Decision Analysis of Spent Power Battery Recovery Mode under Hybrid Dual-Channel Collection

Xuedong Liang¹, Bangyi Yao¹, Meng Ye¹, Yaqi Wang¹, Ziyang Li∗

¹ Business School, Sichuan University, Chengdu, Sichuan, 610065, China
∗Corresponding author’s e-mail: lzy_feng@scu.edu.cn

Abstract. Recycling spent power battery is an important measure to alleviate energy shortage and environmental pollution. However, at present, there is no uniform standard for the recycling channels of spent power battery, and the construction of recycling channels of various recycling subjects is chaotic, and the mode with the highest efficiency is still inconclusive. Therefore, based on the current situation of spent power battery recycling, combined with the closed-loop supply chain channel decision-making theory, this paper studies three hybrid dual-channel recycling modes, compares and analyses the recycling rate and profit under different modes, and finally discusses the influence of different factors and recycling modes through numerical analysis. The results show that: (1) The hybrid dual-channel recycling mode of automobile alliance and third-party recycler can bring the maximum recovery rate and profit. (2) The competition between different recycling channels can not only improve the recovery rate, but will lead to the decline of the recovery rate and profit, resulting in a double loss situation. (3) Centralized decision-making brought about by cooperation can improve the total recovery rate and the total channel profit.

1. Introduction

In recent years, the recycling of spent power battery has become the focus of social attention. On the one hand, toxic electrolytes and organic chemicals in spent power batteries will pose a great threat to environment [1, 2], and recycling can reduce environmental pollution. On the other hand, spent power battery can be used for energy storage devices or extracting precious metals, etc. Reuse can save a lot of resources [3]. However, there are different choices for recycling subject to establish recycling channels. Due to the small scale, uniform standards, and difficulty in distribution of responsibilities and benefits, each subject has not yet formed an industry-wide joint recycling alliance, which makes the problem of repeated construction of recycling channels serious, resulting in high cost, low recovery rate and low profit, which is not conducive to the good development of spent power battery recycling.

At present, the related research can be divided into spent power battery recycling mode selection and closed-loop supply chain channel decision. Zhu et al. used fuzzy comprehensive evaluation method to draw the conclusion that SAIC should establish a reverse logistics recycling network of composite spent power battery based on self-operated mode [4]. Gao et al. suggested establishing producer recycling system and lease recycling system [5]. Li et al. studied the upstream and downstream joint recovery and coordination of the three-level closed-loop supply chain of power battery, and thought that centralized decision-making was more favourable [6]. In the study of closed-loop supply chain recycling channel decision-making, Savaskan et al. first proposed and compared three single-channel recycling modes, which are manufacturer, retailer and third party, and found that retailer has the highest recycling efficiency [7]. Hong et al. studied the decision-making model of remanufacturing closed-loop supply...
chain with hybrid collection [8], and extended the one-way channel studied by Savaskan et al. [7] to the hybrid channel. Liu et al. further analysed the competition among channels on the basis of Hong [9], and compared it with the conclusions of Savaskan [7] and Hong [8]. The results show that the competition among channels does not affect the channel selection [9]. Atasu’s research on Savaskan [8] has been further expanded, and the influence of economies of scale on manufacturers’ reverse channel decision-making has been studied [10]. Huang et al. studied the channel decision-making problem under the background of construction machinery [11]. Chuang et al. focused on the reverse channel selection of a high-tech product manufacturer with short life cycle and unstable demand [12], and expanded the channel decision research to more specific fields.

To sum up, related research focuses on closed-loop supply chain channel decision-making and spent power battery recycling mode. However, spent power battery has the characteristics of large unit value and complex recycling. If the variables such as wholesale price and retail price in the forward supply chain and recycling in the reverse process are considered at the same time, it is difficult to accurately describe the current situation, and it is impossible to focus on channel selection. This is something that has not been considered in related studies. Therefore, this paper focuses on the reverse process of spent power battery recycling, studies three hybrid dual-channel recycling modes based on the existing closed-loop supply chain channel decision-making theory, and establishes models to compare and analyse the recovery rate and profit of different recycling modes, provide suggestions for related recycling subjects, and promote the good development of this industry.

2. Model description

In the process of recycling spent power battery, the main participants are battery manufacturer, automobile manufacturer and automobile dealer, third-party recycler and consumer. Suppose that in the process of battery recycling, driven by the responsibility system and interests of the recycling subjects, automobile manufacturers will form alliances with automobile distribution networks to recycle power battery, which is called automobile alliance here. In this paper, we consider the market with battery manufacturer, automobile alliance and third-party recycler, and mainly study three modes, namely, the hybrid dual-channel recycling mode of battery manufacturer and automobile alliance (Figure 1a), the hybrid dual-channel recycling mode of battery manufacturer and third-party recycler (Figure 1b), and the hybrid dual-channel recycling mode of automobile alliance and third-party recycler (Figure 1c).

![Figure 1. Structural models of hybrid dual-channels. a Mode M&A. b Mode M&T. c Mode A&T.](image-url)

The stackberg game models are established in this paper, and the objective function is to maximize the profit of each recycling subject. Considering the competition between different channels, refer to Liu’s setting of recycling channel competition [10]. For example, the competitive relationship between battery manufacturers and automobile alliance is expressed as $\tau_m = \frac{h_m - \alpha p}{h_m}$.

In the recovery cost of power battery, the recovery subject has to pay the recovery cost including fixed investment. Refer to setting of Savaskan [8], setting the cost of recovery investment is $I = h_t \tau_t^2$, where $h_t$ is the recovery cost coefficient. Due to the different channels of each recycling subject, it is assumed that $h_m > h_t > h_a$. It is assumed that after the recovery market tends to be stable, the recovery price $p$ is stable, and in order to be profitable, $\Delta > b > p$ should be satisfied.
The summary of the symbols used in the mathematical model can be seen in Table 1.

| Symbol | Definition |
|--------|------------|
| \( \mu \) | Proportion of spent power battery used for disassembly |
| \( p_0 \) | Average raw material value obtained by disassembling unit battery |
| \( p_s \) | Average selling price of unit battery cascade utilization |
| \( s \) | Unit battery recovery subsidy |
| \( c \) | Unit cost of battery manufacturer to dispose of battery |
| \( \Delta \) | Use value of unit spent power battery, \( \Delta = s + \mu p_0 + (1 - \mu)p_s - c \) |
| \( b \) | Repurchase price paid by battery manufacturer to automobile alliance and third-party |
| \( i \) | \( i = m, a, t \), respectively is battery manufacturer, automobile alliance and third-party |
| \( \tau_i \) | Recovery rate |
| \( \alpha \) | Competition coefficient |
| \( h_i \) | Recovery cost coefficient |
| \( I_i \) | Recovery of investment cost |
| \( \pi_j \) | The economic benefits of each recycling subject, \( j = M & A, M & T, A & T \) |
| * | Superscript * indicates the obtained equilibrium solution |

3. Modeling and analysis

3.1. Hybrid dual-channel recycling model of battery manufacturer and automobile alliance (M&A)
In this model, the battery manufacturer chooses to recycle the spent power battery through the hybrid dual-channel of itself and the automobile alliance, in which the battery manufacturer pays the second repurchase price \( b \) to the automobile alliance. In this game model, the battery manufacturer sets the repurchase price \( b \) and its recovery rate \( \tau_m \) to maximize its profit, and then the automobile alliance chooses the recovery rate \( \tau_a \) to maximize its profit. The profit functions are

\[
\pi_{\text{M&A}}^M = Q(r_m + r_a)\Delta - Qr_ab - Qr_mp - \frac{h_m r_m^2 + a h_a r_a^2}{1 - \alpha^2}
\]

\[
\pi_{\text{M&A}}^A = Qr_i(b - p) - \frac{h_a r_a^2 + a h_m r_m^2}{1 - \alpha^2}
\]

The results obtained by backward induction are \( b_{\text{M&A}}^* = \frac{(\alpha^2 - 1)(1 - \alpha^2)}{2h_a(2 + \alpha)} \), \( r_{\text{M&A}}^M = \frac{Q(\alpha - p)}{2h_m} \), and \( r_{\text{M&A}}^A = \frac{Q(\alpha - p)(1 - \alpha^2)}{2h_a(2 + \alpha)} \). The profits of battery manufacturer and automobile alliance are respectively

\[
\pi_{\text{M&A}}^M = \frac{Q^2(1 - \alpha^2)(1 - \alpha - p)^2}{4 \left( \frac{1}{h_m} + \frac{1}{h_a(2 + \alpha)} \right)} \quad \pi_{\text{M&A}}^A = \frac{Q^2(\alpha - p)^2(1 - \alpha^2)}{4(2 + \alpha)^2} \left( \frac{1}{h_a} - \frac{\alpha}{h_m} \right)
\]

Due to the limitation of space, the proof process is omitted. So is the later process.

3.2. Hybrid dual-channel recycling model of battery manufacturer and third-party recycler (M&T)
In this model, the battery manufacturer chooses to recycle the spent power battery through the hybrid dual-channel of itself and the automobile alliance, in which the battery manufacturer pays the second repurchase price \( b \) to the automobile alliance. In this game model, the battery manufacturer sets the repurchase price \( b \) and its recovery rate \( \tau_m \) to maximize its profit, and then the third-party recycler chooses the recovery rate \( \tau_t \) to maximize its profit. The profit functions are

\[
\pi_{\text{M&T}}^M = Q(r_m + r_t)\Delta - Qr_tb - Qr_mp - \frac{h_m r_m^2 + a h_t r_t^2}{1 - \alpha^2}
\]
The profits of battery manufacturer and third-party recycler are respectively
$
\pi_t^{M&T} = Q_t (b - p) - \frac{h_t \tau_t^2 + a h_m \tau_m^2}{1 - \alpha^2}.
$
(4)

The results obtained by backward induction are $b^{M&T\ast} = \frac{d + (1 + \alpha) p}{2 + \alpha}$, $\tau_m^{M&T\ast} = \frac{Q(d-p)(1-\alpha^2)}{2h_m}$ and $\tau_t^{M&T\ast} = \frac{Q(d-p)(1-\alpha^2)}{2h_t}$.

The profits of battery manufacturer and third-party recycler are very low, so in order to promote the healthy development of the industry, battery manufacturer should formulate corresponding profit transfer mechanisms to improve the enthusiasm of third-party recycler choose the recovery rates
$
\tau_m \text{ and } \tau_t \text{ to maximize its profit. The profit functions are}
$
\pi_m^{A&T} = Q (\tau_a + \tau_t)(d - b)
(5)

\pi_a^{A&T} = Q \tau_a (b - p) - \frac{h_a \tau_a^2 + a h_t \tau_t^2}{1 - \alpha^2}
(6)

\pi_t^{A&T} = Q \tau_t (b - p) - \frac{h_t \tau_t^2 + a h_m \tau_m^2}{1 - \alpha^2}
(7)

The results obtained by backward induction are $b^{A&T\ast} = \frac{d + p}{2}$, $\tau_a^{A&T\ast} = \frac{Q(d-p)(1-\alpha^2)}{2h_a(2+\alpha)}$, $\tau_t^{A&T\ast} = \frac{Q(d-p)(1-\alpha^2)}{2h_t(2+\alpha)}$.

The profits of battery manufacturer, automobile alliance and third-party recycler are respectively
$
\pi_m^{A&T\ast} = \frac{Q^2(d-p)(1-\alpha^2)}{4(2+\alpha)} \left( \frac{1}{h_m} + \frac{1}{h_t} \right), \pi_a^{A&T\ast} = \frac{Q^2(d-p)(1-\alpha^2)}{4(2+\alpha)} \left( \frac{1}{h_a} + \frac{1}{h_t} \right) \pi_t^{A&T\ast} = \frac{Q^2(d-p)(1-\alpha^2)}{4(2+\alpha)} \left( \frac{1}{h_a} + \frac{1}{h_m} \right).
$

3.3. Hybrid dual-channel recycling model of automobile alliance and third-party recycler (A&T)

In this model, battery manufacturer chooses to recycle through the hybrid dual-channel of automobile alliance and third-party recycler. The battery manufacturer pays the second repurchase price $b$ to the automobile alliance and third-party recycler. In this game model, the battery manufacturer sets the repurchase price $b$ by maximizing its own profit, and then the automobile alliance and the third-party recycler choose the recovery rates $\tau_a$ and $\tau_t$, respectively, to maximize their profits. The profit relationship of automobile alliance is
$\pi_a = \frac{Q^2(d-p)(1-\alpha^2)}{4(2+\alpha)} \left( \frac{1}{h_a} + \frac{1}{h_t} \right)$

Proposition 1 shows that the repurchase price of battery manufacturer under three hybrid dual-channel recycling models is $b^{M&T\ast} > b^{M&A\ast} > b^{A&T\ast}$. When $h_m > (2 + \alpha) h_a$, the relationship between the total recovery rates under three hybrid recovery models is $\tau_t^{M&T\ast} > \tau_t^{M&A\ast} > \tau_t^{A&T\ast}$.

Proposition 1 shows that the repurchase price of A&T model is the highest, the total recovery rate of $A&T$ mode is the highest.

Proposition 2 Under different models, the profit of battery manufacturer is $\pi_m^{A&T\ast} > \pi_m^{M&A\ast} > \pi_m^{M&T\ast}$, The profit relationship of automobile alliance is $\pi_a^{M&A\ast} > \pi_a^{A&T\ast}$, The profit of the third-party recycler $\pi_t^{M&T\ast} > \pi_t^{A&T\ast}$, The relationship among the total channel profit is $\pi_t^{M&T\ast} > \pi_t^{M&A\ast} > \pi_t^{A&T\ast}$.

Proposition 2 shows that A&T model can bring the biggest profit to battery manufacturer, so battery manufacturer should choose A&T model. However, the profits of automobile alliance and third-party recycler are very low, so in order to promote the healthy development of the industry, battery manufacturer should formulate corresponding profit transfer mechanisms to improve the enthusiasm of automobile alliance and third-party recycler.

3.4. Comparison and analysis of the three hybrid dual-channel recycling models

By comparing the solution results of the different models, the following propositions are obtained.

Proposition 1 When $\Delta > p$, the repurchase price of battery manufacturer under three hybrid recovery models is $b^{A&T\ast} > b^{M&A\ast} > b^{M&T\ast}$. When $h_m > (2 + \alpha) h_a$, the relationship between the total recovery rates under three hybrid recovery models is $\tau_t^{M&T\ast} > \tau_t^{M&A\ast} > \tau_t^{A&T\ast}$.

Proposition 1 shows that the repurchase price of A&T model is the highest, the total recovery rate of A&T mode is the highest.

Proposition 2 Under different models, the profit of battery manufacturer is $\pi_m^{A&T\ast} > \pi_m^{M&A\ast} > \pi_m^{M&T\ast}$, The profit relationship of automobile alliance is $\pi_a^{M&A\ast} > \pi_a^{A&T\ast}$, The profit of the third-party recycler $\pi_t^{M&T\ast} > \pi_t^{A&T\ast}$, The relationship among the total channel profit is $\pi_t^{M&T\ast} > \pi_t^{M&A\ast} > \pi_t^{A&T\ast}$.

Proposition 2 shows that A&T model can bring the biggest profit to battery manufacturer, so battery manufacturer should choose A&T model. However, the profits of automobile alliance and third-party recycler are very low, so in order to promote the healthy development of the industry, battery manufacturer should formulate corresponding profit transfer mechanisms to improve the enthusiasm of automobile alliance and third-party recycler.

3.5. Cooperative game model of automobile alliance and third-party recycler (A&T<sup>(CO)</sup>)

Through analysis, battery manufacturer will get the greatest profits by choosing A&T mode. However, decentralized decision-making always leads to excessive investment in capital and resources, which will leads to decline of profits. Therefore, a cooperative game model is established to analyse the situation of centralized decision-making and decentralized decision-making. In the model, objective function has nothing to do with the repurchase price $b$ of battery manufacturer, but only with the recovery rate of automobile alliance and third-party recycler. The function of total channel profit is
$\pi_t^{A&T\ast} = Q (\tau_a + \tau_t)(d - p) - \frac{h_t \tau_t^2 + h_m \tau_m^2}{1 - \alpha}$
(8)
The results obtained are $\tau_{d}^{A&TCO} = \frac{Q(a-p)(1-\alpha)}{2h_{a}}$ and $\tau_{t}^{A&TCO} = \frac{Q(a-p)(1-\alpha)}{2h_{t}}$. Total channel profit is $\pi_{d}^{A&TCO} = \frac{Q^{2}(d-p)^{2}(1-\alpha)}{4} (\frac{1}{h_{a}} + \frac{1}{h_{t}})$.

**Proposition 3**  The total recovery rate in $A&T^{CO}$ model is greater than that in $A&T$ model, i.e., $\tau_{d}^{A&T^{CO}} > \tau_{d}^{A&T}$. The total channel profit in $A&T^{CO}$ model is also greater than that in $A&T$ model, i.e., $\pi_{d}^{A&T^{CO}} > \pi_{d}^{A&T}$.

Proposition 3 show that centralized decision-making brought about by cooperation increases the total recovery rate and total profit. Therefore, all subjects, especially battery manufacturers, should strive to achieve strategic cooperation, so as to reduce the repeated recovery investment and competition in the region, improve the recovery efficiency, and then improve the total recovery rate and total profit.

4. Numerical analysis

In this section, MATLAB is used for simulation analysis to verify the proposition and get more management opinions. Parameter settings are as follows: $\mu = 0.5$, $p_{p} = 4000$, $p_{s} = 6000$, $s = 2000$, $c = 1000$, $p = 5000$, $\alpha = 0.2$, $h_{m} = 1 \times 10^{10}$, $h_{t} = 7.5 \times 10^{9}$, $h_{a} = 5 \times 10^{9}$.

![Figure 2](image1.png)

(a) Comparison of total recovery rate and profit of battery manufacturer

It can be seen from Figure 2 that the total recovery rate decreases with the increase of competition coefficient, and the total recovery rate of $A&T$ model is the largest. The profit of battery manufacturer decreases with the increase of competition coefficient, and the profit of battery manufacturer in $A&T$ model is the largest.

![Figure 3](image2.png)

(b) Figure 3. Comparison of total recovery rate and total channel profit in $A&T$ and $A&T^{CO}$ model

It can be seen from Figure 3(a) and (b), both of the two upper surfaces are the results of $A&T^{CO}$ model. The total recovery rate and channel profit in $A&T^{CO}$ model are always higher than that in $A&T$ model. Therefore, in order to promote the improvement of total recovery rate and total profit, we should strive to achieve strategic cooperation, and formulate the optimal recycling site layout through centralized decision-making to form a more economical recycling channel to reduce cost.
5. Conclusion
In this paper, based on the current situation of spent power battery recycling, combined with the closed-loop supply chain decision theory, three hybrid dual-channel recycling modes are studied, and models are established to compare and analyse the recovery rate and profit under different models.

Through analysis, it is found that the hybrid dual-channel recycling mode of automobile alliance and third-party recycler can bring higher recovery rate and profit. Competition between different channels will increase the cost of the recycling subject. Therefore, battery manufacturer should recycle spent power battery through the hybrid dual-channel of automobile alliance and third-party recycler, and at the same time, reduce the competition between the two channels as much as possible, so as to improve the total recovery rate and profit.

In addition, it is found that the centralized decision-making brought by cooperation can improve the total recovery rate and the total profit of the channel. Therefore, battery manufacturer should make efforts to promote the strategic cooperation among the recycling subject, so as to achieve overall planning and centralized decision-making, avoid the waste of funds and resources, reduce the recycling cost brought by overlapping investment and competition in the same region. With the rapid growth of the scale of spent power battery, the scale effect will flatten the fixed investment cost of recycling, and the technological progress and wider cascade utilization channels can also expand the source of profit.

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