as the research subject, this paper considers the energy density of power batteries and the recycling service level, and constructs three game models of closed-loop supply chains where power battery manufacturers, new energy vehicle enterprises, and third-party recycling enterprises are responsible for recycling, respectively. Through a comparative analysis of the optimal decisions among different models, it is found that improving the recycling service level can significantly enhance the overall recovery rate and the total profit of the supply chain. Among the three modes, the recycling mode led by power battery manufacturers exhibits the greatest advantages in both the recovery rate and the total system profit. This study provides a theoretical basis for the selection of recycling modes and the optimization of service decisions in the closed-loop supply chain of new energy power batteries.

Keywords

Closed-loop Supply Chain; Power Battery; Recycling Service Level; Game Theory; Recycling Mode.

1. Introduction

Guided by the "dual carbon" goals, the development of China's new energy vehicle industry is accelerating. As the core component of new energy vehicles, the demand for power batteries is increasing accordingly, making the proper disposal of large-scale retired power batteries a critical issue that urgently needs to be addressed. Among the factors influencing consumers' active participation in the recycling of end-of-life products, economic and service factors account for a significant proportion [1]. Meanwhile, the adoption of power batteries with high energy density can not only increase the driving range but also gain more policy incentives [2]. Therefore, it is of great significance to study the impact of the recycling service level of recycling enterprises and the energy density of power batteries on decision-making within the closed-loop supply chain. This paper aims to explore the optimal decisions and profit distribution across different recycling channels by constructing power battery closed-loop supply chain models under various dominant modes, thereby identifying the relatively optimal recycling mode.

2. Model Description and Assumptions

2.1. Model Assumptions

To simplify the research process and accurately establish the closed-loop supply chain model, this paper proposes the following assumptions:

(1) It is assumed that the power batteries sold and recycled in this paper are of the same model, and there is no difference between remanufactured power batteries and new ones. To simplify the calculation, the wholesale price of the power battery is regarded as the manufacturing cost of the new energy vehicle.

(2) It is assumed that the consumer demand for new energy vehicles in the market is equivalent to the demand for power batteries. The market demand for new energy vehicles is a linear decreasing function of the retail price of new energy vehicles and an increasing function of the battery energy density: $D=\alpha-\beta p+\delta h$, where $\alpha-\beta p>0$.

(3) In order to improve the comprehensive utilization rate of resources, the recycled waste power batteries in this paper are first subjected to echelon utilization, followed by dismantling, raw material extraction, and recycling. Considering the technical level and actual conditions, this paper only applies waste power batteries to energy storage systems. According to previous research [3], it is assumed that each unit of remaining capacity L of the waste power battery is positively correlated with the net profit obtained by the energy storage system during its operating life, with a profit coefficient of λ. Therefore, the total revenue Δ obtained by the power battery manufacturer through recycling power batteries consists of two parts: the revenue from recycling and reuse, and the revenue from echelon utilization after recycling, summarized as: $\Delta=c_n-c_r+\lambda L$.

(4) According to the survey results of existing studies [4], the most important factor affecting consumers' return of waste power batteries is the recycling price. In this paper, it is assumed that the recycling quantity of waste batteries is also closely related to the recycling service level of the recycling enterprise. Referring to the study by Wu et al. [5], the recycling quantity of power batteries in the model of this paper is $Q=A+kp_i+\gamma s_i$, where A represents the quantity of waste batteries returned voluntarily by consumers. To simplify the calculation, it is assumed that A is 0, then $Q=kp_i+\gamma s_i$, and the recycling rate τ is expressed as $\frac{Q}{D}$.

(5) Referring to the cost assumption in related literature [6], an increasing convex function is used to represent the R&D investment cost of battery energy density. That is, the R&D cost that the power battery manufacturer needs to pay for the R&D of battery energy density is $\frac{1}{2}\mu h^2$, where μ represents the R&D cost coefficient of power battery energy density.

(6) During the recycling process, the enterprise responsible for recycling will provide consumers with recycling services for their waste batteries, such as free door-to-door testing, evaluation and quotation, and discounts for trading in old for new. Therefore, referring to the study by Sarkar and Pal [7], $C(s)=\frac{1}{2}\varphi s^2$ is used to represent the cost function of recycling services, where φ is the cost coefficient of the recycling service level.

(7) To recycle a unit of waste power battery, the enterprise responsible for recycling should invest an average recycling cost of I per battery, which mainly includes the cost of building a recycling network, advertising expenses, temporary storage fees, handling fees, and transportation costs.

The specific parameters designed in this paper are as follows:

w: Wholesale price of the power battery;

h: Energy density of the power battery;

t:Recycling transfer price paid by the power battery manufacturer to the recycling enterprise for waste power batteries;

p: Retail price of the new energy vehicle;

p_i: Recycling price when the recycling entity i recycles waste power batteries;

s_i:Recycling service level of the recycling enterprise i;

D:Consumer demand for new energy vehicles;

Q:Quantity of recycled waste power batteries;

$\mathrm{c_n}$:Cost for the power battery manufacturer to produce power batteries using new raw materials;

$\mathrm{c_r}$:Cost to produce power batteries using recycled materials;

β:Consumers' sensitivity coefficient to the retail price of new energy vehicles;

δ:Consumers' sensitivity coefficient to the energy density of power batteries;

Δ: Total revenue obtained by the power battery manufacturer through recycling power batteries;

γ:Consumers' sensitivity to the recycling service level;

k:Consumers' sensitivity to the recycling price;

μ: R&D cost coefficient for power battery energy density;

φ: Cost coefficient for the recycling service level;

I: Cost of recycling a unit of waste power battery;

τ^j: Recycling rate of waste power batteries under model j;

π_i^j: Profit of supply chain member i under model j;

Where the right subscripts $i = m, r, t, c$ represent the power battery manufacturer, the new energy vehicle enterprise, the third-party recycling enterprise, and the entire supply chain, respectively; the right superscripts $j = M, R, T$ represent the recycling mode of the power battery manufacturer, the recycling mode of the new energy vehicle enterprise, and the recycling mode of the third-party enterprise, respectively.

2.2. Model Construction and Solution of Different Recycling Strategies

2.2.1. Recycling Mode of Power Battery Manufacturers(M)

In this model, the power battery manufacturer recycles waste power batteries from consumers, and then carries out echelon utilization and remanufacturing. This forms a Stackelberg game relationship with the power battery manufacturer as the leader and the new energy vehicle enterprise as the follower, both of which make decisions aimed at maximizing their own profits. Therefore, in the decision-making process, the power battery manufacturer first determines the wholesale price of the power battery w^M,Energy density of the power battery h^M,the recycling price p_m,and the recycling service level s_m; then, the new energy vehicle enterprise determines the retail price of the new energy vehicle p^M.

At this point, the profit functions of the power battery manufacturer and the new energy vehicle enterprise are respectively as follows:

$$\pi_m^M=(w^M-c_n)\left(\alpha-\beta p^M+\delta h^M\right)-\frac{1}{2}\mu {h^M}^2+\left(\Delta-p_m-I\right)\left(kp_m+\gamma s_m\right)-\frac{1}{2}\varphi {s_m}^2 \tag{1}$$

$$\pi_r^M=(p^M-w^M)(\alpha-\beta p^M+\delta h^M) \tag{2}$$

Proposition 1: Under the model where the power battery manufacturer is responsible for recycling, the optimal decisions of each entity are as follows:

$$w^{M*}=\frac{2\alpha\mu+c_n(-\delta^2+2\beta\mu)}{-\delta^2+4\beta\mu}$$

$$h^{M*}=\frac{\delta(\alpha\text{-}\beta c_n)}{\text{-}\delta^2+4\beta\mu}$$

$$p_m^*=\frac{(\Delta\text{-}I)(\text{-}\gamma^2+k\varphi)}{\text{-}\gamma^2+2k\varphi}$$

$$s_m^*=\frac{k\gamma(\Delta\text{-}I)}{\text{-}\gamma^2+2k\varphi}$$

$$p^{M*}=\frac{3\alpha\mu+\beta c_n\mu\text{-}\delta^2c_n}{\text{-}\delta^2+4\beta\mu}$$

Therefore, the optimal profits of the power battery manufacturer and the new energy vehicle enterprise, as well as the optimal recycling rate, are as follows:

$$\pi_m^{M*}=\frac{k^2\varphi(\Delta\text{-}I)^2}{\text{-}2(\gamma^2+2k\varphi)}+\frac{\mu(\alpha\text{-}\beta c_n)^2}{\text{-}2(\delta^2+4\beta\mu)}$$

$$\pi_r^{M*}=\frac{\beta\mu^2(\alpha\text{-}\beta c_n)^2}{(\text{-}\delta^2+4\beta\mu)^2}$$

$$\tau^{M*}=\frac{k^2\varphi(\Delta\text{-}I)(\text{-}\delta^2+4\beta\mu)}{\beta\mu(\alpha\text{-}\beta c_n)(\text{-}\gamma^2+2k\varphi)}$$

Proof: Using backward induction, we first calculate the second-order derivative of the new energy vehicle enterprise's profit π_r^M with respect to p^M from Equation (2). It is easy to see that $\frac{\partial^2\pi_r^M}{\partial^2 p^M}=-2\beta<0$, which indicates that π_r^M is a strictly concave function with respect to p^M, and a unique optimal solution exists. Therefore, by setting $\frac{\partial\pi_r^M}{\partial p^M}=0$, the reaction function for the retail price can be obtained as $p^M=\frac{\alpha+\beta w^M+\delta h^M}{2\beta}$. Substituting this reaction function into Equation (3-1), the Hessian matrix of π_m^M with respect to w^M, h^M, p_m, and s_m can then be obtained as: $\begin{bmatrix}\text{-}\beta & \frac{\delta}{2} & 0 & 0\\ \frac{\delta}{2} & \text{-}\mu & 0 & 0\\ 0 & 0 & \text{-}2k & \text{-}\gamma\\ 0 & 0 & \text{-}\gamma & \text{-}\varphi\end{bmatrix}$,,When the third-order leading principal minor is $\frac{k}{2}(\delta^2-4\beta\mu)<0$ and the fourth-order leading principal minor is $\frac{1}{4}(\gamma^2-2k\varphi)(\delta^2-4\beta\mu)>0$, the Hessian matrix of π_m^M with respect to w^M, h^M, p_m, and s_m is negative definite. Thus, π_m^M is a jointly concave function of (w^M,h^M,p_m,s_m), and an optimal solution exists. Therefore, by solving the system of first-order conditions: $\frac{\partial\pi_m^M}{\partial w^M}=0,\frac{\partial\pi_m^M}{\partial h^M}=0,\frac{\partial\pi_m^M}{\partial p_m}=0,\frac{\partial\pi_m^M}{\partial s_m}=0$, the optimal decisions of the power battery manufacturer $w^{M*}, h^{M*}, p_m^*, s_m^*$ are obtained. By substituting these optimal decisions back into the reaction function, the optimal retail price p^{M*} is derived. Subsequently, substituting these values back into Equations (1) and (2) yields the optimal profits of the power battery manufacturer and the new energy vehicle enterprise, π_m^{M*} and π_r^{M*}, as well as the optimal recycling rate of the power battery closed-loop supply chain, τ^{M*}.

2.2.2. Recycling Mode of New Energy Vehicle Enterprises(R)

In this model, the power battery manufacturer entrusts the new energy vehicle enterprise to recycle waste power batteries from consumers, and then carries out echelon utilization and remanufacturing. This forms a Stackelberg game relationship with the power battery manufacturer as the leader and the new energy vehicle enterprise as the follower, both of which make decisions aimed at maximizing their own profits. Therefore, in the decision-making process, the power battery manufacturer first determines the wholesale price of the power battery w^R, the energy density h^R, and the recycling transfer price t^R; then, the new energy vehicle enterprise determines the retail price of the new energy p^R vehicle, the recycling price p_r, and the recycling service level s_r.

In this case, the profit functions of the power battery manufacturer and the new energy vehicle enterprise are respectively as follows:

$$\pi_m^R=(w^R-c_n)\left(\alpha-\beta p^R+\delta h^R\right)+(\Delta-t^R)(kp_r+\gamma s_r)-\frac{1}{2}\mu h^{R^2} \tag{3}$$

$$\pi_r^R=(p^R-w^R)\left(\alpha-\beta p^R+\delta h^R\right)+(t^R-p_r-I)(kp_r+\gamma s_r)-\frac{1}{2}\varphi s_r^{\,2} \tag{4}$$

Proposition 2: Under the model where the new energy vehicle enterprise is responsible for recycling, the optimal decisions of each entity are as follows:

$$w^{R*}=\frac{2\alpha\mu+c_n(-\delta^2+2\beta\mu)}{-\delta^2+4\beta\mu}$$

$$h^{R*}=\frac{\delta(\alpha-\beta c_n)}{-\delta^2+4\beta\mu}$$

$$t^{R*}=\frac{\Delta+I}{2}$$

$$p_r^*=\frac{(\Delta-I)(-\gamma^2+k\varphi)}{2(-\gamma^2+2k\varphi)}$$

$$s_r^*=\frac{k\gamma(\Delta-I)}{2(-\gamma^2+2k\varphi)}$$

$$p^{R*}=\frac{3\alpha\mu+\beta c_n\mu-\delta^2 c_n}{-\delta^2+4\beta\mu}$$

Therefore, the optimal profits of the power battery manufacturer and the new energy vehicle enterprise, as well as the optimal recycling rate, are as follows:

$$\pi_m^{R*}=\frac{k^2\varphi(\Delta-I)^2}{4(-\gamma^2+2k\varphi)}+\frac{\mu(\alpha-\beta c_n)^2}{2(-\delta^2+4\beta\mu)}$$

$$\pi_r^{R*}=\frac{k^2\varphi(\Delta-I)^2}{8(-\gamma^2+2k\varphi)}+\frac{\beta\mu^2(\alpha-\beta c_n)^2}{(-\delta^2+4\beta\mu)^2}$$

$$\tau^{R*}=\frac{k^2\varphi(\Delta-I)(-\delta^2+4\beta\mu)}{2\beta\mu(\alpha-\beta c_n)(-\gamma^2+2k\varphi)}$$

Proof: The proof is similar to the above.

2.2.3. Recycling Mode of Third-party Enterprises(T)

In this model, the power battery manufacturer entrusts a third-party recycling enterprise to recycle waste power batteries from consumers, and then carries out echelon utilization and remanufacturing. This forms a Stackelberg game relationship with the power battery manufacturer as the leader, while the new energy vehicle enterprise and the third-party recycling enterprise act as the followers, all of which make decisions aimed at maximizing their own profits. Therefore, in the decision-making process, the power battery manufacturer first determines the wholesale price w^T, energy density h^T, and recycling transfer price of the power battery t^T; subsequently, the new energy vehicle enterprise determines the retail price of the new energy vehicle p^T, while the third-party recycling enterprise simultaneously determines the recycling price p_t and the recycling service level s_t.

In this case, the profit functions of the power battery manufacturer, the new energy vehicle enterprise, and the third-party recycling enterprise are respectively as follows:

$$\pi_m^T=(w^T-c_n)(\alpha-\beta p^T+\delta h^T)+(\Delta-t^T)(kp_t+\gamma s_t)-\frac{1}{2}\mu h^{T^2} \tag{5}$$

$$\pi_r^T=(p^T-w^T)(\alpha-\beta p^T+\delta h^T) \tag{6}$$

$$\pi_t^T=(t^T-p_t-I)(kp_t+\gamma s_t)-\frac{1}{2}\varphi s_t^2 \tag{7}$$

Proposition 3: Under the model where the third-party enterprise is responsible for recycling, the optimal decisions of each entity are as follows:

$$w^{T*}=\frac{2\alpha\mu+c_n(-\delta^2+2\beta\mu)}{-\delta^2+4\beta\mu}$$

$$h^{T*}=\frac{\delta(\alpha-\beta c_n)}{-\delta^2+4\beta\mu}$$

$$t^{T*}=\frac{\Delta+I}{2}$$

$$p_t^*=\frac{(\Delta-I)(-\gamma^2+k\varphi)}{2(-\gamma^2+2k\varphi)}$$

$$s_t^*=\frac{k\gamma(\Delta-I)}{2(-\gamma^2+2k\varphi)}$$

$$p^{T*}=\frac{3\alpha\mu+\beta c_n\mu-\delta^2c_n}{-\delta^2+4\beta\mu}$$

Therefore, the optimal profits of the power battery manufacturer, the new energy vehicle enterprise, and the third-party recycling enterprise, as well as the optimal recycling rate, are as follows:

$$\pi_m^{T*}=\frac{k^2\varphi(\Delta-I)^2}{4(-\gamma^2+2k\varphi)}+\frac{\mu(\alpha-\beta c_n)^2}{2(-\delta^2+4\beta\mu)}$$

$$\pi_r^{T*}=\frac{\beta\mu^2(\alpha-\beta c_n)^2}{(-\delta^2+4\beta\mu)^2}$$

$$\pi_t^{T*}=\frac{k^2\varphi(\Delta-I)^2}{8(-\gamma^2+2k\varphi)}$$

$$\tau^{T*}=\frac{k^2\varphi(\Delta-I)(-\delta^2+4\beta\mu)}{2\beta\mu(\alpha-\beta c_n)(-\gamma^2+2k\varphi)}$$

Proof: The proof is similar to the above.

3. Equilibrium Result Analysis

Theorem 3.1 $w^{M*}=w^{R*}=w^{T*}$, $h^{M*}=h^{R*}=h^{T*}$, $p^{M*}=p^{R*}=p^{T*}$

According to Theorem 3.1, under the three different recycling modes, the optimal wholesale price of the power battery manufacturer, the optimal energy density of the power battery, and the optimal retail price of the new energy vehicle enterprise remain identical.

Theorem 3.2 1)$p_m^* > p_r^* = p_t^*$, $\tau^{M*} > \tau^{R*} = \tau^{T*}$, $s_m^* > s_r^* = s_t^*$. 2)$t^{R*} = t^{T*}$

According to Theorem 3.2: Among the three recycling modes, the recycling price, recycling service level, and recycling rate are maximized when the power battery manufacturer is responsible for recycling waste power batteries, whereas these values are equal in the other two modes. Meanwhile, under the other two recycling modes, the recycling transfer prices offered by the power battery manufacturer to the new energy vehicle enterprise and the third-party recycling enterprise are identical.

Theorem 3.3$\pi_m^{M*} > \pi_m^{R*} = \pi_m^{T*}$, $\pi_r^{R*} > \pi_r^{M*} = \pi_r^{T*}$, $\pi_c^{M*} > \pi_c^{R*} = \pi_c^{T*}$

According to Theorem 3.3: The profits of the power battery manufacturer and the new energy vehicle enterprise are both maximized when they are respectively responsible for the recycling process, while their profits remain identical under the other two recycling modes. Furthermore, the total profit of the power battery closed-loop supply chain is maximized when the power battery manufacturer is responsible for recycling.

Theorem 3.4 s_m^*, s_r^*, s_t^* all decrease as the recycling service cost coefficient increases, whereas p_m^*, p_r^*, p_t^* all increase as the recycling service cost coefficient increases.

According to Theorem 3.4, the recycling service level of the recycling enterprise is inversely proportional to the recycling service cost coefficient, whereas the recycling price is directly proportional to it. This is because when the cost of providing the recycling service level increases, recycling enterprises, in order to control costs and ensure profitability, tend to reduce the service level. This directly affects customer groups with higher demands for recycling service quality and experience. These customers may focus more on convenience, transparency, and service quality during the recycling process, prioritizing value-added services such as door-to-door collection, prompt processing, and information feedback. Therefore, recycling enterprises need to strike a balance between price and service; once the service level declines, consumers who originally relied on a high-quality recycling experience may turn to other competitors, thereby adversely affecting the enterprise's market share and customer loyalty. Furthermore, the waste power battery recycling market is not solely driven by the recycling price but is jointly influenced by the recycling service level. To improve recycling performance, recycling enterprises are forced to raise the recycling price to attract customers. However, such a situation is detrimental to their own profit margins and is fundamentally unsustainable in the long run.

Therefore, while ensuring that the recycling price remains competitive, recycling enterprises must explore innovative service approaches and balance the relationship between price and service level. This will better satisfy market demand, enhance recycling benefits, and ultimately achieve highly efficient resource recycling and utilization. Alternatively, interventions through external factors, such as government subsidies, can be implemented. Reasonable government intervention can promote the healthy development of the power battery closed-loop supply chain, generating greater resource benefits while protecting the environment.

Theorem 3.5 $\pi_m^{M*}, \pi_m^{R*}, \pi_m^{T*}, \pi_r^{R*}, \pi_t^{T*}$ and the recycling rates $\tau^{M*}, \tau^{R*}, \tau^{T*}$ all decrease as the recycling service cost coefficient increases.

According to Theorem 3.5, the profits of the power battery manufacturer, the profits of the recycling enterprise, and the recycling rate are all inversely proportional to the recycling service cost coefficient. This is because when the recycling service cost coefficient increases, the challenges faced by recycling enterprises are not merely related to the direct increase in costs. The improvement of the recycling service level is often accompanied by more resource investments, including manpower, equipment, transportation, and service guarantees. As these costs continue to rise, recycling enterprises, under the premise of ensuring profits, often choose to lower their service levels to reduce expenditures. Although this practice can reduce operational costs in the short term, in the long run, it may trigger a series of adverse consequences, especially concerning the recycling rate and profits. The decline in the collection volume will directly lead to a decrease in the overall recycling rate. This not only diminishes the profitability of recycling enterprises but may also exert a negative impact on the recycling efficiency of the entire industry, subsequently affecting the reuse rate of waste materials and resource recycling, which is detrimental to the development of the power battery closed-loop supply chain.

When facing cost pressures, rather than simply lowering service levels, recycling enterprises need to find more sustainable solutions by improving operational efficiency, innovating service models, and strengthening communication with customers. In this way, they can ensure recycling benefits without sacrificing the collection volume and service quality.

4. Numerical Simulation

To more intuitively illustrate the validity of the aforementioned conclusions, this section conducts numerical simulations using MATLAB software to compare the impacts of key parameters on the recycling rate, the profits of individual supply chain members, and the total supply chain profit under the three recycling modes. Drawing on existing research findings, the values of the relevant parameters are summarized below, as detailed in Table 1.

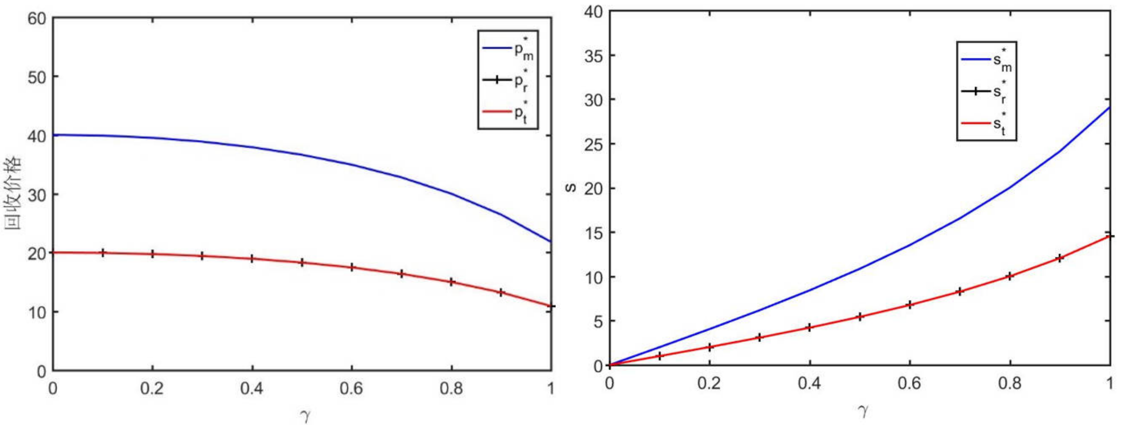
Table 1. Summary of parameter values

Symbol	Value	Symbol	Value
Δ	100	β	1
k	0.8	δ	0.8
I	20	μ	3
α	2000	c_n	25

(1) Comparison of optimal decisions under different recycling modes

This subsection compares the optimal decision variables under each recycling mode, setting the relevant parameters and $\varphi = 2$. Figure 1 illustrates the comparison of the recycling prices and recycling service levels of different recycling entities concerning the variation in the consumer sensitivity coefficient to the recycling service level under different recycling modes. As can be seen from the figure, when consumers' sensitivity to recycling services increases, the recycling price offered by the recycling enterprise decreases accordingly. Conversely, the recycling service level of the recycling enterprise increases. This is because when consumers pay more attention to the recycling service level, recycling enterprises are motivated to improve their service quality to attract consumers to participate in the recycling of waste batteries. Meanwhile, recycling enterprises also bear higher costs for these improved service levels; in the pursuit of reducing costs and maximizing profits, they tend to suppress the recycling price. Currently, consumers are increasingly valuing the services provided by businesses. If recycling enterprises can enhance their service attitude and service quality during the recycling process, it will not only help improve their market competitiveness but also promote the healthy development of the market economy, while exerting a positive impact on environmental protection and resource reuse.

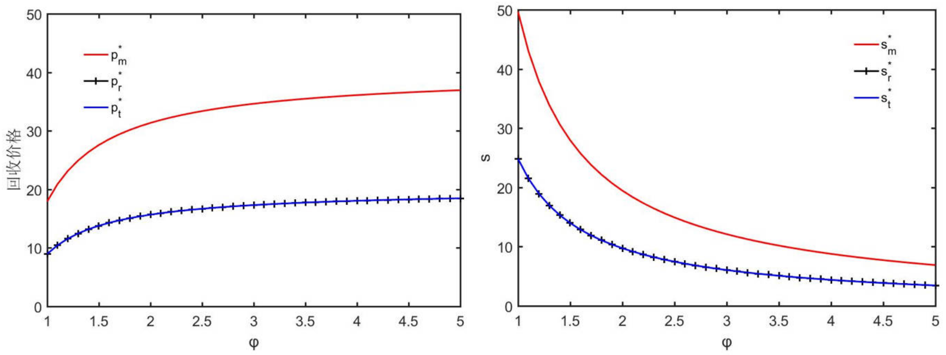
Furthermore, among the different recycling modes, it can be seen that when the power battery manufacturer is responsible for recycling, both the recycling price and the recycling service level are superior to those in the other two recycling modes, which is consistent with the conclusion of Theorem 3.2. For current power battery manufacturers, proactively establishing a recycling chain for waste power batteries and responding swiftly to the waste battery recycling market is highly beneficial to their own development.



(a) (b)

Fig 1. Comparison chart of the impact of γ on the optimal decision. (a) Impact of γ on recycling price;(b) Impact of γ on recycling service level

(2) Impact of the recycling service level cost coefficient on relevant decisions

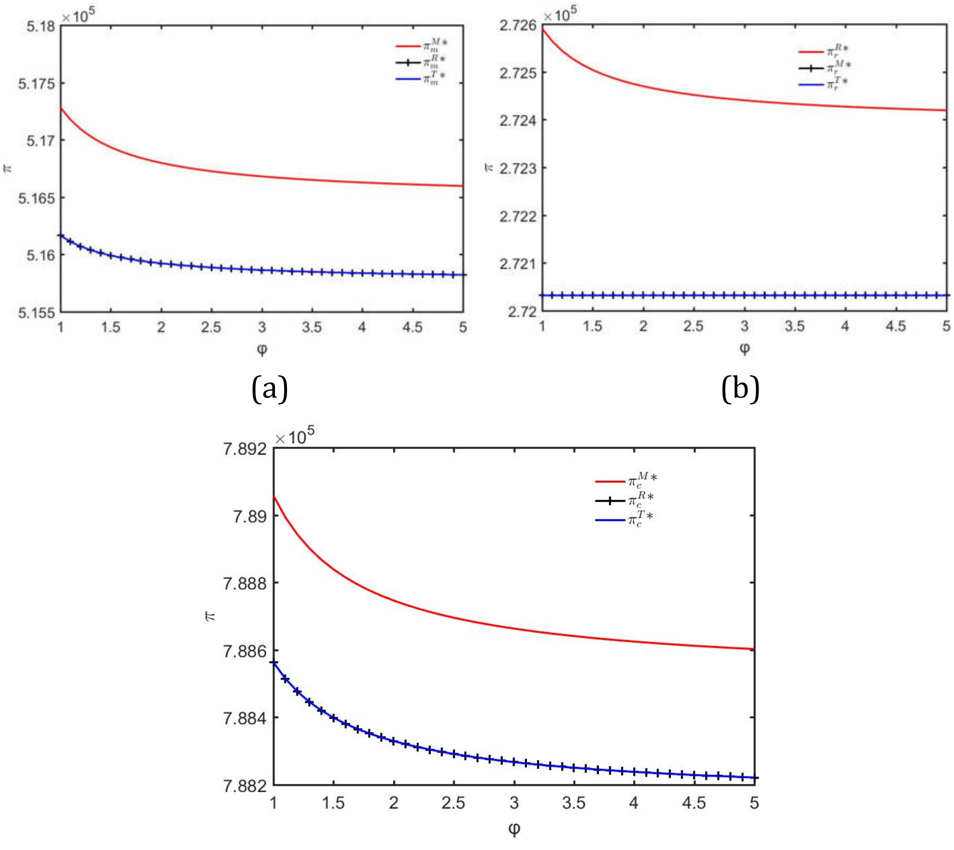


(a) (b)

Fig 2. Comparison chart of the impact of φ on the optimal decision.(a) Impact of φ on recycling price;(b) Impact of φ on recycling service level

This subsection explores and compares the impact of the recycling service level cost coefficient on the relevant optimal decisions, setting the relevant parameters and $\gamma = 0.7$. Figure 2 illustrates a comparative analysis of how the recycling prices and recycling service levels of different recycling entities vary with the recycling service cost coefficient under different recycling modes. As can be observed from the figure, the recycling service level cost coefficient is positively correlated with the recycling price offered by the recycling enterprise, and negatively correlated with the recycling service level. This indicates that a larger cost coefficient implies a higher cost for providing a specific level of recycling service. Consequently, the recycling enterprise will reduce its investment in the recycling service level. However, reluctant to forgo the profits from the recycling process, the enterprise increases the recycling price to attract consumers. This results in a trade-off relationship between the recycling service level and the recycling price of the recycling enterprise. Furthermore, the figure demonstrates that both the recycling price and the recycling service level reach their highest values under the power battery manufacturer recycling mode, while they are lower and equal in the other two modes. This is consistent with the conclusion of Theorem 3.4.

Figure 3 illustrates how the profits of the power battery manufacturer, the new energy vehicle enterprise, and the overall supply chain vary with the recycling service level cost coefficient under different recycling modes. As can be observed from the figure, the recycling service cost coefficient has a negative impact on the profits of both the enterprise responsible for recycling waste power batteries and the overall supply chain, and its impact on the profit of the power battery manufacturer is consistently negative. This is primarily because an increase in the recycling service cost imposes greater cost pressure on the recycling enterprise when providing high-level recycling services, thereby making it reluctant to proactively improve the service level. This behavior leads to a decline in the overall recycling volume of waste power batteries, which in turn reduces the revenue enterprises obtain from the reverse supply chain. Ultimately, this chain reaction results in a subsequent decline in the overall profit level of the supply chain, forming a systemic negative effect. For the power battery manufacturer, acting as the source of the recycling end, the recycling benefits continuously affect its profit. In contrast, for enterprises not responsible for recycling, they do not need to consider the impact of the recycling process on themselves; therefore, their profits are independent of the recycling service level cost coefficient.



(a) (b)

(c)

Fig 3. Comparison chart of the impact of φ on profits. (a)Impact of φ on the profits of power battery manufacturers; (b)Impact of φ on the profits of new energy vehicle enterprises;(c) Impact of φ on the total profit of supply chain

Meanwhile, the figure also shows that the power battery manufacturer and the automaker each achieve their maximum profit when they are respectively responsible for the recycling process. Among the three recycling modes, the overall supply chain profit is maximized when the power battery manufacturer is responsible for recycling. This is because the enterprise responsible for recycling can obtain more revenue from the reverse supply chain, which also verifies the conclusion of Theorem 3.5. Therefore, for the power battery manufacturer, recycling waste power batteries on its own yields the highest profit, allowing it to fully leverage the advantages of being the source of power battery production and to achieve greater synergy between production and recycling. If the recycling process is entrusted to the automaker or a third-party recycling enterprise, sufficient incentives must be provided to compel them to exert enough effort to increase the recycling volume.

As for automakers and third-party recycling enterprises, they can only obtain more profits by directly participating in the recycling process themselves. Compared with manufacturers, automakers and third-party recycling enterprises possess unique information advantages. Automakers, in particular, due to their direct connection with consumers, can more accurately grasp dynamic information regarding battery usage status and replacement needs. This characteristic of being close to end consumers makes their operations in the recycling process more convenient and simultaneously reduces costs in certain recycling stages. Third-party recycling enterprises, on the other hand, can secure a place in the market by leveraging their professional capabilities in logistics, recycling channel construction, and service network coverage. By integrating resources and maintaining close contact with consumers, these enterprises can rapidly establish themselves in the recycling market, seize waste power battery resources, achieve scale effects, and further enhance recycling efficiency and profits. Therefore, automakers and third-party recycling enterprises can fully utilize their advantages in information acquisition and market proximity to actively improve recycling networks and service models, optimize recycling efficiency through technological means, and enhance their control over waste power battery resources. Through this strategy, they can not only effectively compete for market share but also play a significant role in the transition to a green economy, creating more economic and social value for the enterprises.

(3) Impact of relevant coefficients on the recycling rate of waste batteries

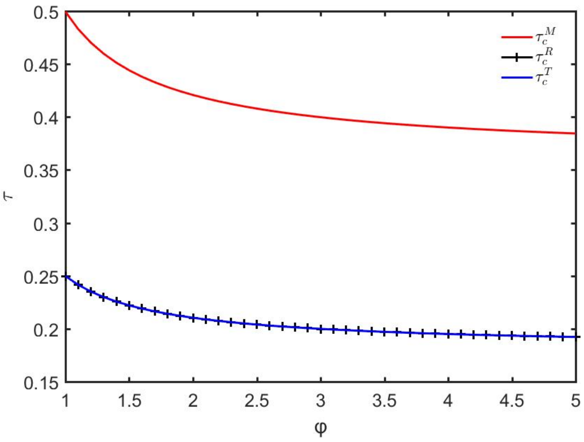


Fig 4. Comparison chart of φ effect on recovery rate

This subsection explores the impact of relevant coefficients on the recycling rate of waste power batteries. As can be seen from Figure 4, there is a clear negative correlation between the recycling rate and the recycling service level cost coefficient. This phenomenon occurs primarily because the increase in the cost of the recycling service level directly dampens the enthusiasm of recycling enterprises to provide high-quality recycling services. The decline in the recycling service level further affects the collection volume of waste power batteries, subsequently leading to a decrease in the overall recycling rate. This reduction in the recycling rate not only poses a challenge to the operational efficiency of recycling enterprises but also exerts an adverse effect on the sustainable development of the entire power battery closed-loop supply chain, highlighting the importance of cost control and recycling service optimization. Meanwhile, the recycling rate is maximized under the power battery manufacturer recycling mode, which is consistent with the conclusion in Theorem 3.2.

As shown in Figure 5, the recycling rate of waste power batteries increases as the revenue obtained from recycling increases. This indicates that when the economic benefits of recycling waste power batteries increase, the power battery manufacturer, acting as the source of waste power battery recycling and utilization, will correspondingly enhance its willingness to recycle. Whether it chooses to undertake the recycling task independently or entrusts it to automakers or third-party enterprises, it will inevitably intensify its recycling efforts and resource investments to improve the recycling efficiency of waste power batteries, thereby obtaining higher profits. The recycling profit is composed of echelon utilization revenue and remanufacturing revenue; therefore, the power battery manufacturer can approach from these two directions to optimize technical paths and recycling modes to maximize recycling benefits. This not only helps to enhance the economic benefits and social responsibility of the enterprise but also promotes the sustainable development of the industry, driving the formation of a virtuous ecosystem for resource recycling. Furthermore, as can be seen from the figure, the recycling rate is maximized when the power battery manufacturer is responsible for recycling.

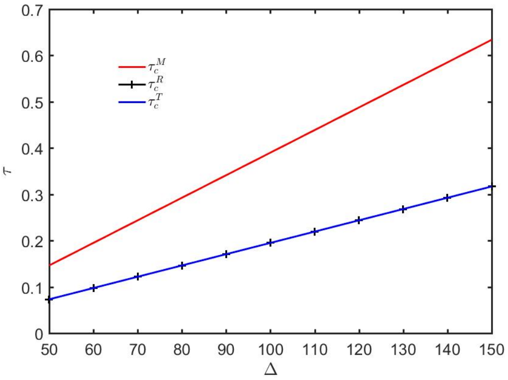


Fig 5. Comparison chart of effect of Δ on recovery rate

In summary, whether in terms of the overall profit or the overall recycling efficiency of the closed-loop supply chain, the model where the power battery manufacturer is responsible for recycling yields the highest outcomes. This conclusion indicates that, as the leading enterprise in the power battery closed-loop supply chain, it is essential for the manufacturer to fully leverage its core position and resource integration capabilities, proactively strategize, and deeply engage in the recycling process of waste power batteries. By improving the recycling mechanism and optimizing resource allocation, the enterprise can not only enhance the economic benefits and efficiency of the recycling process but also drive the power battery closed-loop supply chain toward green and sustainable development, providing robust support for the long-term healthy growth of the industry.

5. Summary

The research in this paper demonstrates that improving the recycling service level can significantly enhance the overall recovery rate and system profit of the power battery closed-loop supply chain. When faced with high service costs, the service provision capacity of enterprises is constrained, resulting in a subsequent decline in total profit and the recovery rate. Among the three different recycling modes, the mode led by the power battery manufacturer shows a significant advantage in both profit generation and recovery rate improvement. Therefore, manufacturers should proactively establish and lead the recycling chain for waste batteries, while focusing on balancing the optimization of recycling service quality and costs to facilitate the sustainable development of the industry.

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