Study on the Selection Strategy of Power Battery Recycling Model Considering Blockchain Technology Inputs

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Abstract. In recent years, the rapid development of new energy vehicles has been accompanied by the problem of recycling and disposal of used power batteries. The current market is flooded with informal recyclers, so some power battery manufacturers have started to invest in blockchain technology to realize the tracking of power batteries and improve the formal recycling rate. This paper constructs a closed-loop supply chain consisting of power battery suppliers, electric vehicle manufacturers and consumers, establishes two recycling modes: supplier recycling and manufacturer recycling, and comparatively analyzes the pricing decision problem of supply chain members under different recycling modes by considering consumers' traceability preference and the cost of unit blockchain verification. The study shows that the manufacturer's profit is higher than the manufacturer's recycling model under the supplier recycling model, and the supplier's profit is higher than the manufacturer's recycling model under the manufacturer recycling model.

Keywords: Power Battery Recycling; Blockchain Technology; Stackelberg Game

1 Introduction

Accompanied by the explosive growth of new energy vehicle sales, a large number of new energy vehicle batteries will soon face disposal, battery recycling issues to environmental protection and sustainable development has brought a major challenge, it is expected that by 2025 the annual end-of-life amount of power batteries or up to 800,000 tons[1]. If such a large-scale decommissioned power battery cannot be reasonably recycled, the development of the electric vehicle industry will encounter a new bottleneck[2]. How to fully and efficiently recycle and reuse used power batteries has become an urgent problem to be solved[3]. Currently, there are two main modes of power battery recycling: supplier recycling and manufacturer recycling[4]. However, due to the imperfect recycling network of power batteries, some small-scale and irregular recycling enterprises recycle used batteries through high prices, resulting in a low recycling rate of power batteries in regular recycling channels[5]. Relying on the traceability of blockchain technology, blockchain technology has begun to be applied in the field of waste product recycling[6]. Some power battery manufacturing enterprises began to invest in blockchain technology to traceability of power batteries, such as Ningde Times[7].

In the context of closed-loop supply chain of power battery, this paper compares the pricing and profit of supply chain members under different recycling modes, and conducts a

MSEA 2024, May 24-26, Jinan, People's Republic of China

DOI 10.4108/eai.24-5-2024.2350069

comparative analysis of decision-making under different recycling channels, so as to derive the equilibrium strategy for the selection of recycling channels in the case of suppliers investing in blockchain technology.

2. Variable instructions and basic assumptions

2.1 Variable instructions

The parameters in this paper are explained in Table 1.

Table 1. Model Parameter Setting

notation	description
p	Unit sales price of electric vehicles
ω	Unit wholesale price of power batteries
τ	Recycling rate of power batteries
c_n	Unit manufacturing cost of power battery using raw materials
c_r	Unit manufacturing cost of power battery using remanufactured materials
c_s	Recycling costs for recyclers to recover units of used power batteries
b	Unit transfer payment costs for suppliers to recover used power batteries from recyclers
C	Recovery scale parameters
$\triangle$	Cost savings from using remanufactured materials for power cells, and it is equal to the difference between b and c_s
α	The potential market demand

2.2 Assumption

Assumption 1. Supply chain members are assumed to be perfectly rational and risk-neutral, all aiming to maximize their respective profits.

Assumption 2. The market demand function of electric vehicles be $D = \alpha - p + \gamma g$。

Assumption 3. For the cost of recycling effort, it is assumed that the cost of recycling is $I = C\tau^2,\ C > 0$.

Assumption 4. $I = \frac{kg^2}{2}$ denotes the cost of traceability, i.e., the operational cost of blockchain technology, invested by member suppliers.

Assumption 5. All Power Batteries are sold at the same price in the same market.

3. Model building and solving

3.1 Supplier recycling model

In this model, the decision sequence is: the supplier first determines the wholesale price ω^S, the recycling rate τ^S, and the blockchain traceability level g^S of the power battery, and then the manufacturer decides the sales price p^S based on the supplier's decision.

The profit functions of the supplier, and the manufacturer are respectively:

$$\pi_s^S = (\omega^S - c_n)D + (\triangle - c_s)\tau^S D - I^S - I_s^S \tag{1}$$
$$\pi_m^S = (p^S - \omega^S)D \tag{2}$$

Proposition 1. Under the supplier recycling model, the optimal decisions of power battery suppliers and electric vehicle manufacturers are as follows:

$$\omega^S = \frac{k\alpha(Y^2 - 4C) + Cc_n(-4k + \gamma^2)}{X} \tag{3}$$
$$\tau^S = -\frac{Yk(\alpha - c_n)}{X} \tag{4}$$
$$g_s^S = \frac{C\gamma(-\alpha + c_n)}{X} \tag{5}$$
$$p^S = \frac{(Y^2 - 6C)k\alpha + Cc_n(-2k + \gamma^2)}{X} \tag{6}$$
$$\pi_s^S = -\frac{Ck(\alpha - c_n)^2}{X} \tag{7}$$
$$\pi_m^S = \frac{4C^2k^2(\alpha - c_n)^2}{X^2} \tag{8}$$
$$\pi_z^S = \frac{Ck[(Y^2 - 12C)k + C\gamma^2](\alpha - c_n)^2}{X^2} \tag{9}$$

Where $X = [(A + B)^2 - 8C]k + C\gamma^2, Y = \triangle - c_s$.

3.2 Manufacturer recycling model

In this model, the decision sequence is: the supplier first determines the wholesale price ω^M and the blockchain traceability level g^M of the power battery, and the manufacturer decides the sales price p^M and the recycling rate τ^M based on the supplier's decision.

The profit functions of the supplier and the manufacturer are respectively:

$$\pi_s^M = (\omega^M - c_n)d + (\triangle - b + e)\tau^M d - I_s^M \tag{10}$$
$$\pi_m^M = (p^M - \omega^M)d + (b - e - c_s)\tau^M d - I^M \tag{11}$$

Proposition 2. Under the model of manufacturer recycling, the optimal decisions of power battery suppliers, and electric vehicle manufacturers are as follows:

$$\omega^M = \frac{k\alpha[-4C + (B - e)(2A + B + e)] + [(-4C + (B - e)^2)k + C\gamma^2]c_n}{Z} \tag{12}$$
$$g^M = \frac{C\gamma(-\alpha + c_n)}{Z} \tag{13}$$
$$p^M = \frac{2k\alpha[-3C + (A + B)(B - e)] + Cc_n(-2k + \gamma^2)}{Z} \tag{14}$$
$$\tau^M = -\frac{k(B - e)(\alpha - c_n)}{Z} \tag{15}$$
$$\pi_s^M = -\frac{Ck(\alpha - c_n)^2}{Z} \tag{16}$$
$$\pi_m^M = -\frac{Ck^2[-4C + (B - e)^2](\alpha - c_n)^2}{Z^2} \tag{17}$$
$$\pi_z^M = -\frac{Ck[-12Ck + (B - e)(2A + 3B - e)k + C\gamma^2](\alpha - c_n)^2}{Z^2} \tag{18}$$

Where $Z = -8Ck + 2(A + B)(B - e)k + C\gamma^2, A = \triangle - b, B = b - c_s$.

4 Comparative analysis of different recycling models

The following corollaries can be drawn from the comparative analysis of the above equilibrium solutions:

Corollary 1. The magnitude of the wholesale price for different recycling modes in the case where suppliers are invested in the blockchain is $\omega^M > \omega^S$.

Proof 1. $\omega^M - \omega^S = [k\alpha(Y^2 - 4C) + Cc_n(-4k + \gamma^2)]/X - \{k\alpha[-4c + (B - e)(2A + B + e)] + [(-4c + (B - e)^2)k + c\gamma^2]c_n\}/Z > 0$.

Corollary 1 shows that the wholesale price is highest in the manufacturer recycling mode and lowest in the supplier recycling mode when the supplier invests in the blockchain technology. This is because in the supplier recycling mode, the supplier directly recycles is more conducive to controlling the costs incurred in recycling, and can maximize the revenue by controlling the recycling cost.

Corollary 2. In the scenario where the supplier invests in the blockchain, the relationship between the magnitude of the sales price in different recycling modes is $p^M > p^S$ when $A - B + 2e < 0$; $p^M < p^S$ when $A - B + 2e > 0$.

Proof 2. $p^M - p^S = [Ck(A + B)(A - B + 2e)(2k - \gamma^2)(\alpha - c_n)]/XZ,$ when $A - B + 2e < 0, p^M - p^S > 0,$ when $A - B + 2e > 0, p^M - p^S < 0.$

Corollary 2 shows that in the scenario where the supplier is invested in blockchain technology, the sales price under different recycling models is related to A, B and e. When $A - B + 2e < 0$, the sales price under the manufacturer recycling model is higher than that under the supplier recycling model, and when $A - B + 2e > 0$, the sales price under the supplier recycling model is higher than that under the manufacturer recycling model.

Corollary 3. In the scenario where the supplier invests in the blockchain, the relationship between the magnitude of the recycling rate under different recycling modes is $\tau^M > \tau^S$.

Proof 3.$\tau^S - \tau^M = k(\alpha - c_n)[(B - e)X - (A + B)Z]/XZ < 0$, so $\tau^S < \tau^M$.

Corollary 3 shows that the sensitivity factors of blockchain unit verification cost and traceability level affect the recycling rate of used power batteries. The recycling rate of used power batteries under the manufacturer recycling model is higher than the supplier recycling model. This is because the manufacturer is closer to the consumer and the investment in blockchain technology improves consumer trust, hence the highest recycling rate.

Corollary 4. The relationship between the magnitude of the traceability level of different recycling modes in the case where the supplier puts in the blockchain is $g^S > g^M$ when $A - B + 2e > 0$; $g^S < g^M$ when $A - B + 2e < 0$.

Proof 4. $g^S - g^M = C\gamma k(-\alpha + c_n)(A + B)(A - B + 2e)/XZ,$ when $A - B + 2e < 0, g^S - g^M < 0,$ when $A - B + 2e > 0, g^S - g^M > 0.$

Corollary 4 shows that the level of blockchain traceability is related to A, e of remanufacturing savings in the case where the supplier invests in blockchain technology. The traceability level under the manufacturer recycling model is higher when $A - B + 2e < 0$, and the traceability level under the supplier recycling model is higher when $A - B + 2e > 0$.

Corollary 5. In the case of suppliers investing in blockchain, the relationship between the size of profits under different recycling modes is $\pi_s^S > \pi_s^M$, $\pi_m^S > \pi_m^M$.

Proof 5. $\pi_s^S - \pi_s^M = Ck(\alpha - c_n)^2[\mathrm{Y}^2k - 16Ck + 2Y(B-e)k + 2c\gamma^2]/XZ > 0$,$\pi_m^S - \pi_m^M = Ck^2(B-e)^2Y^2k^2(\alpha - c_n)^2/X^2Z^2 > 0$.

Corollary 5 shows that when suppliers invest in blockchain technology, both supplier profits and manufacturer profits are higher in the supplier recycling model,because the supplier commissions the manufacturer to recycle and saves the cost of constructing recycling facilities.

5 Numerical analysis

The following analysis is based on data from available references[8], the parameters are $\alpha = 500$,$c_r = 30, c_n = 80$,$\triangle = c_n - c_r = 50, b = 15, c_s = 5, c = 200$ and $k = 3$.

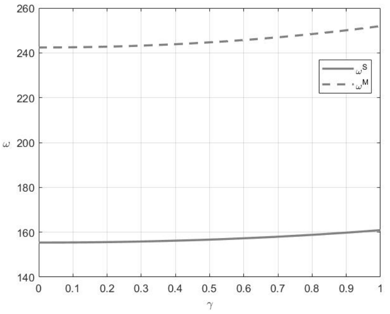

Fig. 1. Comparison of Wholesale Prices

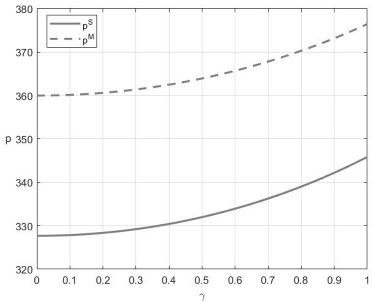

Fig. 2. Comparison of Sales Prices

Fig. 1 indicates that for the set parameter values, the wholesale price of power batteries increases as the consumer preference for traceability increases. It can also be observed that the wholesale price of power batteries is relatively high under the manufacturer recycling model.

Fig. 2 indicates that power battery sales prices increase with consumer traceability preference and are highest in the manufacturer recycling model.

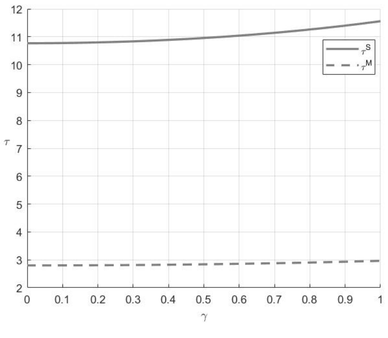

Fig. 3. Comparison of Recycling Rates

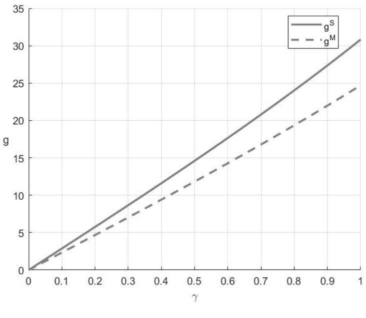

Fig. 4. Comparison of the Level of Traceability

Fig. 3 shows that the recovery rate increases with increasing consumer traceability preference in both recovery modes and is highest in the manufacturer recovery mode.

Fig. 4 shows that the level of blockchain technology traceability increases with increasing consumer traceability preference and is highest under the supplier recycling model.

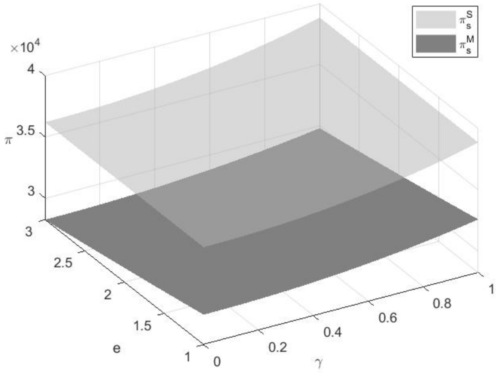

Fig. 5. Comparison of Supplies' Profits

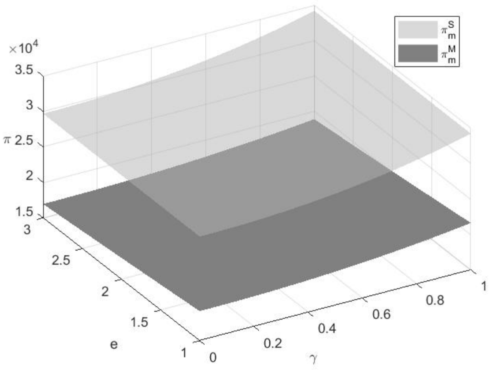

Fig. 6. Comparison of Manufacturers' Profits

Fig. 5 indicates that the suppliers' profits increase with increasing consumer traceability preference and decrease with increasing unit validation cost, and supplier profit under supplier's recycling mode is higher than that under manufacturer's recycling mode.

Fig. 6 indicates that the manufacturers' profits increase with consumer traceability preference, decrease with increasing unit verification costs, and manufacturer profits under the supplier recycling model are higher than manufacturer profits under the manufacturer recycling model.

6 Conclusion

This paper considers the introduction of blockchain technology in the closed-loop supply chain of power batteries to solve the problem of power battery traceability, and analyzes the pricing decisions of the supply chain members under the adoption of blockchain technology by comparing the two closed-loop supply chain models of recycling by power battery suppliers and recycling by electric vehicle manufacturers. The study finds:

(1) The wholesale price and recovery rate under the manufacturer recycling model are higher than those under the supplier recycling model in the case where the supplier invests in blockchain technology.

(2) The magnitude of selling price and traceability level under different recycling models is related to the unit cost saved by suppliers using remanufactured materials, the unit revenue from manufacturer recycling, and the blockchain unit validation cost, and there exists a certain threshold. When the unit validation cost is above a certain threshold, the sales price and the level of blockchain traceability are higher in the supplier recycling model and lower in the manufacturer recycling model. Conversely, when the unit verification cost is below a certain threshold, the sales price and blockchain traceability levels are higher under the manufacturer recovery model and lower under the supplier recovery model.

(3) In the scenario where the supplier invests in blockchain technology, both supplier profit and manufacturer profit are higher in the supplier recovery model, and both increase with the consumer sensitivity factor.

In summary, the following management insights can be drawn: suppliers investing in blockchain technology can effectively improve consumer trust in the source of power batteries, increase sales prices and the recycling rate of used power batteries as a way to increase the profits of supply chain members. Therefore, in the actual operation process, suppliers need to improve the regulation of the power battery recycling process, so as to improve the quantity and quality of the recycling of used products. However, due to the complexity of blockchain technology, there are certain difficulties in the specific implementation process, and enterprises should strengthen the investment and improvement of technology when implementing blockchain.

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