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Blockchain Traceability and Recycling Mode Choice for Retired Power Batteries: Decentralized vs. Cooperative Recycling

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ABSTRACT

To improve the low efficiency of retired power battery recycling caused by information asymmetry, low trust, and channel competition, this paper develops a two-level closed-loop supply chain model including a power battery supplier and an electric vehicle manufacturer. Both firms recycle batteries in parallel and compete with each other. A blockchain-based traceability level is introduced to show how better information transparency affects market demand and recycling quantity. Blockchain investment cost and platform access fee are also considered. Under Stackelberg game and centralized decision-making, four scenarios are studied: no blockchain with separate recycling, no blockchain with cooperative recycling, blockchain with separate recycling, and blockchain with cooperative recycling. Equilibrium solutions are derived by backward induction, and comparative analysis and numerical experiments are conducted. The results show that cooperative recycling can reduce double marginalization and ease inefficient competition, thus improving supply chain performance. Blockchain adoption increases the optimal traceability level, market demand, and recycling quantity, which further improves total profit. The proposed model also provides strategic insights for the closed-loop management of emerging smart textile energy systems. The best outcome appears when cooperative recycling and blockchain are used together. Numerical results also show that stronger blockchain market effects increase these benefits, while higher blockchain cost reduces traceability investment and makes profits closer to the no-blockchain case.

KEYWORDS
retired power batteries, closed-loop supply chain, blockchain traceability, stackelberg game

INTRODUCTION

Addressing global warming has become one of the most urgent issues in the world today. The Chinese government has deeply recognized the significance of reducing carbon emissions. Based on the responsibility of promoting the building of a community with a shared future for mankind and the inherent requirements of achieving sustainable development, it has made the major strategic decision to peak carbon emissions before 2030 and achieve carbon neutrality before 2060. Since then, the “dual carbon” goals, centered on carbon peaking and carbon neutrality, have become the core guidance for Chinas ecological civilization construction and green and low-carbon transformation.

In this context, the automotive industry, as a pillar of the national economy and a major consumer of energy, has drawn significant attention to its green and low-carbon development. Traditional fuel vehicles generate a large amount of pollutants and greenhouse gases, exerting dual pressures on regional air quality and global climate change. According to statistics, the carbon emissions in the transportation sector account for nearly one-third of the global total emissions, making it a key area for reducing greenhouse gas emissions. Moreover, Chinas dependence on oil imports remains at a high level. In recent years, energy uncertainty, geopolitical conflicts, and militarization have prompted governments to promote the transformation of the transportation energy structure, in order to ensure national energy security [1].

New energy vehicles, as an ideal alternative to traditional fuel vehicles, have experienced explosive growth in recent years. This trend is also evident in the textile industry, where the development of electronic textiles (E-textiles) has integrated advanced energy storage components into wearable devices, further intensifying the demand for battery lifecycle management. In 2024, the production and sales of Chinese new energy vehicles reached 12.88 million and 12.866 million respectively. However, with the large-scale popularization of new energy vehicles, the recycling and resource utilization of retired battery packs have become increasingly prominent issues. On one hand, As the core component of new energy vehicles, the average service life of power batteries is only 5 to 8 years. When their performance drops to 70% - 80% of the initial capacity, they need to be replaced; otherwise, it will affect the overall performance and safety of the vehicle [2]; On the other hand, retired batteries contain valuable metal resources such as lithium, nickel, and cobalt. If they are not properly recycled and utilized efficiently, it will lead to resource waste and environmental risks [3].

However, the current battery recycling system is facing numerous challenges: Firstly, the recycling channels are scattered. A large number of used batteries still end up in non-regulated recycling enterprises, causing environmental pollution and resource waste [4]. Secondly, the technical requirements are high. The recovery rate of key metals such as lithium and cobalt is less than 90%, and there are technical bottlenecks in the second-life utilization technology, such as inconsistent battery quality. Thirdly, the industry standard system is not yet complete. Under the Extended Producer Responsibility (EPR) system, information asymmetry is severe, and the overall supply chain collaboration efficiency is low. Nowadays, with the rise of blockchain technology, it can systematically solve the three major problems of information asymmetry, unclear responsibility, and inefficient processes, ultimately reducing transaction costs, enhancing consumer trust, and optimizing reverse logistics efficiency. Therefore, establishing an efficient, standardized, and traceable reverse recycling system for used battery packs has become an important link in promoting the sustainable development of the entire chain of the new energy vehicle industry. At present, scholars both at home and abroad have mainly focused on the decentralized, non-modifiable and traceable technical characteristics of blockchain. Li Yongjian and Chen Ting systematically reviewed the mechanisms and cases of how blockchain empowers supply chain management through three major approaches: information sharing, information tracing and trust establishment [5]. Babich et al. filled the gap in the field of blockchains operational management [6]. Gong Yu and others collected a large amount of secondary data and used blockchain technology to study the platforms supply chain. They compared the data of 5 leading recycling institutions abroad and concluded that blockchain technology can improve the utilization rate of enterprise resources [7].

Meanwhile, as a decentralized and traceable distributed database, blockchain has been successfully applied in various scenarios such as the traceability system of organic food, prevention of product fraud and counterfeiting, etc. It is even regarded as a “miracle cure” for resource conservation and the establishment of a circular economy [8]. Michael et al. demonstrated through cases involving food companies that blockchain effectively enhances the transparency and reliability of transactions in a fully digitalized supply chain, and prevents the circulation of counterfeit goods [9]. Centobelli et al. aimed to connect the three reverse processes of the circular supply chain (recycling, redistribution, and remanufacturing) with the three factors that affect blockchain technology (trust, traceability, and transparency). They designed a supply chain consisting of manufacturers, reverse logistics service providers, selection centers, recycling centers, and landfill sites, and constructed a circular blockchain platform [10].

In the field of battery recycling, Zhang Meimei and others have designed a blockchain-based battery full life cycle information storage chain, providing a consensus mechanism support for enterprises engaged in secondary utilization to reduce transaction costs [11]; Cheng et al. conducted a comparative analysis of the changes in the profits of various stakeholders involved in the battery power traceability management under different government mechanisms before and after the application of blockchain technology [12]; Júnior et al. investigated the situation in the battery industry in order to establish a blockchain-based platform, thereby better controlling the performance and environmental impact of batteries [13]; Ren et al. built a cost model for the recycling of used lithium-ion batteries based on blockchain cost accounting, and proposed the problems encountered in the reverse supply chain recycling and the corresponding countermeasure [14]; Xing et al.s research focused on the battery manufacturers and recycling participants, and found that as the preference coefficient for traceability information increased, the integration degree of blockchain technology also improved [15].

MODEL DESCRIPTION AND BASIC ASSUMPTIONS

This paper constructs a two-level closed-loop supply chain consisting of a battery power supplier (S) and a vehicle manufacturer (M). In the forward supply chain, the supplier provides battery power to the manufacturer, who uses the battery and other components to produce new energy vehicles and sells them to the market at a unit retail price. In the reverse supply chain, retired battery power is directly recovered by the supplier and the manufacturer. The manufacturer recycles the used batteries at a transfer price and sells them to the supplier for dismantling or remanufacturing. Manufacturers are often closer to end consumers through vehicle sales and after-sales service networks, while suppliers usually possess stronger dismantling and remanufacturing capabilities. Therefore, each party may hold different comparative advantages in recycling, although these advantages can vary across industries and firms. At the same time, the coexistence of the two recovery channels may lead to competition and occupation of recovery resources: one party increasing the recovery investment will to some extent divert the recovery volume that the other party can obtain, thereby causing problems such as repeated investment.

In the traditional recycling model, there are problems such as information asymmetry and opaque battery health status, which lead to low recycling efficiency and lack of trust from consumers in remanufactured products. Blockchain technology, with its decentralized, immutable, and traceable characteristics, can establish a full life cycle traceability system for battery power. This paper explores two scenarios of decentralized and centralized recycling by the core enterprise (supplier S or manufacturer M) of the supply chain, as well as whether to consider applying blockchain technology to the battery recycling supply chain.

The basic assumptions of this article are as follows:

Assumption 1: The market demand for the product is $D = a - \beta p + kr$. Here, a represents the potential market size, β represents the price sensitivity coefficient, p is the retail price of new energy vehicles, r represents the investment level of blockchain traceability technology, k represents the positive impact coefficient of blockchain on market demand, and all parameters are positive numbers. When blockchain technology is not employed, $r = 0$.

Assumption 2: The unit cost C of power battery production by the supplier is composed of manufacturing costs c_m and raw material costs m , $C = c_m + m$. The manufacturer purchases the power batteries from the supplier at the wholesale price w . The cost of other components and manufacturing expenses is c_n . It then sells the new energy vehicles to the market at the retail price p . To ensure the economic significance of the decision, assume $p > w + c_n$ and $w > C$. The research, maintenance and operation of blockchain construction require certain costs, $C_B(r) = \frac{1}{2}k_b r^2$, $k_b > 0$ is the marginal cost coefficient of blockchain construction costs. When manufacturers connect to the blockchain platform, they need to pay a one-time access fee $C_s > 0$ to the suppliers as the cost for using the blockchain traceability technology. This fee is treated as an exogenous parameter in the model, primarily affecting profit distribution rather than the optimal decisions of supply chain members. Here, to ensure the economic viability, we impose a participation constraint: the manufacturer will only pay C_s if its post-fee profit in the blockchain scenario is no less than that in the corresponding no-blockchain scenario. Assumption 3: Both the supplier and the manufacturer can directly recycle retired power batteries. Let the suppliers recycling effort is $e_s \geq 0$, and the manufacturers recycling effort is $e_m \geq 0$. Then the recovery quantity functions are respectively $Q_S = Q_{S0} + \lambda_s r + \eta e_S - \theta e_M$, $Q_M = Q_{M0} + \lambda_M r + \eta e_M - \theta e_S$ (Q_{S0} , $Q_{M0} \geq 0$ are Reference recovery amount); $\eta > 0$ represents the marginal contribution of ones own efforts to the recycling volume; $\theta \geq 0$ represents the competitive coefficient reflecting the efforts of the other party in terms of the recycling volume. For the convenience of analysing, θ is interpreted as a reduced-form net competition parameter that summarizes the effects of overlapping networks, geographic proximity, consumer loyalty, service accessibility and so on. $\lambda_s, \lambda_m \geq 0$ represent the positive marginal promoting effect of blockchain technology investment on the recycling efforts of suppliers and manufacturers. To ensure that the net marginal contribution of the recycling efforts to the total recycling volume is positive, the following assumption is made: $\eta > \theta$.

Assumption 4: The costs of the recycling efforts by the suppliers and the manufacturers are respectively $C_s(e_s) = \frac{1}{2}k_s e_S^2$ and $C_M(e_M) = \frac{1}{2}k_M e_M^2$. Here, $k_S > 0$ and $k_M > 0$ respectively represent the effort cost coefficients of the suppliers and the manufacturers.

Assumption 5: The unit profit obtained by the supplier from the used lithium-ion batteries is v , the unit marginal cost of the supplier for the recycling is c_s , and the unit marginal cost of the manufacturer for the recycling is c_M . The manufacturer sells the recycled batteries to the supplier at a unit transfer price of t . Therefore, the unit net profit that the supplier obtains from the recycled products of the manufacturer is $v - t$, the net profit of the manufacturer for the recycling is $t - c_M$, and the unit net profit of the supplier from the recycling is $v - c_s$. To ensure that the recycling is economically viable, $v > c_s$ and $t > c_M$.

The variable and parameter symbols used in this model comparison analysis are as shown in the Table 1 below:

Table 1. The main notations in this paper

Symbol	Explanation
S	Battery power supplier
M	Vehicle manufacturer
w	Wholesale price (Supplier → manufacturer)
P	Wholesale price (Supplier → manufacturer)
t	Unit transfer payment price (Manufacturer → Supplier)
D	Market demand
a	Potential market size parameter
β	Price sensitivity coefficient
r	Blockchain traceability technology investment level
k	Blockchains impact coefficient on market demand
c_m	Supplier manufacturing unit cost
m	Supplier raw material unit cost
C	Supplier battery unit cost $C = c_m + m$
c_n	Manufacturers unit cost excluding batteries
X	Total marginal cost of the forward supply chain per unit $X = C + c_n$
k_b	Marginal cost coefficient of blockchain construction cost
C_s	Cost of manufacturers access to blockchain
e	Level of recovery efforts
Q_S	Supplier recovery volume
Q_M	Supplier recovery volume
Q	Total recovery volume
Q_0	Base recovery volume
η	Marginal contribution of their own efforts to recovery volume $\eta > 0$
θ	Competitive coefficient, $\theta \geq 0$ and $\eta > \theta$
k_s	Supplier recovery effort cost coefficient
k_M	Manufacturer recovery effort cost coefficient
v	Manufacturer recovery effort cost coefficient
c_s	Marginal cost of suppliers self-recovery unit

Symbol	Explanation
c_M	Marginal cost of manufacturers recovery unit
π_s	Supplier profit
π_M	Manufacturer profit
Π_{SC}	Total profit of the supply chain system

MODEL CONSTRUCTION AND SOLUTION

The traditional recycling model without any blockchain investment

Dispersed Recycling Model (NA)

Under this mode, the suppliers and manufacturers separately recover the used battery power. The game sequence is as follows: The supplier, as the leader, first decides the wholesale price, the recovery effort level and the resale price. The manufacturer, as the follower, observes the suppliers decision and then selects the retail price and the recovery effort level to maximize its own profit.

The profit function of the battery power supplier is:

$$\pi_S^{NA} = (w - C)D + (v - c_s)Q_S + (v - t)Q_M - \frac{1}{2}k_s(e_S^{NA})^2 \tag{1}$$

The profit function of the new energy vehicle manufacturers is:

$$\pi_M^{NA} = (p - w - c_n)D + (t - c_M)Q_M - \frac{1}{2}k_M(e_M^{NA})^2 \tag{2}$$

The total profit of the supply chain system is:

$$\Pi_{SC}^{NA} = \pi_S^{NA} + \pi_M^{NA} \tag{3}$$

Using the reverse induction method, we solve equations (1) and (2) sequentially, and thereby obtain the optimal market demand quantity and the optimal profit by back-substitution step by step. The equilibrium strategy choices of all parties in the supply chain under the NA model can be derived as shown in Lemma 2.1.

Lemma 2.1 In the NA mode, the average retail price is $p^{NA*} = \frac{3a+\beta(C+c_n)}{4\beta}$; the equilibrium demand quantity is $D^{NA*} = \frac{a-\beta(C+c_n)}{4}$; the equilibrium profit of the supply chain system is $\Pi_{SC}^{NA*} = \frac{(a-\beta X)^2}{16\beta} + (v - c_s)Q_S^{NA*} + (v - c_M)Q_M^{NA*} - \frac{1}{2}k_s(e_S^{NA*})^2 - \frac{1}{2}k_M(e_M^{NA*})^2$.

To ensure the existence of a balanced solution and its economic significance, all discussions are based on the following conditions: $a > \beta(C + c_n)$, $2\eta^2 k_s - k_M\theta^2 > 0$, and $t^{NA*} > c_M$, $e_S^{NA*} \geq 0$, $e_M^{NA*} \geq 0$, $Q_S^{NA*} \geq 0$, $Q_M^{NA*} \geq 0$.

Collaborative Recycling Model (NB)

Under this mode, suppliers and manufacturers collaborate to recycle used battery power. The suppliers and manufacturers make centralized overall decisions for the supply chain system, aiming to maximize the total system profit and determining the retail price and recycling investment. In the centralized coordination situation, the unit transfer payment price is the internal settlement price within the system and cancels out with each other in the system profit. Therefore, it does not affect the optimal decision of the system but only influences the profit distribution.

The total profit of the supply chain system is:

$$\Pi_{SC}^{NB} = (p - X)D + (v - c_s)Q_S + (v - c_M)Q_M - \frac{1}{2}k_s(e_S^{NB})^2 - \frac{1}{2}k_M(e_M^{NB})^2 \tag{4}$$

The equilibrium strategy choices of all parties in the supply chain under the NB model are as shown in Lemma 2.2.

Lemma 2.2 In the NB mode, the average retail price is $p^{NB*} = \frac{a+\beta(C+c_n)}{2\beta}$; the equilibrium demand quantity is $D^{NB*} = \frac{a-\beta(C+c_n)}{2}$; the equilibrium profit of the supply chain system is $\Pi_{SC}^{NB*} = \frac{(a-\beta X)^2}{4\beta} + (v - c_s)Q_{S0} + (v - c_M)Q_{M0} + \frac{T_S^2}{2k_s} + \frac{T_M^2}{2k_M}$. Here, $T_S = (v - c_s)\eta - (v - c_M)\theta$, $\quad T_M = (v - c_M)\eta - (v - c_s)\theta$.

To ensure the existence of a balanced solution and its economic significance, all discussions are based on the following conditions: $a > \beta(C + c_n)$, $\quad T_S, T_M, Q_S^{NB*}, Q_M^{NB*} \geq 0$.

In summary, in the NA mode, suppliers simultaneously influence the forward and reverse supply chains through the wholesale price w and the transfer payment price t . Among them, it has a positive incentive effect on the manufacturers recovery effort level. However, when setting the t , suppliers face the choice of either increasing the acquisition price to increase the recovery quantity or lowering the acquisition price to maintain the unit net income. Due to the decentralized decision-making in the forward supply chain, there is a double markup in the terminal retail price. In the recovery end, when the competition coefficient $\theta \geq 0$ between the supplier and the manufacturer exists, the NA mode is more likely to generate competitive recovery investment and lead to repeated investment, while the NB mode enables both parties to cooperate and makes the optimal recovery effort level more restrained.

The Recycling Model Based on Blockchain Technology

Dispersed Recycling Model (YA)

Under this model, the supplier builds a blockchain platform and acts as the leader, determining the wholesale price, transfer payment price, recovery effort level and blockchain investment level first. The manufacturer, as the follower, then decides the retail price and its own recovery effort level, and pays C_S for accessing the blockchain.

The profit function of the battery power supplier is:

$$\pi_S^{YA} = (w - C)D + (v - c_s)Q_S + (v - t)Q_M - \frac{1}{2}k_s(e_S^{YA})^2 - \frac{1}{2}k_b r^2 + C_S \tag{5}$$

The profit function of the new energy vehicle manufacturers is:

$$\pi_M^{YA} = (p - w - c_n)D + (t - c_M)Q_M - \frac{1}{2}k_M(e_M^{YA})^2 - C_S \tag{6}$$

The total profit of the supply chain system is:

$$\Pi_{SC}^{YA} = \pi_S^{YA} + \pi_M^{YA} \tag{7}$$

Using the backward induction method, we can successively solve equations (5) and (6), and thereby obtain the optimal market demand quantity and the optimal profit by back-substitution step by step. The equilibrium strategy choices of all parties in the supply chain under the YA model can be derived as shown in Lemma 2.3.

Lemma 2.3 In the YA mode, the average retail price is $p^{YA*} = \frac{3(a+kr*)+\beta(C+c_n)}{4\beta}$; the equilibrium demand quantity is $D^{YA*} = \frac{a+kr*-\beta(C+c_n)}{4}$; the equilibrium profit of the supply chain system is $\Pi_{SC}^{YA*} = \frac{[a+kr-\beta(C+c_n)]^2}{16\beta} + (v - c_s)Q_{S0} + (v - c_M)Q_{M0} + \frac{1}{2}k_s(e_S^{YA*})^2 + \frac{1}{2}k_M(e_M^{YA*})^2$.

To ensure the existence of a balanced solution and its economic significance, all discussions are based on the following conditions: $C_S \leq \tilde{\pi}_M^{YA} - \pi_M^{NA}$. Here, $\tilde{\pi}_M^{YA} = (p - w - c_n)D + (t - c_M)Q_M - \frac{1}{2}k_M(e_M^{YA})^2$, $\pi_M^{NA} = (p - w - c_n)D + (t - c_M)Q_M - \frac{1}{2}k_M(e_M^{NA})^2$.

Collaborative Recycling Model (YB)

Under this mode, suppliers and manufacturers collaborate to recycle used battery power. The suppliers and manufacturers make centralized overall decisions for the supply chain system, aiming to maximize the total system profit and determining the retail price and recycling investment. In the centralized coordination situation, the unit transfer payment price is the internal settlement price within the system and cancels out with each other in the system profit. Therefore, it does not affect the optimal decision of the system but only influences the profit distribution.

The total profit of the supply chain system is:

$$\Pi_{SC}^{YB} = (p - X)D + (v - c_s)Q_S + (v - c_M)Q_M - \frac{1}{2}k_s(e_S^{YB})^2 - \frac{1}{2}k_M(e_M^{YB})^2 - \frac{1}{2}k_b r^2 \tag{8}$$

Taking the first-order conditions for p , e_S^{YB} , e_M^{YB} , and r , we can obtain the equilibrium solution. Revert back to the total profit of the supply chain system Π_{SC}^{YB} , and the equilibrium solution can be obtained as shown in Lemma 2.4.

Lemma 2.4 Under the YB model, the optimal retail price is $p^{YB*} = \frac{a+kr+\beta(C+c_n)}{2\beta}$; The optimal demand quantity is $D^{YB*} = \frac{a+kr*-\beta(C+c_n)}{2}$; The equilibrium profit of the supply chain system is $\Pi_{SC}^{YB*} = \frac{[a+kr-\beta(C+c_n)]^2}{4\beta} + (v - c_s)Q_{S0} + (v - c_M)Q_{M0} + \frac{T_S^2}{2k_S} + \frac{T_M^2}{2k_M} - \frac{1}{2}k_b r^2$.

To ensure the existence of a balanced solution and its economic significance, all discussions are based on the following conditions: $C_S \leq \tilde{\pi}_M^{YB} - \pi_M^{NB}$. Here, $\tilde{\pi}_M^{YB} = (p - w - c_n)D + (t - c_M)Q_M - \frac{1}{2}k_M(e_M^{YB})^2$, $\pi_M^{NB} = (p - w - c_n)D + (t - c_M)Q_M - \frac{1}{2}k_M(e_M^{NB})^2$.

MODEL COMPARISON ANALYSIS

The following is a comparative analysis of the NA, NB, YA, and YB models, along with the management insights derived from it.

Proposition 1 $e_S^{YA*} > e_S^{NA*}$, $e_M^{YA*} > e_M^{NA*}$, $Q_S^{YA*} < Q_S^{NB*}$, $Q_M^{YA*} < Q_M^{NB*}$;
$e_S^{YB*} < e_S^{NB*}$, $e_M^{YB*} < e_M^{NB*}$, $Q_S^{YB*} > Q_S^{NB*}$, $Q_M^{YB*} > Q_M^{NB*}$.

After the introduction of blockchain, in the decentralized recycling model, the recycling efforts of suppliers and manufacturers are relatively high, but due to the competition between the two parties, the increase in recycling volume is relatively small; while in the cooperative recycling model, due to the internalization of the externality at the recycling end, the recycling efforts are optimized, and by reducing the repetitive competition at the recycling end, the recycling volume has increased significantly.

Proposition 2 $p^{YB*} < p^{NB*}$, $D^{YB*} > D^{NB*}$; $p^{YA*} > p^{NA*}$, $D^{YA*} > D^{NA*}$.

In the cooperative recycling model, the blockchain eliminates the double marginal effect, reduces the repetitive competition in recycling efforts, lowers the retail prices of manufacturers, and thereby increases market demand. In the decentralized recycling model, although the prices are higher, due to the blockchains enhancement of demand and recycling volume, market demand also increases.

Proposition 3 $\Pi_{SC}^{NB*} > \Pi_{SC}^{NA*}$, $\Pi_{SC}^{YB*} > \Pi_{SC}^{NB*}$, $\Pi_{SC}^{YA*} > \Pi_{SC}^{NA*}$.

$\Pi_{SC}^{NB*} - \Pi_{SC}^{NA*} = \frac{3(a-\beta X)^2}{16\beta} + \frac{1}{2}k_S(e_S^{NA*} - e_S^{NB*})^2 + \frac{1}{2}k_M(e_M^{NA*} - e_M^{NB*})^2 > 0$. Therefore, it can be concluded that the cooperative recycling model is more profitable compared to the decentralized recycling model. This is because, on the one hand, there is a loss of profit due to the double marginalization of the forward supply chain, and on the other hand, the decentralized recycling by suppliers and manufacturers in the reverse supply chain leads to a loss in recycling efficiency. After the introduction of blockchain, the total profit of the supply chain system can be increased by enhancing demand and recycling volume. Especially in the cooperative recycling model, by making centralized decisions to optimize recycling efforts and resource allocation, the profit can be significantly increased.

CASE STUDY ANALYSIS

This section will analyze the influence coefficients of blockchain on market demand and its impact on other factors through numerical examples. Relevant parameters in the model will be assigned according to the references: $a = 120$, $\beta = 1$, $C = 10$, $c_n = 5$, $\eta = 0.8$, $k_S = 2$, $k_M = 2$, $v = 8$, $c_S = 2$, $c_M = 3$, $Q_{S0} = 1$, $Q_{M0} = 1$, $\lambda_S = 0.2$, $\lambda_M = 0.2$, $k_b = 20$, $C_S = 2$, $\theta = 0.3$. To ensure the rationality of the results, the range of the value is set as: $0 < k < 2.5$.

From Figures 1 to 3, it can be seen that as the coefficient k of the blockchain market demand influence increases, in the two scenarios of the YA model and the YB model where blockchain is applied, the retail price p shows an upward trend. This indicates that the stronger the demand gain brought by blockchain, the more likely enterprises are to obtain higher profits by increasing the terminal selling price. However, from a horizontal comparison, the retail price of the YA decentralized recovery model is always higher than that of the YB cooperative recovery model. This is because the double addition of the wholesale price of the supplier and the retail price of the manufacturer under decentralized recovery results in a significantly higher terminal retail price than the cooperative recovery model. While the cooperative recovery reduces the terminal pricing level through centralized planning, the retail price of the YB model is overall lower. At the same time, the market demand D and the total recovery volume Q both increase significantly with k in both the YA and YB models, indicating that the improvement of consumer trust and information transparency brought by blockchain can effectively expand demand and further drive the growth of the recovery scale. Moreover, at the same k , the demand and total recovery volume of the YB model are always higher than those of the YA model. This reflects that the cooperative recovery model, by coordinating the allocation of recovery resources and alleviating channel congestion and repeated investment, enables the demand expansion effect and recovery promotion effect brought by blockchain to be more fully released.

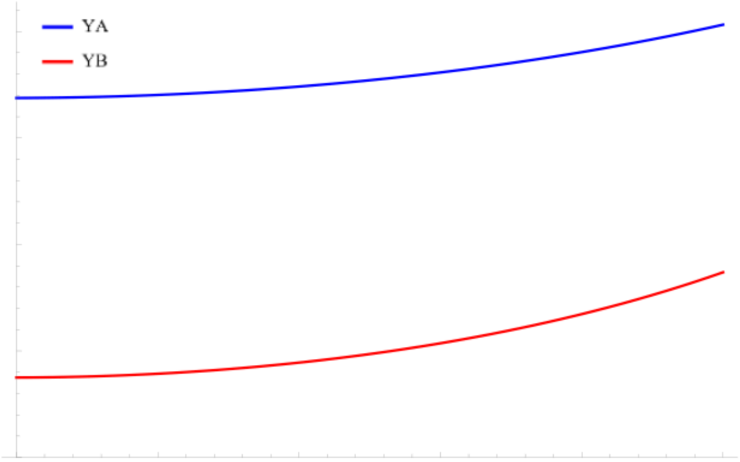

Figure 1. The impact of k on retail prices

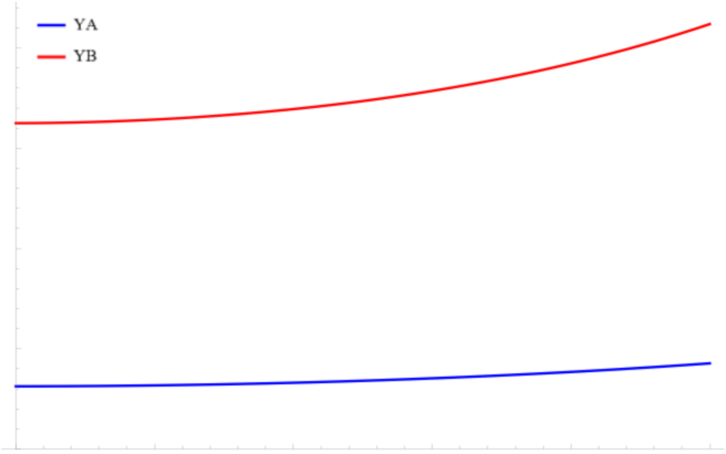

Figure 2. The impact of k on market demand

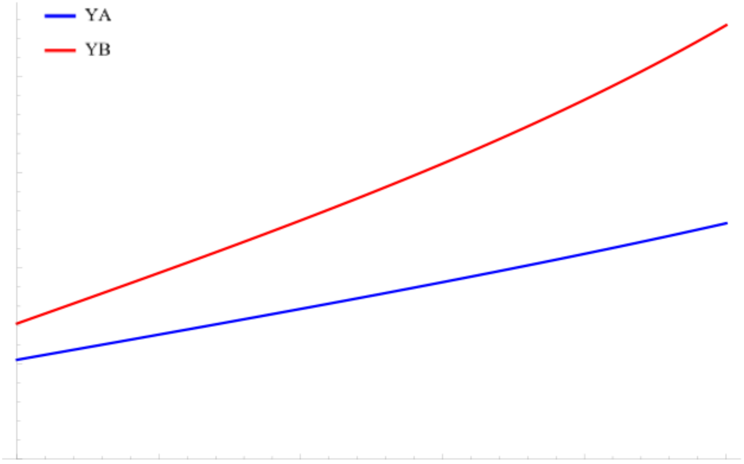

Figure 3. The impact of k on total recovery amount

From Figure 4 to Figure 5, it can be seen that in the NA and NB modes without the introduction of blockchain, $r = 0$. Therefore, the total system profit basically does not change with k ; while in the YA and YB modes with the introduction of blockchain, the optimal traceability level r increases monotonically with k , and the YB modes r is significantly higher than the YA mode. This indicates that when the marginal promoting effect of blockchain on demand strengthens, enterprises will increase traceability investment to amplify the market effect. In the YB cooperation recovery mode, suppliers and manufacturers can better coordinate the blockchain investment benefits and thus choose a higher optimal traceability level. Further, the total system profit Π_{SC} in the YA and YB modes increases significantly with k , $\Pi_{SC}^{YB} > \Pi_{SC}^{NB} > \Pi_{SC}^{YA} > \Pi_{SC}^{NA}$, and it shows that whether or not blockchain is introduced, the cooperation recovery mode can improve recovery efficiency and increase recovery profits. On this basis, the combination of blockchain and cooperation recovery can most effectively increase the total profit of the supply chain system.

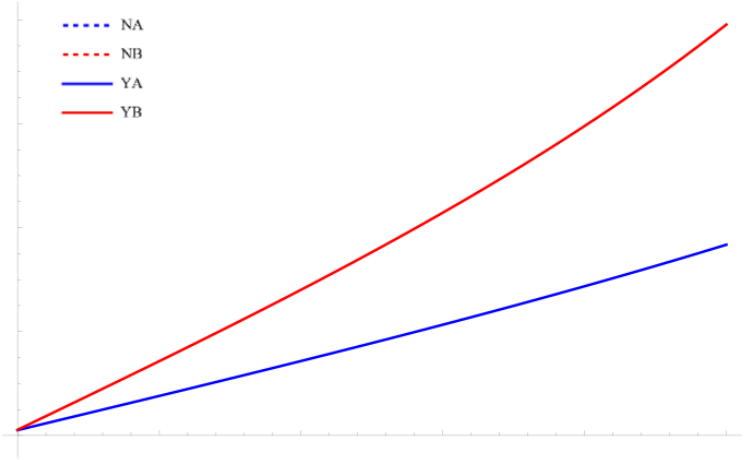

Figure 4. The impact of k on the level of traceability

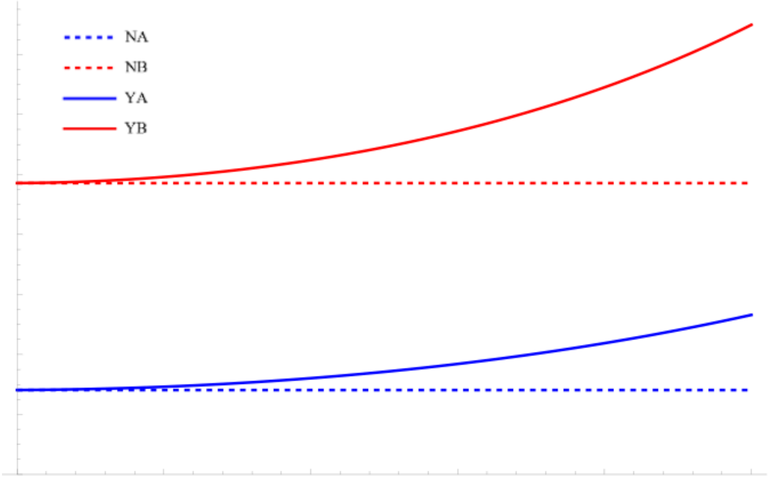

Figure 5. The impact of k on total profit

From Figure 6, it can be seen that in the NA and NB models without blockchain, the system profit is not related to k_b . On the contrary, in the YA and YB models with the introduction of blockchain, the two curves decrease significantly as k_b increases and gradually approach a stable state: when k_b is smaller, that is the cost of blockchain is lower, the total supply chain system will choose a higher traceability investment level, thereby bringing stronger demand and recovery gains, and the profit is significantly higher than the baseline without blockchain; but as k_b increases, the marginal cost of blockchain investment increases rapidly, the optimal traceability level is compressed, the marginal revenue brought by blockchain decreases, and thus the profits of YA and YB models gradually decrease and converge to their respective baseline NA and NB models without blockchain. Therefore, when the construction cost of blockchain is lower, it is advisable to prioritize the introduction of blockchain in the cooperative recovery model to obtain the maximum system profit; when the construction cost of blockchain is higher, the marginal revenue of blockchain is insufficient, the system profit will gradually deteriorate to the level of the traditional model, at this time, more attention should be paid to the recovery organization collaboration of suppliers and manufacturers or through technical subsidies or platform discounts to expand the feasible range of blockchain.

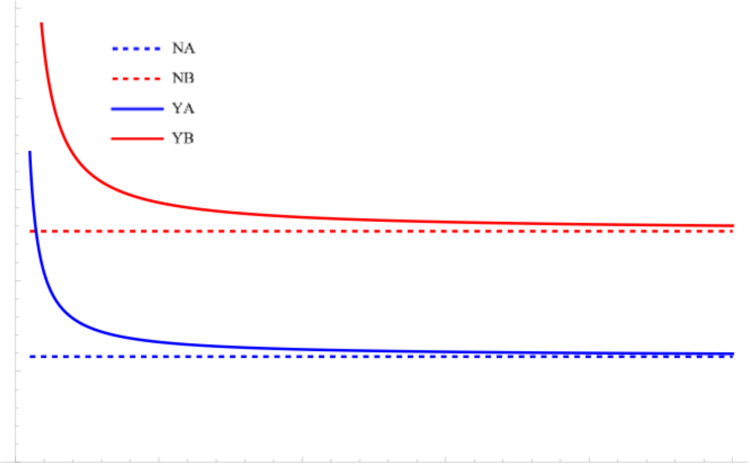

Figure 6. The impact of k_b on total profit

CONCLUSION

This paper develops a closed-loop supply chain model for retired power batteries, involving a supplier and a manufacturer who can both collect used batteries. The results offer a theoretical framework that is not only applicable to the automotive sector but also extendable to other industries dealing with integrated power units, such as the smart apparel and electronic textile sectors. Four scenarios are examined: separate recycling without blockchain (NA), cooperative recycling without blockchain (NB), separate recycling with blockchain (YA), and cooperative recycling with blockchain (YB). Using Stackelberg game and centralized decision-making, we derive equilibrium solutions and conduct comparative analysis and numerical experiments.

Main Contributions and Managerial Implications

The results show that cooperative recycling (NB, YB) effectively alleviates the negative impact of competition between the two collectors, reduces double marginalization in the forward channel, and improves overall supply chain profit. Blockchain adoption (YA, YB) increases market demand and total collection volume by enhancing information transparency and consumer trust, which further boosts profitability. The best performance is achieved when blockchain and cooperative recycling are combined (YB), because the synergy of centralized decisions and traceability technology maximizes both forward sales and reverse recovery.

Numerical analysis reveals that a stronger positive effect of blockchain on demand (higher k) increases the optimal traceability level, retail price, demand, collection quantity, and total profit. Conversely, a higher blockchain construction cost coefficient (higher k_b) reduces the incentive to invest in traceability, making the profits of YA and YB converge to those of NA and NB, respectively. Therefore, when blockchain costs are low, firms should prioritize implementing it under cooperative recycling to capture the greatest gains; when costs are high, improving coordination between collectors becomes more important.

These findings provide insights for battery suppliers and vehicle manufacturers in designing efficient recycling strategies and deciding whether to adopt blockchain technology. Policymakers may consider subsidizing blockchain infrastructure to lower adoption costs and promote sustainable closed-loop supply chains. For the textile industry, encouraging cross-sectoral collaboration between battery producers and functional textile brands will be crucial for the effective implementation of the Extended Producer Responsibility (EPR) system. Future research can extend the model by considering dynamic competition, asymmetric information, or the role of government regulations.

Limitations and Future Directions

This paper adopts a linear specification for the competition effect and the blockchain impact on recycling volume, which serves as a first-step approximation to maintain analytical tractability. However, in reality, the recycling supply chain may exhibit diminishing marginal returns or follow nonlinear patterns such as logarithmic or square-root forms. Moreover, competition between collectors is often influenced by spatial factors like geographic proximity and consumer loyalty, which call for a spatial differentiation framework. Future research could extend our model by incorporating nonlinear effort-recovery functions or spatial competition to capture these complexities. Another important extension lies in the endogenous determination of the blockchain access fee C_S . In our current setting, C_S is treated as an exogenous parameter; endogenizing it—for instance, through bargaining between supply chain members—would provide deeper insights into the feasibility and stability of blockchain adoption.

Author Contributions

Conceptualization – R. N.; methodology – J. W. and R. N.; model construction – J. W. and R. N.; model analysis – J. W. and R. N.; writing-original draft preparation – R. N.; writing-review and editing – Wang and R. N.; visualization – R. N.; supervision – J. W. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

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APPENDIX

Proof of Lemma 2.1

Firstly, by taking the second derivatives of p and e_M respectively, we obtain $\frac{\partial^2 \pi_M^{NA}}{\partial p^2} = -2\beta < 0$ and $\frac{\partial^2 \pi_M^{NA}}{\partial (e_M^{NA})^2} = -k_M < 0$. Therefore, π_M is a strictly concave function with respect to p and e_M and there exists a unique optimal solution for each. Let the first-order conditions $\frac{\partial \pi_M}{\partial p} = 0$ and $\frac{\partial \pi_M}{\partial e_M} = 0$ be given, we can obtain the pricing response function of the manufacturer and the effort recovery response function of the manufacturer: $p(w) = \frac{a}{2\beta} + \frac{w+c_n}{2}$. Then, substituting $p(w)$ and $e_M(t)$ into π_S^{NA} and solving, we obtain the optimal wholesale price $w^{NA*} = \frac{a+\beta(C-c_n)}{2\beta}$. Since $\frac{\partial^2 \pi_S}{\partial w^2} = -\beta < 0$, w^{A*} is the unique solution that makes the objective function optimal; the optimal transfer payment price $t^{NA*} = \frac{-Q_{M0}k_M k_S + c_M \eta^2 k_S + c_S \eta\theta(k_S - k_M) + v[\eta^2 k_S - k_M\theta^2 + \eta\theta(k_M - k_S)]}{2\eta^2 k_S - k_M \theta^2}$ and the optimal effort recovery level $e_S^{NA*} = \frac{-Q_{M0}k_M\theta + c_M\eta^2\theta + c_S\eta(\theta^2 - 2\eta^2) + v\eta(2\eta+\theta)(\eta-\theta)}{2\eta^2 k_S - k_M\theta^2}$ and $e_M^{NA*} = \frac{\eta(t^{NA*} - c_M)}{k_M}$. To determine whether is the optimal solution, we construct the Hessian matrix: $H_{(t,e_S^{NA})} = \begin{pmatrix} \frac{\partial^2 \tilde{\pi}_S^{NA}}{\partial t^2} & \frac{\partial^2 \tilde{\pi}_S^{NA}}{\partial t \partial e_S^{NA}} \\ \frac{\partial^2 \tilde{\pi}_S^{NA}}{\partial e_S^{NA} \partial t} & \frac{\partial^2 \tilde{\pi}_S^{NA}}{\partial (e_S^{NA})^2} \end{pmatrix} = \begin{pmatrix} -\frac{2\eta^2}{k_M} & \theta \\ \theta & -k_S \end{pmatrix}$,negative definite at $2\eta^2 k_S - k_M\theta^2 > 0$, Therefore, the solution obtained is the optimal solution.

Proof of Lemma 2.2

For ease of calculation, two marginal net benefit coefficients for recycling efforts are constructed: $T_S = (v - c_S)\eta - (v - c_M)\theta$, $T_M = (v - c_M)\eta - (v - c_S)\theta$. First, take the second derivative of p , $\frac{\partial^2 \Pi_{SC}^{NB}}{\partial p^2} = -2\beta < 0$, thus Π_{SC}^{NB} is a strictly concave function with respect to p . There exists a unique optimal solution. By applying the first-order condition $\frac{\partial \Pi_{SC}^{NB}}{\partial p} = 0$, the optimal retail price can be obtained as $p^{NB*} = \frac{a+\beta(C+c_n)}{2\beta}$. Then, take the second derivative of e_S^{NB} , $\frac{\partial^2 \Pi_{SC}^{NB}}{\partial (e_S^{NB})^2} = -k_S < 0$, so Π_{SC}^{NB} is a strictly concave function with respect to e_S^{NB} . By applying the first-order condition $\frac{\partial \Pi_{SC}^{NB}}{\partial e_S} = 0$, the optimal recovery effort level for the supplier can be obtained as $e_S^{NB*} = \frac{T_S}{k_S}$, and similarly, the optimal recovery effort level for the manufacturer can be obtained as $e_M^{NB*} = \frac{T_M}{k_M}$. Finally, substituting back, we can get the equilibrium strategy choices of all parties in the supply chain under the NB model.

Proof of Lemma 2.3

Firstly, by taking the second derivatives of p and e_M respectively, we can obtain $\frac{\partial^2 \pi_M^{YA}}{\partial p^2} = -2\beta < 0$ and $\frac{\partial^2 \pi_M^{YA}}{\partial (e_M^{YA})^2} = -k_M < 0$. Therefore, π_M is a strictly concave function with respect to p and e_M

and there exists a unique optimal solution for each of them. From the first-order conditions $\frac{\partial \pi_M}{\partial p} = 0$ and $\frac{\partial \pi_M}{\partial e_M} = 0$, we can obtain the manufacturers pricing response function $p(w) = \frac{a+kr}{2\beta} + \frac{w+c_n}{2}$ and the manufacturers effort recovery response function $e_M^{YA}(t) = \frac{\eta(t-c_M)}{k_M}$. Substituting $p(w)$ and $e_M^{YA}(t)$ into π_S^{YA}, we can obtain the optimal wholesale price $w^{YA*} = \frac{a+kr+\beta(C-c_n)}{2\beta}$. Since $\frac{\partial^2 \pi_S}{\partial w^2} = -\beta < 0$, w^{A*} is the unique solution that makes the objective function optimal; taking the first-order derivatives of t and e_S^{YA} and solving simultaneously, we can obtain the optimal transfer payment price $t^{YA*} = \frac{-Q_{M0}k_M k_s + c_M \eta^2 k_s + c_s \eta\theta(k_s - k_M) + v[\eta^2 k_s - k_M \theta^2 + \eta\theta(k_M - k_s)]}{2\eta^2 k_s - k_M \theta^2}$ and the optimal effort recovery level $e_S^{YA*} = \frac{-Q_{M0}k_M\theta + c_M\eta^2\theta + c_s\eta(\theta^2 - 2\eta^2) + v\eta(2\eta+\theta)(\eta-\theta)}{2\eta^2 k_s - k_M\theta^2}$ and $e_M^{YA*} = \frac{\eta(t^{YA*} - c_M)}{k_M}$ .Since $\frac{\partial^2 \pi_S}{\partial w^2} = -\beta < 0$, $\frac{\partial^2 \pi_S}{\partial (e_S^{YA})^2} = -k_s < 0$, therefore, the transfer payment price and the effort recovery level are both the unique optimal solutions. The Hessian matrix of the supply chain system is . $H_{(w, e_S^{YA}, e_M^{YA})} = \begin{pmatrix} -\beta & 0 & 0 \\ 0 & -k_s & 0 \\ 0 & 0 & -k_M \end{pmatrix}$ All the diagonal elements are negative and it is a diagonal matrix, thus it is negative definite, indicating that the overall profit function is strictly concave and the optimal solution is unique.

Proof of Lemma 2.4

To verify the uniqueness of the total profit equilibrium solution, a Hessian matrix is constructed: $H_{(p, e_s, e_M, r)} = \begin{pmatrix} -\beta & 0 & 0 & 0 \\ 0 & -k_s & 0 & 0 \\ 0 & 0 & -k_M & 0 \\ 0 & 0 & 0 & -k_b \end{pmatrix}$, All the diagonal elements are negative and it is a diagonal matrix, thus it is negative definite, indicating that the overall profit function is strictly concave and the optimal solution is unique.