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Collaborative Dynamic Optimization of New Energy Vehicle Power Battery Recycling and Reuse Strategies Driven by Blockchain

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ABSTRACT

Effective recycling and reuse of retired power batteries have become a critical issue for their sustainable development in the future. Currently, the market for retired power battery recycling is plagued by problems such as mixed recycling channels and lack of information transparency. Blockchain offers solutions for the full life-cycle management of power batteries. Thus, how to leverage blockchain to promote the efficient recycling and reuse of retired power batteries has emerged as a key issue. Considering two recycling channels and reuse modes empowered by blockchain, this paper establishes long-term dynamic decision-making models of the power battery closed-loop supply chain (PB-CLSC) using differential game, derives the feedback equilibrium strategies of all stakeholders. Furthermore, the impact of different recycling and reuse strategies with blockchain is thoroughly investigated, identifying the optimal recycling and reuse strategies.

KEYWORDS

Power Battery Closed-loop Supply Chain; Blockchain Technology; Reuse Mode; Recycling Channel; Differential Game.

1. INTRODUCTION

Currently, countries worldwide are actively fostering the growth of the new energy vehicle (NEV) industry. By 2030, developed countries are projected to have 145 million electric vehicles in operation, with over 12 million tons of power batteries reaching end-of-life. China is a prime example. Its traditional fuel vehicle fleet has hit 353 million, accounting for about 25% of the global total and contributing roughly 8% of China's carbon emissions. According to the "Annual Report on Environmental Management of Motor Vehicles in China (2024)", the average carbon emissions from traditional fuel vehicles are 3 to 5 times higher than those from new energy vehicles, clearly demonstrating the advantages of new energy vehicles in terms of energy conservation, emission reduction, and environmental protection.

Facing the impending battery retirement wave, establishing an efficient recycling system for retired power batteries is crucial for the sustainable development of the PB-CLSC. In recent years, China has introduced policies to promote a power battery recycling system. However, challenges persist: (1) Fragmented recycling channels: China's primary recycling channels, including manufacturer-led and third-party enterprise recycling, lack standardized processes and unified criteria, resulting in disorganization and inefficiency. (2) Inefficient recycling and utilization: retired power batteries contain high-voltage DC, posing combustion and explosion risks if mishandled. Extracting valuable metals like nickel, cobalt, and lithium involves complex processes and high barriers to entry. (3) Significant informal channel leakage: due to a lack of traceability, about 70% of retired batteries enter the gray market through unregulated "small workshops." These operators, with low compliance costs,

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offer higher purchase prices, crowding out legitimate enterprises and causing environmental pollution and safety hazards.

2. LITERATURE REVIEW

2.1. Power Battery Closed Loop Supply Chain

(1) Recycling channels

In recent years, the design of recycling channels has become a core issue in the research on PB-CLSC. Existing studies have mainly focused on single-channel, dual-channel, and mixed-channel models. Research shows that in terms of increasing the recycling volume of retired power batteries and the overall profit of the supply chain, the mixed recycling channel is superior to the single channel, but this is on the premise that the conflicts of interest among the various entities in the supply chain can be effectively coordinated. The manufacturer-led recycling model is optimal in the single-channel recycling mode, while in the mixed-channel model, the decisions of each entity are significantly influenced by the competition coefficient[1], [2]. Additionally, the recycling strategy based on echelon use model can enhance resource utilization, but it requires the recycler to have a high level of technological maturity and a cost-sharing mechanism [3], [4].

(2) Reuse modes

After the recycling of power batteries, there are two utilization modes, which can be divided into the echelon use mode and the regeneration use mode according to the difference in remaining battery capacity. The echelon use mode is generally applicable to power batteries with a remaining capacity of 60%-80%, while power batteries with a remaining capacity of less than 60% will be disassembled to extract raw materials such as cobalt for remanufacturing [5], [6]. Technological innovation has a two-way impact on the economic and environmental benefits of PB-CLSC. Chu et al. found in their research that investment in emission reduction technologies requires policy support in the early stage, but shifts to relying on market mechanisms in the later stage [7]. Although the echelon use mechanism of power batteries reduces carbon emissions throughout the whole life cycle of power batteries, its economy is restricted by factors such as patent authorization and carbon price fluctuations [8]. Therefore, to achieve the comprehensive optimization of PB-CLSC in the three dimensions of economy, environment, and society, multi-objective optimization models have been applied to the network design and operation strategies of PB-CLSC. For example, Çakır and Serdarasan [9] used a facility location model based on Markov chains in their research to realize the dual collaborative optimization of social benefits and environmental benefits. It is worth mentioning that in PB-CLSC, dynamic quality tracking technology and blockchain technology can improve the transparency of reverse logistics [10], [11].

2.2. Application of Blockchain Technology

(1) Application of blockchain technology in CLSC

In the research field of the integration of closed-loop supply chain and blockchain technology, existing literature mainly focuses on core issues such as technology empowerment and recycling strategies. Ma and Hu [12] focused on the closed-loop supply chain and mainly studied the issue of used product recycling empowered by blockchain technology, conducting an analysis through differential games and discovering three major effects of blockchain: brand premium effect, forward and backward attraction effect, and optimal combination effect. Wang et al. (2022) [13] emphasized the traceability role of blockchain technology in the operation of e-commerce platforms, finding that the introduction of blockchain technology can offset the double marginalization effect. Sarabi et al. [14] discussed the objective existence of consumers' distrust of pricing and "greenwashing" behavior, and found that blockchain technology can ensure the transparency and sustainability of CLSC.

(2) Application of blockchain technology in PB-CLSC

With the rapid advancement of the electric vehicle industry, the PB-CLSC has become an increasingly prominent area of academic research. The emergence of blockchain technology has introduced innovative approaches to optimizing and managing the recycling of retired power batteries. Zhang et al. [15] proposed a blockchain-based recycling platform for power batteries, which comprises four layers: the perception layer, blockchain layer, application layer, and user layer. Their analysis and validation demonstrate that the dual-chain architecture offers significant advantages in reducing transaction delays and improving system efficiency. Umar et al. [16] examined the application of blockchain technology in decentralized energy trading within community microgrids, emphasizing its role in enabling efficient and transparent peer-to-peer energy transactions at the consumer end.

3. PROBLEM DESCRIPTION AND MODEL ASSUMPTIONS

3.1. Problem Description

For the PB-CLSC, choosing different recycling channels and reuse modes has a significant impact on the interests of each entity. This study builds PB-CLSC under the manufacturer recycling scenario composed of power battery manufacturers (M) and power battery retailers (R), and under the third-party recycling scenario composed of power battery manufacturers (M), power battery retailers (R), and third-party recyclers (T) through differential games, comprehensively considers the impact of blockchain empowerment, and through mathematical derivation and case simulation analysis, explores the optimal feedback equilibrium strategies of each subject in four scenarios (MEB, MRB, TEB, TRB) to investigate the optimal combination strategies of the two different recycling channels (manufacturer recycling or third-party recycler recycling) and the two different utilization modes (echelon utilization or regeneration utilization) under blockchain empowerment.

3.2. Model Assumptions

To make the model establishment more reasonable, the following assumptions are made in this paper:

Assumption 1: The demand for power batteries is primarily influenced by the reputation of power battery manufacturers and the selling price of the batteries. Drawing on existing research regarding the formulation of power battery demand functions, this study establishes the following demand function:

$$D(t) = \alpha\sqrt{G(t)} - \beta p(t) \tag{1}$$

Assumption 2: The demand for recycling retired power batteries is primarily influenced by the recycling price and the battery lifespan. The recycling price is positively correlated with consumers' willingness to return used power batteries, whereas the battery lifespan is negatively correlated with such willingness. This paper formulates the following demand function for the recycling of retired power batteries:

$$D_r(t) = \eta r(t) - \lambda\sqrt{S(t)} \tag{2}$$

Assumption 3: Battery power commercial reputation serves as a key driver in stimulating demand within the forward supply chain market. It is typically modeled as a weighted average of big data marketing inputs and manufacturers' innovation efforts, and exhibits exponential decay over time [17]. Drawing on prior studies with similar frameworks [18], this paper represents battery power commercial reputation using the following linear differential equation:

$$\dot{G(t)} = \varepsilon_I I(t) + \varepsilon_L L(t) - \chi G(t) \tag{3}$$

Assumption 4: The lifespan of power batteries is influenced by two key factors. First, it is determined by the level of manufacturers' innovation efforts—higher innovation input leads to longer battery lifespan. Second, it is also shaped by the extent of manufacturers' investment in blockchain technology, as blockchain enables real-time data tracking and traceability, thereby enhancing the authenticity and reliability of battery lifespan information. Considering the realistic characteristic that battery lifespan continuously degrades over time, this paper models it using the following linear differential equation:

$$\dot{S}(t) = \gamma_I I(t) + \gamma_L L(t) - \delta S(t) \tag{4}$$

Assumption 5: There are primarily two channels for the recycling of power batteries: manufacturer-led recycling and third-party recycler-based recycling. This paper assumes that when the reverse supply chain for power batteries adopts the third-party recycling mode, the manufacturer pays a fixed proportion (Ω) of commission to the third-party recycler, with both parties sharing the resulting profits.

4. MODEL CONSTRUCTION AND SOLUTION

4.1. Manufacturer Recycling and Echelon Utilization Enabled by Blockchain (MEB)

Under the MEB scenario, the manufacturer is responsible for both the production and recycling of power batteries. After recycling, the manufacturer conducts echelon utilization of retired power batteries, while the retailer is solely responsible for the sales of power batteries. The decision-making sequence in this scenario is as follows: first, the manufacturer determines the wholesale price of power batteries $w(t)$, the recycling price $r(t)$, the technological innovation level $I(t)$, and the blockchain level $L(t)$, subsequently, the retailer sets the retail price $p(t)$.

Therefore, the differential game model can be expressed as follows:

$$\begin{aligned}
&\max_{w(t),r(t),I(t),L(t)} \Pi_M^{MEB} = \int_0^\infty e^{-\rho t}\left\{w(t)D(t) + \left[p_e(t) - r(t)\right]D_r(t) - \frac{1}{2}k_I I^2(t) - \frac{1}{2}k_L L^2(t)\right\}dt \\
&s.t.\begin{cases}
\max\limits_{p(t)} \Pi_R^{MEB} = \int_0^\infty e^{-\rho t}\left\{\left[p(t) - w(t)\right]D(t)\right\}dt \\
\dot{S}(t) = \gamma_I I(t) + \gamma_L L(t) - \delta S(t) \\
\dot{G}(t) = \varepsilon_I I(t) + \varepsilon_L L(t) - \chi G(t)
\end{cases}
\end{aligned} \tag{5}$$

where $D(t) = \alpha\sqrt{G(t)} - \beta p(t)$, $D_r(t) = \eta r(t) - \lambda\sqrt{S(t)}$, $p_e(t) = \nu\sqrt{S(t)}$.

Lemma 1. (1) Under the MEB scenario, the optimal wholesale price, retail price, recycling price, technological innovation level and blockchain level are as follows:

$$w^{MEB} = \frac{\alpha\sqrt{\mathrm{G}^{MEB}}}{2\beta},\ p^{MEB} = \frac{3\alpha\sqrt{\mathrm{G}^{MEB}}}{4\beta},\ r^{MEB} = \frac{(\nu\eta + \lambda)\sqrt{\mathrm{S}^{MEB}}}{2\eta},\ \mathrm{I}^{MEB} = \frac{A\varepsilon_I + B\gamma_I}{k_I},\ L^{MEB} = \frac{A\varepsilon_L + B\gamma_L}{k_L},$$

where $A = \dfrac{\alpha^2}{8\beta(\chi + \rho)}$, $B = \dfrac{(\nu\eta - \lambda)^2}{4\eta(\delta + \rho)}$.

(2) The dynamic evolution trajectory of the power battery lifespan over time is as follows:

$$S^{MEB}(t) = \left(S_0 - S_\infty^{MEB}\right)e^{-\delta t} + S_\infty^{MEB},$$

when $t \to \infty$, $S_{\infty}^{MEB} = \frac{1}{\delta}\left[\frac{\alpha^2\left(k_I\varepsilon_L\gamma_L + k_L\varepsilon_I\gamma_I\right)}{8\beta k_I k_L(\chi+\rho)} + \frac{\left(k_I\gamma_L{}^2 + k_L\gamma_I{}^2\right)(\eta\nu-\lambda)^2}{4\eta k_I k_L(\delta+\rho)}\right]$ is steady-state value.

(3) The dynamic evolution trajectory of the goodwill for power battery enterprises over time is as follows:

$$G^{MEB}(t) = \left(G_0 - G_{\infty}^{MEB}\right)e^{-\chi t} + G_{\infty}^{MEB},$$

when $t \to \infty$, $G_{\infty}^{MEB} = \frac{1}{\chi}\left[\frac{\alpha^2\left(k_I\varepsilon_L{}^2 + k_L\varepsilon_I{}^2\right)}{8\beta k_I k_L(\chi+\rho)} + \frac{\left(k_I\gamma_L\varepsilon_L + k_L\gamma_I\varepsilon_I\right)(\eta\nu-\lambda)^2}{4\eta k_I k_L(\delta+\rho)}\right]$ is the steady-state value.

(4) The dynamic evolution trajectory of the selling price over time after recycling is as follows:

$$p_e^{MEB}(t) = \left(p_{e0} - p_{e\infty}^{MEB}\right)e^{-\delta t} + p_{e\infty}^{MEB}, \quad p_{e0} = \nu\sqrt{S_0},$$

when $t \to \infty$, $p_{e\infty}^{MEB} = \nu\sqrt{\frac{1}{\delta}\left[\frac{\alpha^2\left(k_I\varepsilon_L\gamma_L + k_L\varepsilon_I\gamma_I\right)}{8\beta k_I k_L(\chi+\rho)} + \frac{\left(k_I\gamma_L{}^2 + k_L\gamma_I{}^2\right)(\eta\nu-\lambda)^2}{4\eta k_I k_L(\delta+\rho)}\right]}$ is the steady-state value.

(5) The dynamic evolution trajectory of the profits of manufacturers and retailers over time are as follows:

$$V_M^{MEB}(t) = a\left(G_0 - G_{\infty}^{MEB}\right)e^{-\chi t} + b\left(S_0 - S_{\infty}^{MEB}\right)e^{-\delta t} + V_{M\infty}^{MEB},$$

$$V_R^{MEB}(t) = c\left(G_0 - G_{\infty}^{MEB}\right)e^{-\chi t} + V_{R\infty}^{MEB},$$

when $t \to \infty$, their steady-state profits are as follows:

$$V_{M\infty}^{MEB} = \frac{\alpha^2}{8\beta(\chi+\rho)}G_{\infty}^{MEB} + \frac{(\nu\eta-\lambda)^2}{4\eta(\delta+\rho)}S_{\infty}^{MEB} + \frac{1}{2k_I\rho}\left[\frac{\alpha^2\varepsilon_I}{8\beta(\chi+\rho)} + \frac{(\nu\eta-\lambda)^2\gamma_I}{4\eta(\delta+\rho)}\right]^2,$$
$$+\frac{1}{2k_L\rho}\left[\frac{\alpha^2\varepsilon_L}{8\beta(\chi+\rho)} + \frac{(\nu\eta-\lambda)^2\gamma_L}{4\eta(\delta+\rho)}\right]^2$$

$$V_{R\infty}^{MEB} = \frac{\alpha^2}{16\beta(\chi+\rho)}G_{\infty}^{MEB} + \frac{\alpha^2\left[2\beta(\chi+\rho)\left(k_L\gamma_I\varepsilon_I + k_I\lambda_L\varepsilon_L\right)(\nu\eta-\lambda)^2 + \eta\alpha^2(\delta+\rho)\left(k_L\varepsilon_I^2 + k_I\varepsilon_L^2\right)\right]}{128\eta k_L k_I\rho\beta^2(\delta+\rho)(\chi+\rho)^2}.$$

4.2. Manufacturer Recycling and Regeneration Utilization Enabled by Blockchain (MRB)

Under the MRB scenario, the manufacturer is responsible for the production and recycling of power batteries. After recycling, the retired power batteries are regenerated through disassembly and material recovery processes. The retailer is solely responsible for the sales of power batteries. The decision-making sequence in this scenario is as follows: first, the manufacturer determines the wholesale price $w(t)$, the recycling price $r(t)$, the technological innovation level $I(t)$, and the blockchain level $L(t)$, subsequently, the retailer sets the retail price $p(t)$.

Therefore, the differential game model can be expressed as follows:

$$\max_{w(t),r(t),I(t),L(t)} \Pi_M^{MRB} = \int_0^{\infty} e^{-\rho t}\left\{w(t)D(t) + \left[\Delta\tau(t) - \mu\sqrt{S(t)} - r(t)\right]D_r(t) - \frac{1}{2}k_I I^2(t) - \frac{1}{2}k_L L^2(t)\right\}dt$$
$$s.t.\begin{cases}\max\limits_{p(t)} \Pi_R^{MRB} = \int_0^{\infty} e^{-\rho t}\left\{\left[p(t) - w(t)\right]D(t)\right\}dt \\ \dot{S}(t) = \gamma_I I(t) + \gamma_L L(t) - \delta S(t) \\ \dot{G}(t) = \varepsilon_I I(t) + \varepsilon_L L(t) - \chi G(t)\end{cases} \tag{6}$$

where $D(t)=\alpha\sqrt{G(t)}-\beta p(t)$, $D_r(t)=\eta r(t)-\lambda\sqrt{S(t)}$, $\Delta=c_m-c_r$, $\tau(t)=\xi\sqrt{S(t)}$.

Lemma 2. (1) Under the MRB scenario, the optimal wholesale price, retail price, recycling price, the technological innovation level and blockchain level are as follows:

$$w^{MRB}=\frac{\alpha\sqrt{\mathrm{G}^{MRB}}}{2\beta},\ p^{MRB}=\frac{3\alpha\sqrt{\mathrm{G}^{MRB}}}{4\beta},\ r^{MRB}=\frac{(\theta\eta+\lambda)\sqrt{\mathrm{S}^{MRB}}}{2\eta},\ \mathrm{I}^{MRB}=\frac{E\varepsilon_I+F\gamma_I}{k_I},\ L^{MRB}=\frac{E\varepsilon_L+F\gamma_L}{k_L},$$

where $E=\frac{\alpha^2}{8\beta(\chi+\rho)}$, $F=\frac{(\eta\theta-\lambda)^2}{4\eta(\delta+\rho)}$, $\theta=\Delta\xi-\mu$.

(2) The dynamic evolution trajectory of the power battery lifespan over time is as follows:

$$S^{MRB}(t)=\left(S_0-S_\infty^{MRB}\right)e^{-\delta t}+S_\infty^{MRB},$$

when $t\to\infty$, $S_\infty^{MRB}=\frac{1}{\delta}\left[\frac{\alpha^2\left(k_I\varepsilon_L\gamma_L+k_L\varepsilon_I\gamma_I\right)}{8\beta k_I k_L(\chi+\rho)}+\frac{\left(k_I\gamma_L{}^2+k_L\gamma_I{}^2\right)(\lambda-\eta\theta)^2}{4\eta k_I k_L(\delta+\rho)}\right]$ is the steady-state value.

(3) The dynamic evolution trajectory of the goodwill for power battery enterprises over time is as follows:

$$G^{MRB}(t)=e^{-\chi t}\left(G_0-G_\infty^{MRB}\right)+G_\infty^{MRB},$$

when $t\to\infty$, $G_\infty^{MRB}=\frac{1}{\chi}\left[\frac{\alpha^2\left(k_I\varepsilon_L{}^2+k_L\varepsilon_I{}^2\right)}{8\beta k_I k_L(\chi+\rho)}+\frac{(k_I\gamma_L\varepsilon_L+k_L\gamma_I\varepsilon_I)(\lambda-\eta\theta)^2}{4k_I k_L\eta(\delta+\rho)}\right]$ is the steady-state value.

(4) The dynamic evolution trajectory of the remanufacturing rate over time is as follows:

$$\tau^{MRB}(t)=\left(\tau_0-\tau_\infty^{MRB}\right)e^{-\delta t}+\tau_\infty^{MRB},\quad \tau_0=\xi\sqrt{S_0},$$

when $t\to\infty$, $\tau_\infty^{MRB}=\xi\sqrt{\frac{1}{\delta}\left[\frac{\alpha^2\left(k_I\varepsilon_L\gamma_L+k_L\varepsilon_I\gamma_I\right)}{8\beta k_I k_L(\chi+\rho)}+\frac{\left(k_I\gamma_L{}^2+k_L\gamma_I{}^2\right)(\lambda-\eta\theta)^2}{4\eta k_I k_L(\delta+\rho)}\right]}$ is the steady-state value.

(5) The dynamic evolution trajectory of the profits of manufacturers and retailers over time are as follows:

$$V_M^{MRB}(t)=d\left(G_0-G_\infty^{MRB}\right)e^{-\chi t}+f\left(S_0-S_\infty^{MRB}\right)e^{-\delta t}+V_{M\infty}^{MRB},$$

$$V_R^{MRB}(t)=g\left(G_0-G_\infty^{MRB}\right)e^{-\chi t}+V_{R\infty}^{MRB},$$

when $t\to\infty$, their steady-state profits are as follows:

$$V_{M\infty}^{MRB}=\frac{\alpha^2}{8\beta(\chi+\rho)}G_\infty^{MRB}+\frac{(\lambda-\eta\theta)^2}{4\eta(\delta+\rho)}S_\infty^{MRB}+\frac{1}{2k_I\rho}\left[\frac{\alpha^2\varepsilon_I}{8\beta(\chi+\rho)}+\frac{(\lambda-\eta\theta)^2\gamma_I}{4\eta(\delta+\rho)}\right]^2,$$
$$+\frac{1}{2k_L\rho}\left[\frac{\alpha^2\varepsilon_L}{8\beta(\chi+\rho)}+\frac{(\lambda-\eta\theta)^2\gamma_L}{4\eta(\delta+\rho)}\right]^2$$

$$V_{R\infty}^{MRB}=\frac{\alpha^2}{16\beta(\chi+\rho)}G_\infty^{MRB}+\frac{\alpha^2\left[2\beta(\chi+\rho)(k_L\gamma_I\varepsilon_I+k_I\gamma_L\varepsilon_L)(\lambda-\eta\theta)^2+\eta\alpha^2(\delta+\rho)\left(k_L\varepsilon_I^2+k_I\varepsilon_L^2\right)\right]}{128\eta k_L k_I\rho\beta^2(\delta+\rho)(\chi+\rho)^2}.$$

4.3. Third-party Recycling and Echelon Utilization Enabled by Blockchain (TEB)

Under the TEB scenario, the manufacturer is responsible for the production of power batteries, the retailer handles the sales of power batteries, and the third-party recycler is primarily responsible for

recycling retired power batteries. After recycling, the manufacturer sells the recovered power batteries into the echelon utilization market and pays the third-party recycler a commission based on a predetermined proportion Ω of the revenue generated from echelon utilization. The decision-making sequence in this scenario is as follows: first, the manufacturer determines the wholesale price $w(t)$, the technological innovation level $I(t)$, and the blockchain level $L(t)$, subsequently, the retailer sets the retail price $p(t)$, while the third-party recycler sets the recycling price $r(t)$.

Therefore, the differential game model can be expressed as follows:

$$\max_{w(t),I(t),L(t)} \Pi_M^{TEB} = \int_0^\infty e^{-\rho t}\left\{w(t)D(t)+(1-\Omega)\left[p_e(t)-r(t)\right]D_r(t)-\frac{1}{2}k_I I^2(t)-\frac{1}{2}k_L L^2(t)\right\}dt$$

$$s.t.\begin{cases}\max\limits_{p(t)} \Pi_R^{TEB} = \int_0^\infty e^{-\rho t}\left\{\left[p(t)-w(t)\right]D(t)\right\}dt \\ \max\limits_{r(t)} \Pi_T^{TEB} = \int_0^\infty e^{-\rho t}\left\{\Omega\left[p_e(t)-r(t)\right]D_r(t)\right\}dt \\ \dot{S}(t)=\gamma_I I(t)+\gamma_L L(t)-\delta S(t) \\ \dot{G}(t)=\varepsilon_I I(t)+\varepsilon_L L(t)-\chi G(t)\end{cases} \tag{7}$$

where $D(t)=\alpha\sqrt{G(t)}-\beta p(t)$, $D_r(t)=\eta r(t)-\lambda\sqrt{S(t)}$, $p_e(t)=\nu\sqrt{S(t)}$.

Lemma 3. (1) Under the TEB scenario, the optimal wholesale price, retail price, recycling price, the technological innovation level and the blockchain level are as follows:

$$w^{TEB}=\frac{\alpha\sqrt{\mathrm{G}^{TEB}}}{2\beta},\ p^{TEB}=\frac{3\alpha\sqrt{\mathrm{G}^{TEB}}}{4\beta},\ r^{TEB}=\frac{(\nu\eta+\lambda)\sqrt{\mathrm{S}^{TEB}}}{2\eta},\ \mathrm{I}^{TEB}=\frac{C\varepsilon_I+D\gamma_I}{k_I},\ L^{TEB}=\frac{C\varepsilon_L+D\gamma_L}{k_L},$$

where $C=\dfrac{\alpha^2}{8\beta(\chi+\rho)}$, $D=\dfrac{(1-\Omega)(\eta\nu-\lambda)^2}{4\eta(\delta+\rho)}$.

(2) The dynamic evolution trajectory of the power battery lifespan over time is as follows:

$$S^{TEB}(t)=\left(S_0-S_\infty^{TEB}\right)e^{-\delta t}+S_\infty^{TEB},$$

when $t\to\infty$, $S_\infty^{TEB}=\dfrac{1}{\delta}\left[\dfrac{\alpha^2\left(k_L\varepsilon_I\gamma_I+k_I\varepsilon_L\gamma_L\right)}{8\beta k_L k_I(\chi+\rho)}+\dfrac{(1-\Omega)\left(k_L\gamma_I{}^2+k_I\gamma_L{}^2\right)(\eta\nu-\lambda)^2}{4\eta k_L k_I(\delta+\rho)}\right]$ is the steady-state value.

(3) The dynamic evolution trajectory of the goodwill for power battery enterprises over time is as follows:

$$G^{TEB}(t)=\left(G_0-G_\infty^{TEB}\right)e^{-\chi t}+G_\infty^{TEB},$$

when $t\to\infty$, $G_\infty^{TEB}=\dfrac{1}{\chi}\left[\dfrac{\alpha^2\left(k_I\varepsilon_L{}^2+k_L\varepsilon_I{}^2\right)}{8\beta k_I k_L(\chi+\rho)}+\dfrac{(1-\Omega)\left(k_I\gamma_L\varepsilon_L+k_L\gamma_I\varepsilon_I\right)(\eta\nu-\lambda)^2}{4\eta k_I k_L(\delta+\rho)}\right]$ is the steady-state value.

(4) The dynamic evolution trajectory of the selling price after recycling over time is as follows:

$$p_e^{TEB}(t)=\left(p_{e0}-p_{e\infty}^{TEB}\right)e^{-\delta t}+p_{e\infty}^{TEB},\ p_{e0}=\nu\sqrt{S_0},$$

when $t\to\infty$, $p_{e\infty}^{TEB}=\nu\sqrt{\dfrac{1}{\delta}\left[\dfrac{\alpha^2\left(k_L\varepsilon_I\gamma_I+k_I\varepsilon_L\gamma_L\right)}{8\beta k_L k_I(\chi+\rho)}+\dfrac{(1-\Omega)\left(k_L\gamma_I{}^2+k_I\gamma_L{}^2\right)(\eta\nu-\lambda)^2}{4\eta k_L k_I(\delta+\rho)}\right]}$ is the steady-state value.

(5) The dynamic evolution trajectory of the profits of manufacturers, retailers, and third-party recyclers are as follows:

$$V_M^{TEB}(t)=h\left(G_0-G_\infty^{TEB}\right)e^{-\chi t}+j\left(S_0-S_\infty^{TEB}\right)e^{-\delta t}+V_{M\infty}^{TEB},$$

$$V_R^{TEB}(t)=k\left(G_0-G_\infty^{TEB}\right)e^{-\chi t}+V_{R\infty}^{TEB},$$

$$V_T^{TEB}(t)=l\left(S_0-S_\infty^{TEB}\right)e^{-\delta t}+V_{T\infty}^{TEB},$$

when $t\to\infty$, their steady-state profits are as follows:

$$V_{M\infty}^{TEB}=\frac{\alpha^2}{8\beta(\chi+\rho)}G_\infty^{TEB}+\frac{(1-\Omega)(\nu\eta-\lambda)^2}{4\eta(\delta+\rho)}S_\infty^{TEB}+\frac{1}{2k_I\rho}\left[\frac{\alpha^2\varepsilon_I}{8\beta(\chi+\rho)}+\frac{\gamma_I(1-\Omega)(\nu\eta-\lambda)^2}{4\eta(\delta+\rho)}\right]^2,$$
$$+\frac{1}{2k_L\rho}\left[\frac{\alpha^2\varepsilon_L}{8\beta(\chi+\rho)}+\frac{\gamma_L(1-\Omega)(\nu\eta-\lambda)^2}{4\eta(\delta+\rho)}\right]^2$$

$$V_{R\infty}^{TEB}=\frac{\alpha^2}{16\beta(\chi+\rho)}G_\infty^{TEB}+\frac{\alpha^2\left[2\beta(1-\Omega)(\chi+\rho)\left(k_L\gamma_I\varepsilon_I+k_I\lambda_L\varepsilon_L\right)(\nu\eta-\lambda)^2+\eta\alpha^2(\delta+\rho)\left(k_L\varepsilon_I^2+k_I\varepsilon_L^2\right)\right]}{128\eta k_Lk_I\rho\beta^2(\delta+\rho)(\chi+\rho)^2},$$

$$V_{T\infty}^{TEB}=\frac{\Omega(\eta\nu-\lambda)^2}{4\eta(\delta+\rho)}\left[S_\infty^{TEB}+\frac{\alpha^2\left(k_L\varepsilon_I\gamma_I+k_I\varepsilon_L\gamma_L\right)}{8\beta\rho k_Lk_I(\chi+\rho)}+\frac{(1-\Omega)\left(k_L{\gamma_I}^2+k_I{\gamma_L}^2\right)(\eta\nu-\lambda)^2}{4\eta\rho k_Lk_I(\delta+\rho)}\right].$$

4.4. Third-party Recycling and Regeneration Utilization Enabled by Blockchain (TRB)

Under the TRB scenario, the manufacturer is responsible for the production of power batteries, the retailer handles the sales of power batteries, and the third-party recycler is responsible for recycling retired power batteries. The collected power batteries are regenerated and reused by the manufacturer. The decision-making sequence in this scenario is as follows: first, the manufacturer determines the wholesale price $w(t)$, the technological innovation level $I(t)$, and the blockchain level $L(t)$, subsequently, the retailer sets the retail price $p(t)$, while the third-party recycler sets the recycling price $r(t)$.

Therefore, the differential game model can be expressed as follows:

$$\max_{w(t),I(t),L(t)}\Pi_M^{TRB}=\int_0^\infty e^{-\rho t}\left\{w(t)D(t)+(1-\Omega)\left[\Delta\tau(t)-\mu\sqrt{S(t)}-r(t)\right]D_r(t)-\frac{1}{2}k_II^2(t)-\frac{1}{2}k_LL^2(t)\right\}dt$$
$$s.t.\begin{cases}\max\limits_{p(t)}\Pi_R^{TRB}=\int_0^\infty e^{-\rho t}\left\{\left[p(t)-w(t)\right]D(t)\right\}dt\\ \max\limits_{r(t)}\Pi_T^{TRB}=\int_0^\infty e^{-\rho t}\left\{\Omega\left[\Delta\tau(t)-\mu\sqrt{S(t)}-r(t)\right]D_r(t)\right\}dt\\ \dot{S}(t)=\gamma_II(t)+\gamma_LL(t)-\delta S(t)\\ \dot{G}(t)=\varepsilon_II(t)+\varepsilon_LL(t)-\chi G(t)\end{cases}\tag{8}$$

where $D(t)=\alpha\sqrt{G(t)}-\beta p(t)$, $D_r(t)=\eta r(t)-\lambda\sqrt{S(t)}$, $\Delta=c_m-c_r$, $\tau(t)=\xi\sqrt{S(t)}$.

Lemma 4. (1) Under the TRB scenario, the optimal wholesale price, retail price, recycling price, the technological innovation level and the blockchain level are as follows:

$$w^{TRB}=\frac{\alpha\sqrt{\mathrm{G}^{TRB}}}{2\beta},\ p^{TRB}=\frac{3\alpha\sqrt{\mathrm{G}^{TRB}}}{4\beta},\ r^{TRB}=\frac{(\theta\eta+\lambda)\sqrt{\mathrm{S}^{TRB}}}{2\eta},\ \mathrm{I}^{TRB}=\frac{H\varepsilon_I+J\gamma_I}{k_I},\ L^{TRB}=\frac{H\varepsilon_L+J\gamma_L}{k_L},$$

where $H=\frac{\alpha^2}{8\beta(\chi+\rho)}$, $J=\frac{(1-\Omega)(\theta\eta-\lambda)^2}{4\eta(\delta+\rho)}$, $\theta=\Delta\xi-\mu$.

(2) The dynamic evolution trajectory of the power battery lifespan over time is as follows:

$$S^{TRB}(t)=\left(S_0-S_\infty^{TRB}\right)e^{-\delta t}+S_\infty^{TRB},$$

when $t\to\infty$, $S_\infty^{TRB}=\frac{1}{\delta}\left[\frac{\alpha^2\left(k_L\varepsilon_I\gamma_I+k_I\varepsilon_L\gamma_L\right)}{8\beta k_L k_I(\chi+\rho)}+\frac{(1-\Omega)\left(k_L{\gamma_I}^2+k_I{\gamma_L}^2\right)(\theta\eta-\lambda)^2}{4\eta k_L k_I(\delta+\rho)}\right]$ is the steady-state value.

(3) The dynamic evolution trajectory of the goodwill for power battery enterprises over time is as follows:

$$G^{TRB}(t)=\left(G_0-G_\infty^{TRB}\right)e^{-\chi t}+G_\infty^{TRB},$$

when $t\to\infty$, $G_\infty^{TRB}=\frac{1}{\chi}\left[\frac{\alpha^2\left(k_I{\varepsilon_L}^2+k_L{\varepsilon_I}^2\right)}{8\beta k_I k_L(\chi+\rho)}+\frac{(1-\Omega)(k_I\gamma_L\varepsilon_L+k_L\gamma_I\varepsilon_I)(\theta\eta-\lambda)^2}{4\eta k_I k_L(\delta+\rho)}\right]$ is the steady-state value.

(4) The dynamic evolution trajectory of the remanufacturing rate over time is as follows:

$$\tau^{TRB}(t)=\left(\tau_0-\tau_\infty^{TRB}\right)e^{-\delta t}+\tau_\infty^{TRB},\quad \tau_0=\xi\sqrt{S_0},$$

when $t\to\infty$, $\tau_\infty^{TRB}=\xi\sqrt{\frac{1}{\delta}\left[\frac{\alpha^2\left(k_L\varepsilon_I\gamma_I+k_I\varepsilon_L\gamma_L\right)}{8\beta k_L k_I(\chi+\rho)}+\frac{(1-\Omega)\left(k_L{\gamma_I}^2+k_I{\gamma_L}^2\right)(\theta\eta-\lambda)^2}{4\eta k_L k_I(\delta+\rho)}\right]}$ is the steady-state value.

(5) The dynamic evolution trajectory of the profits of manufacturers, retailers, and third-party recyclers over time are as follows:

$$V_M^{TRB}(t)=m\left(G_0-G_\infty^{TRB}\right)e^{-\chi t}+n\left(S_0-S_\infty^{TRB}\right)e^{-\delta t}+V_{M\infty}^{TRB},$$

$$V_R^{TRB}(t)=o\left(G_0-G_\infty^{TRB}\right)e^{-\chi t}+V_{R\infty}^{TRB},$$

$$V_T^{TRB}(t)=p\left(S_0-S_\infty^{TRB}\right)e^{-\delta t}+V_{T\infty}^{TRB},$$

when $t\to\infty$, their steady-state profits are as follows:

$$V_{M\infty}^{TRB}=\frac{\alpha^2}{8\beta(\chi+\rho)}G_\infty^{TRB}+\frac{(1-\Omega)(\lambda-\eta\theta)^2}{4\eta(\delta+\rho)}S_\infty^{TRB}+\frac{1}{2k_I\rho}\left[\frac{\alpha^2\varepsilon_I}{8\beta(\chi+\rho)}+\frac{\gamma_I(1-\Omega)(\eta\theta-\lambda)^2}{4\eta(\delta+\rho)}\right]^2,$$
$$+\frac{1}{2k_L\rho}\left[\frac{\varepsilon_L\alpha^2}{8\beta(\chi+\rho)}+\frac{\gamma_L(1-\Omega)(\eta\theta-\lambda)^2}{4\eta(\delta+\rho)}\right]^2$$

$$V_{R\infty}^{TRB}=\frac{\alpha^2}{16\beta(\chi+\rho)}G_\infty^{TRB}+\frac{\alpha^2\left[\beta(1-\Omega)(\chi+\rho)\left(k_L\gamma_I\varepsilon_I+k_I\gamma_L\varepsilon_L\right)(\eta\theta-\lambda)^2+\eta\alpha^2(\delta+\rho)\left(k_L\varepsilon_I^2+k_I\varepsilon_L^2\right)\right]}{128\eta k_L k_I\rho\beta^2(\delta+\rho)(\chi+\rho)^2},$$

$$V_{T\infty}^{TRB}=\frac{\Omega(\theta\eta-\lambda)^2}{4\eta(\delta+\rho)}\left[S_\infty^{TRB}+\frac{\alpha^2\left(k_L\varepsilon_I\gamma_I+k_I\varepsilon_L\gamma_L\right)}{8\beta\rho k_L k_I(\chi+\rho)}+\frac{(1-\Omega)\left(k_L{\gamma_I}^2+k_I{\gamma_L}^2\right)(\theta\eta-\lambda)^2}{4\eta\rho k_L k_I(\delta+\rho)}\right].$$

5. COMPARATIVE ANALYSIS AND DISCUSSION

5.1. Analysis of the Impact of Key Parameters on Decision Variables

By further analyzing the conclusions presented in Section 4 and based on the partial derivatives of each decision variable with respect to the key parameters, Corollaries 1–4 can be derived:

Corollary 1. Under the MEB scenario, the sensitivity analysis of each decision variable is presented in Table 1.

Table 1. Sensitivity analysis under the MEB scenario

	w^{MEB}	I^{MEB}	L^{MEB}	p^{MEB}	r^{MEB}
α	$\uparrow$	$\uparrow$	$\uparrow$	$\uparrow$	$\uparrow$
β	$\downarrow$	$\downarrow$	$\downarrow$	$\downarrow$	$\downarrow$
η	$\eta\nu > \lambda, \uparrow$ $\eta\nu < \lambda, \downarrow$	$\eta\nu > \lambda, \uparrow$ $\eta\nu < \lambda, \downarrow$	$\eta\nu > \lambda, \uparrow$ $\eta\nu < \lambda, \downarrow$	$\eta\nu > \lambda, \uparrow$ $\eta\nu < \lambda, \downarrow$	$\eta\nu > \lambda + \Gamma_1, \uparrow$ $\eta\nu < \lambda, \downarrow$
ν	$\eta\nu > \lambda, \uparrow$ $\eta\nu < \lambda, \downarrow$	$\eta\nu > \lambda, \uparrow$ $\eta\nu < \lambda, \downarrow$	$\eta\nu > \lambda, \uparrow$ $\eta\nu < \lambda, \downarrow$	$\eta\nu > \lambda, \uparrow$ $\eta\nu < \lambda, \downarrow$	$\eta\nu > \lambda - \Gamma_2, \uparrow$ $\eta\nu < \lambda - \Gamma_2, \downarrow$
λ	$\eta\nu > \lambda, \downarrow$ $\eta\nu < \lambda, \uparrow$	$\eta\nu > \lambda, \downarrow$ $\eta\nu < \lambda, \uparrow$	$\eta\nu > \lambda, \downarrow$ $\eta\nu < \lambda, \uparrow$	$\eta\nu > \lambda, \downarrow$ $\eta\nu < \lambda, \uparrow$	$\eta\nu > \lambda + \Gamma_3, \downarrow$ $\eta\nu < \lambda + \Gamma_3, \uparrow$
Δ	$\rightarrow$	$\rightarrow$	$\rightarrow$	$\rightarrow$	$\rightarrow$
μ	$\rightarrow$	$\rightarrow$	$\rightarrow$	$\rightarrow$	$\rightarrow$
ξ	$\rightarrow$	$\rightarrow$	$\rightarrow$	$\rightarrow$	$\rightarrow$
Ω	$\rightarrow$	$\rightarrow$	$\rightarrow$	$\rightarrow$	$\rightarrow$

Note: $\uparrow$ represents a positive impact, $\downarrow$ represents a negative impact, and $\rightarrow$ represents no impact. The same applies below. In table 1, $\Gamma_1 = \frac{\lambda\eta\alpha^2(\delta+\rho)(k_L\gamma_I\varepsilon_I + k_I\gamma_L\varepsilon_L)}{(\eta^2\nu^2 + 3\lambda^2)(k_L\gamma_I^2 + k_I\gamma_L^2)(\chi+\rho)\beta}$, $\Gamma_2 = \frac{\alpha^2(\delta+\rho)(k_L\gamma_I\varepsilon_I + k_I\gamma_L\varepsilon_L)}{4\nu\beta(\chi+\rho)(k_L\gamma_I^2 + k_I\gamma_L^2)}$ and $\Gamma_3 = \frac{\eta\alpha^2(\delta+\rho)(k_L\gamma_I\varepsilon_I + k_I\gamma_L\varepsilon_L)}{4\lambda\beta(\chi+\rho)(k_L\gamma_I^2 + k_I\gamma_L^2)}$.

According to Corollary 1, for the influence coefficient η representing the effect of recycling price on recycling demand and the influence coefficient ν capturing the effect of remaining battery life on the resale price for the echelon utilization, when their combined influence exceeds the effect of battery life on recycling demand (i.e., $\eta\nu > \lambda$), the steady-state values of all decision variables increase with respect to both η and ν. Conversely, when $\eta\nu < \lambda$, these steady-state values decrease as η and ν increase. This trend can be explained by consumer behavior in battery recycling decisions: when consumers place less emphasis on the remaining battery life, their sensitivity to the recycling price rises. As a result, the battery manufacturer increases the wholesale price, retail price, and recycling price of the battery pack, along with enhancing technological innovation efforts and investment in blockchain technology.

Corollary 2. Under the MRB scenario, the sensitivity analysis of each decision variable is presented in Table 2.

According to Corollary 2, for the coefficient λ representing the impact of remaining battery life on recycling demand, its effect on the steady-state values of the decision variables is negative when λ is below the threshold $\eta\nu$, and positive when λ exceeds this threshold. This implies that PB-CLSC must assess the extent to which consumers consider the remaining battery life when making recycling decisions. Specifically, when consumers' attention to battery condition is low, they largely disregard the actual remaining capacity and are unwilling to pay a premium for traceable, real-time battery life information, leading to reduced revenue for PB-CLSC. In this case, the steady-state values of the decision variables decrease as λ increases. Conversely, when consumer attention surpasses the threshold ($\eta\nu$), their decision-making becomes more sensitive to battery condition; consumers begin to value the full life cycle perspective and take into account the current remaining lifespan rather than focusing solely on the recycling price. Under such conditions, access to traceable, accurate battery lifespan data satisfies consumer informational needs, thereby enhancing PB-CLSC revenue. Consequently, the steady-state values of all decision variables increase with rising λ.

Table 2. Sensitivity analysis under the MRB scenario

	w^{MRB}	I^{MRB}	L^{MRB}	p^{MRB}	r^{MRB}
α	$\uparrow$	$\uparrow$	$\uparrow$	$\uparrow$	$\uparrow$
β	$\downarrow$	$\downarrow$	$\downarrow$	$\downarrow$	$\downarrow$
η	$\Delta\xi > \mu + \frac{\lambda}{\eta}, \uparrow$ $\Delta\xi < \mu + \frac{\lambda}{\eta}, \downarrow$	$\Delta\xi > \mu + \frac{\lambda}{\eta}, \uparrow$ $\Delta\xi < \mu + \frac{\lambda}{\eta}, \downarrow$	$\Delta\xi > \mu + \frac{\lambda}{\eta}, \uparrow$ $\Delta\xi < \mu + \frac{\lambda}{\eta}, \downarrow$	$\Delta\xi > \mu + \frac{\lambda}{\eta}, \uparrow$ $\Delta\xi < \mu + \frac{\lambda}{\eta}, \downarrow$	$\Delta\xi > \mu + \frac{\lambda}{\eta} + \mathrm{H}_1, \uparrow$ $\Delta\xi < \mu + \frac{\lambda}{\eta} + \mathrm{H}_1, \downarrow$
λ	$\Delta\xi > \mu + \frac{\lambda}{\eta}, \downarrow$ $\Delta\xi < \mu + \frac{\lambda}{\eta}, \uparrow$	$\Delta\xi > \mu + \frac{\lambda}{\eta}, \downarrow$ $\Delta\xi < \mu + \frac{\lambda}{\eta}, \uparrow$	$\Delta\xi > \mu + \frac{\lambda}{\eta}, \downarrow$ $\Delta\xi < \mu + \frac{\lambda}{\eta}, \uparrow$	$\Delta\xi > \mu + \frac{\lambda}{\eta}, \downarrow$ $\Delta\xi < \mu + \frac{\lambda}{\eta}, \uparrow$	$\Delta\xi > \mu + \frac{\lambda}{\eta} + \mathrm{H}_2, \downarrow$ $\Delta\xi < \mu + \frac{\lambda}{\eta} + \mathrm{H}_2, \uparrow$
Δ	$\Delta\xi > \mu + \frac{\lambda}{\eta}, \uparrow$ $\Delta\xi < \mu + \frac{\lambda}{\eta}, \downarrow$	$\Delta\xi > \mu + \frac{\lambda}{\eta}, \uparrow$ $\Delta\xi < \mu + \frac{\lambda}{\eta}, \downarrow$	$\Delta\xi > \mu + \frac{\lambda}{\eta}, \uparrow$ $\Delta\xi < \mu + \frac{\lambda}{\eta}, \downarrow$	$\Delta\xi > \mu + \frac{\lambda}{\eta}, \uparrow$ $\Delta\xi < \mu + \frac{\lambda}{\eta}, \downarrow$	$\Delta\xi > \mu + \frac{\lambda}{\eta} - \mathrm{H}_3, \uparrow$ $\Delta\xi < \mu + \frac{\lambda}{\eta} - \mathrm{H}_3, \downarrow$
μ	$\Delta\xi > \mu + \frac{\lambda}{\eta}, \downarrow$ $\Delta\xi < \mu + \frac{\lambda}{\eta}, \uparrow$	$\Delta\xi > \mu + \frac{\lambda}{\eta}, \downarrow$ $\Delta\xi < \mu + \frac{\lambda}{\eta}, \uparrow$	$\Delta\xi > \mu + \frac{\lambda}{\eta}, \downarrow$ $\Delta\xi < \mu + \frac{\lambda}{\eta}, \uparrow$	$\Delta\xi > \mu + \frac{\lambda}{\eta}, \downarrow$ $\Delta\xi < \mu + \frac{\lambda}{\eta}, \uparrow$	$\Delta\xi > \mu + \frac{\lambda}{\eta} - \mathrm{H}_3, \downarrow$ $\Delta\xi < \mu + \frac{\lambda}{\eta} - \mathrm{H}_3, \uparrow$
ξ	$\Delta\xi > \mu + \frac{\lambda}{\eta}, \uparrow$ $\Delta\xi < \mu + \frac{\lambda}{\eta}, \downarrow$	$\Delta\xi > \mu + \frac{\lambda}{\eta}, \uparrow$ $\Delta\xi < \mu + \frac{\lambda}{\eta}, \downarrow$	$\Delta\xi > \mu + \frac{\lambda}{\eta}, \uparrow$ $\Delta\xi < \mu + \frac{\lambda}{\eta}, \downarrow$	$\Delta\xi > \mu + \frac{\lambda}{\eta}, \uparrow$ $\Delta\xi < \mu + \frac{\lambda}{\eta}, \downarrow$	$\Delta\xi > \mu + \frac{\lambda}{\eta} - \mathrm{H}_3, \uparrow$ $\Delta\xi < \mu + \frac{\lambda}{\eta} - \mathrm{H}_3, \downarrow$
Ω	$\rightarrow$	$\rightarrow$	$\rightarrow$	$\rightarrow$	$\rightarrow$
ν	$\rightarrow$	$\rightarrow$	$\rightarrow$	$\rightarrow$	$\rightarrow$

Note: $\mathrm{H}_1 = \dfrac{\alpha^2\lambda(\delta+\rho)\left(k_L\gamma_I\varepsilon_I + k_I\gamma_L\varepsilon_L\right)}{\beta(\chi+\rho)\left(\gamma_I^2 k_L + \gamma_L^2 k_I\right)\left[\left(-\Delta\xi+\mu\right)^2\eta^2 + 3\lambda^2\right]}$, $\mathrm{H}_2 = \dfrac{\alpha^2\left(k_L\gamma_I\varepsilon_I + k_I\gamma_L\varepsilon_L\right)(\delta+\rho)}{4\lambda\beta\left(\gamma_I^2 k_L + \gamma_L^2 k_I\right)(\chi+\rho)}$ and $\mathrm{H}_3 = \dfrac{\alpha^2\left(k_L\gamma_I\varepsilon_I + k_I\gamma_L\varepsilon_L\right)(\delta+\rho)}{4\beta\eta\left(\gamma_I^2 k_L + \gamma_L^2 k_I\right)(\chi+\rho)(\Delta\xi-\mu)}$.

Table 3. Sensitivity analysis under the TEB scenario

	w^{TEB}	I^{TEB}	L^{TEB}	p^{TEB}	r^{TEB}
α	$\uparrow$	$\uparrow$	$\uparrow$	$\uparrow$	$\uparrow$
β	$\downarrow$	$\downarrow$	$\downarrow$	$\downarrow$	$\downarrow$
η	$\eta\nu > \lambda, \uparrow$ $\eta\nu < \lambda, \downarrow$	$\eta\nu > \lambda, \uparrow$ $\eta\nu < \lambda, \downarrow$	$\eta\nu > \lambda, \uparrow$ $\eta\nu < \lambda, \downarrow$	$\eta\nu > \lambda, \uparrow$ $\eta\nu < \lambda, \downarrow$	$\eta\nu > \lambda + \mathrm{I}_1, \uparrow$ $\eta\nu < \lambda + \mathrm{I}_1, \downarrow$
ν	$\eta\nu > \lambda, \uparrow$ $\eta\nu < \lambda, \downarrow$	$\eta\nu > \lambda, \uparrow$ $\eta\nu < \lambda, \downarrow$	$\eta\nu > \lambda, \uparrow$ $\eta\nu < \lambda, \downarrow$	$\eta\nu > \lambda, \uparrow$ $\eta\nu < \lambda, \downarrow$	$\eta\nu > \lambda - \mathrm{I}_2, \uparrow$ $\eta\nu < \lambda - \mathrm{I}_2, \downarrow$
λ	$\eta\nu > \lambda, \downarrow$ $\eta\nu < \lambda, \uparrow$	$\eta\nu > \lambda, \downarrow$ $\eta\nu < \lambda, \uparrow$	$\eta\nu > \lambda, \downarrow$ $\eta\nu < \lambda, \uparrow$	$\eta\nu > \lambda, \downarrow$ $\eta\nu < \lambda, \uparrow$	$\eta\nu > \lambda + \mathrm{I}_3, \downarrow$ $\eta\nu < \lambda + \mathrm{I}_3, \uparrow$
Δ	$\rightarrow$	$\rightarrow$	$\rightarrow$	$\rightarrow$	$\rightarrow$
μ	$\rightarrow$	$\rightarrow$	$\rightarrow$	$\rightarrow$	$\rightarrow$
ξ	$\rightarrow$	$\rightarrow$	$\rightarrow$	$\rightarrow$	$\rightarrow$
Ω	$\downarrow$	$\downarrow$	$\downarrow$	$\downarrow$	$\downarrow$

Note: $\mathrm{I}_1=\dfrac{\lambda\eta\alpha^2\left(k_L\gamma_I\varepsilon_I+k_I\gamma_L\varepsilon_L\right)(\delta+\rho)}{(1-\Omega)\left(\eta^2\nu^2+3\lambda^2\right)\left(k_L\gamma_I^2+k_I\gamma_L^2\right)(\chi+\rho)\beta}$, $\mathrm{I}_2=\dfrac{\alpha^2\left(k_L\gamma_I\varepsilon_I+k_I\gamma_L\varepsilon_L\right)(\delta+\rho)}{4\nu\beta(1-\Omega)\left(k_L\gamma_I^2+k_I\gamma_L^2\right)(\chi+\rho)}$ and $\mathrm{I}_3=\dfrac{\alpha^2\left(k_L\gamma_I\varepsilon_I+k_I\gamma_L\varepsilon_L\right)(\delta+\rho)}{4\lambda\beta(1-\Omega)\left(k_L\gamma_I^2+k_I\gamma_L^2\right)(\chi+\rho)}$.

Corollary 3. Under the TEB scenario, the sensitivity analysis of each decision variable is presented in Table 3.

According to the conclusions of Corollary 1 and Corollary 3, under the echelon utilization model scenario, the wholesale price, retail price, and recycling price of power batteries, as well as the technological innovation efforts and blockchain adoption intensity by power battery manufacturers, increase with the growing influence of brand reputation on power battery demand, and decrease with higher consumer sensitivity to the retail price. This trend aligns with real-world market dynamics. When consumers place greater emphasis on brand reputation, power battery manufacturers are incentivized to enhance product quality through technological innovation, and retailers become more proactive in marketing to strengthen brand image. However, when consumers exhibit higher price sensitivity, their purchasing decisions are primarily driven by cost considerations, prompting manufacturers and retailers to lower prices accordingly.

Corollary 4. Under the TRB scenario, the sensitivity analysis of each decision variable is presented in Table 4.

Table 4. Sensitivity analysis under the TRB scenario

	w^{TRB}	I^{TRB}	L^{TRB}	p^{TRB}	r^{TRB}
α	$\uparrow$	$\uparrow$	$\uparrow$	$\uparrow$	$\uparrow$
β	$\downarrow$	$\downarrow$	$\downarrow$	$\downarrow$	$\downarrow$
η	$\Delta\xi>\mu+\frac{\lambda}{\eta},\uparrow$ $\Delta\xi<\mu+\frac{\lambda}{\eta},\downarrow$	$\Delta\xi>\mu+\frac{\lambda}{\eta},\uparrow$ $\Delta\xi<\mu+\frac{\lambda}{\eta},\downarrow$	$\Delta\xi>\mu+\frac{\lambda}{\eta},\uparrow$ $\Delta\xi<\mu+\frac{\lambda}{\eta},\downarrow$	$\Delta\xi>\mu+\frac{\lambda}{\eta},\uparrow$ $\Delta\xi<\mu+\frac{\lambda}{\eta},\downarrow$	$\Delta\xi>\mu+\frac{\lambda}{\eta}+\mathrm{K}_1,\uparrow$ $\Delta\xi<\mu+\frac{\lambda}{\eta}+\mathrm{K}_1,\downarrow$
λ	$\Delta\xi>\mu+\frac{\lambda}{\eta},\downarrow$ $\Delta\xi<\mu+\frac{\lambda}{\eta},\uparrow$	$\Delta\xi>\mu+\frac{\lambda}{\eta},\downarrow$ $\Delta\xi<\mu+\frac{\lambda}{\eta},\uparrow$	$\Delta\xi>\mu+\frac{\lambda}{\eta},\downarrow$ $\Delta\xi<\mu+\frac{\lambda}{\eta},\uparrow$	$\Delta\xi>\mu+\frac{\lambda}{\eta},\downarrow$ $\Delta\xi<\mu+\frac{\lambda}{\eta},\uparrow$	$\Delta\xi>\mu+\frac{\lambda}{\eta}+\mathrm{K}_2,\downarrow$ $\Delta\xi<\mu+\frac{\lambda}{\eta}+\mathrm{K}_2,\uparrow$
Δ	$\Delta\xi>\mu+\frac{\lambda}{\eta},\uparrow$ $\Delta\xi<\mu+\frac{\lambda}{\eta},\downarrow$	$\Delta\xi>\mu+\frac{\lambda}{\eta},\uparrow$ $\Delta\xi<\mu+\frac{\lambda}{\eta},\downarrow$	$\Delta\xi>\mu+\frac{\lambda}{\eta},\uparrow$ $\Delta\xi<\mu+\frac{\lambda}{\eta},\downarrow$	$\Delta\xi>\mu+\frac{\lambda}{\eta},\uparrow$ $\Delta\xi<\mu+\frac{\lambda}{\eta},\downarrow$	$\Delta\xi>\mu+\frac{\lambda}{\eta}-\mathrm{K}_3,\uparrow$ $\Delta\xi<\mu+\frac{\lambda}{\eta}-\mathrm{K}_3,\downarrow$
μ	$\Delta\xi>\mu+\frac{\lambda}{\eta},\downarrow$ $\Delta\xi<\mu+\frac{\lambda}{\eta},\uparrow$	$\Delta\xi>\mu+\frac{\lambda}{\eta},\downarrow$ $\Delta\xi<\mu+\frac{\lambda}{\eta},\uparrow$	$\Delta\xi>\mu+\frac{\lambda}{\eta},\downarrow$ $\Delta\xi<\mu+\frac{\lambda}{\eta},\uparrow$	$\Delta\xi>\mu+\frac{\lambda}{\eta},\downarrow$ $\Delta\xi<\mu+\frac{\lambda}{\eta},\uparrow$	$\Delta\xi>\mu+\frac{\lambda}{\eta}-\mathrm{K}_3,\downarrow$ $\Delta\xi<\mu+\frac{\lambda}{\eta}-\mathrm{K}_3,\uparrow$
ξ	$\Delta\xi>\mu+\frac{\lambda}{\eta},\uparrow$ $\Delta\xi<\mu+\frac{\lambda}{\eta},\downarrow$	$\Delta\xi>\mu+\frac{\lambda}{\eta},\uparrow$ $\Delta\xi<\mu+\frac{\lambda}{\eta},\downarrow$	$\Delta\xi>\mu+\frac{\lambda}{\eta},\uparrow$ $\Delta\xi<\mu+\frac{\lambda}{\eta},\downarrow$	$\Delta\xi>\mu+\frac{\lambda}{\eta},\uparrow$ $\Delta\xi<\mu+\frac{\lambda}{\eta},\downarrow$	$\Delta\xi>\mu+\frac{\lambda}{\eta}-\mathrm{K}_3,\uparrow$ $\Delta\xi<\mu+\frac{\lambda}{\eta}-\mathrm{K}_3,\downarrow$
Ω	$\downarrow$	$\downarrow$	$\downarrow$	$\downarrow$	$\downarrow$
ν	$\rightarrow$	$\rightarrow$	$\rightarrow$	$\rightarrow$	$\rightarrow$

Note: $K_1 = \frac{\alpha^2\lambda(\delta+\rho)(k_L\gamma_I\varepsilon_I + k_I\gamma_L\varepsilon_L)}{\beta(\chi+\rho)(\gamma_I^2 k_L + \gamma_L^2 k_I)\left[(-\Delta\xi+\mu)^2\eta^2+3\lambda^2\right]}$, $K_2 = \frac{\alpha^2(k_L\gamma_I\varepsilon_I + k_I\gamma_L\varepsilon_L)(\delta+\rho)}{4\lambda\beta(1-\Omega)(\gamma_I^2 k_L + \gamma_L^2 k_I)(\chi+\rho)}$ and $K_3 = \frac{\alpha^2(k_L\gamma_I\varepsilon_I + k_I\gamma_L\varepsilon_L)(\delta+\rho)}{4\beta\eta(1-\Omega)(\gamma_I^2 k_L + \gamma_L^2 k_I)(\chi+\rho)(\Delta\xi-\mu)}$.

In particular, based on the conclusions of Corollary 2 and Corollary 4, under the regeneration utilization mode, when the unit revenue θ （$\theta = \Delta\xi - \mu$） obtained by the manufacturer from battery remanufacturing exceeds a certain threshold ($\frac{\lambda}{\eta}$), the steady-state values of all decision variables increase with rising remanufacturing unit revenue Δ and the coefficient ξ representing the impact of battery life on the remanufacturing rate, while decreasing with an increase in the coefficient μ reflecting the effect of battery life on potential recycling benefit losses. Conversely, if $\theta < \frac{\lambda}{\eta}$, the trends are reversed. This behavior arises because, when the PB-CLSC achieves higher unit revenue through recycling, it incentivizes the expansion of remanufacturing scale. To enhance recovery volume, the PB-CLSC raises the recycling price, thereby encouraging consumers to return retired batteries. Furthermore, to improve the remanufacturing rate and reduce resource loss during remanufacturing, firms intensify technological innovation efforts and leverage blockchain technology more effectively to obtain accurate lifecycle data of retired batteries. As a result, the steady-state values of the decision variables increase with Δ and ξ, and decrease with μ. However, when $\theta < \frac{\lambda}{\eta}$, the revenue generated from remanufacturing is insufficient to cover the associated costs of recycling, technological innovation, and blockchain implementation. In this case, the PB-CLSC strategically lowers the recycling price to suppress consumer return behavior, while simultaneously reducing wholesale and retail prices to stimulate demand in the forward supply chain. Manufacturers also scale back investments in technological innovation and blockchain utilization. Consequently, the steady-state values of the decision variables decrease with increases in Δ and ξ.

5.2. Comparative Analysis based on Utilization Patterns

Based on Lemma 1 and Lemma 2, a comparison of the steady-state equilibrium outcomes under the same recycling channel but different utilization modes lead to the following conclusions:

Proposition 1. When the PB-CLSC adopts the manufacturer-led recycling channel, it is observed that:

$$w^{MRB} > w^{MEB};\ p^{MRB} > p^{MEB};\quad V_M^{MRB} > V_M^{MEB};\ V_R^{MRB} > V_R^{MEB}.$$

when

$$\begin{cases} \nu \in (0,\frac{\lambda}{\eta}) \text{ and } \theta \in (0,\ \nu) \cup \left(\frac{2\lambda}{\eta} - \nu, \infty\right) \\ \text{or} \\ \nu \in (\frac{\lambda}{\eta},\frac{2\lambda}{\eta}) \text{ and } \theta \in \left(0, \frac{2\lambda}{\eta} - \nu\right) \cup (\nu, \infty) \\ \text{or} \\ \nu \in (\frac{2\lambda}{\eta}, \infty) \text{ and } \theta \in (\nu, \infty) \end{cases}$$

If $\theta > \frac{(n\nu+\lambda)\sqrt{f}-\lambda}{\eta}$, $r^{MRB} > r^{MEB}$;If $\theta > \frac{(n\nu-\lambda)\sqrt{f}+\lambda}{\eta}$, $D_r^{MRB} > D_r^{MEB}$,where f is too comprehensive to be presented here in detail and will be elaborated in the appendix.

Proposition 1 indicates that when the impact of battery life on the resale price of retired batteries for echelon utilization ν is at a medium or low level, the wholesale price, retail price, manufacturer's

profit, and retailer's profit under the MRB scenario are higher than those under the MEB scenario only if θ is at either a low or high level. However, when ν is at a high level, this relationship holds exclusively when θ is also high. This can be explained as follows: when ν is moderate or low, the resale price of retired batteries for echelon utilization exhibits limited sensitivity to battery life. In the case of low θ, although regeneration utilization's revenue may be lower than that generated through the echelon utilization, the associated technical investment for battery disassembly remains relatively modest. Under these conditions, costs can be effectively diluted through large-scale disassembly operations, rendering them significantly lower than the fixed costs—such as testing and reassembly expenses—incurred in the second-hand battery model. As a result, both manufacturers and retailers achieve higher profits under the MRB scenario compared to the MEB scenario. Conversely, when θ is high, regeneration utilization yields substantially greater revenue than the echelon utilization, making MRB more favorable. In contrast, when ν is high, the resale price becomes highly sensitive to battery life, leading to a significant increase in profitability under the echelon utilization model. In this case, the MRB scenario outperforms the MEB scenario only when θ is sufficiently high.

Furthermore, by comparing Lemma 3 with Lemma 4, we can draw the following conclusion:

Proposition 2. When the PB-CLSC adopts third-party recycling channel, it is observed that:

$$w^{TRB} > w^{TEB};\ p^{TRB} > p^{TEB};\quad V_M^{TRB} > V_M^{TEB};\ V_R^{TRB} > V_R^{TEB};\quad V_T^{TRB} > V_T^{TEB}.$$

$$\text{when} \begin{cases} \nu \in (0, \frac{\lambda}{\eta}) \text{ and } \theta \in (0,\ \nu) \cup \left(\frac{2\lambda}{\eta} - \nu, \infty\right) \\ or \\ \nu \in (\frac{\lambda}{\eta}, \frac{2\lambda}{\eta}) \text{ and } \theta \in \left(0, \frac{2\lambda}{\eta} - \nu\right) \cup (\nu, \infty) \\ or \\ \nu \in (\frac{2\lambda}{\eta}, \infty) \text{ and } \theta \in (\nu, \infty) \end{cases}$$

If $\theta > \frac{(n\nu + \lambda)\sqrt{f} - \lambda}{\eta}$, $r^{TRB} > r^{TEB}$; if $\theta > \frac{(n\nu - \lambda)\sqrt{f} + \lambda}{\eta}$, $D_r^{TRB} > D_r^{TEB}$,where f is too comprehensive to be presented here in detail and will be elaborated in the appendix.

By observing Proposition 2, an interesting finding can be made: regardless of whether the closed-loop supply chain of power batteries adopts the manufacturer's recycling channel or the third-party recycling channel, the impact of the power battery life on the resale price for the echelon utilization ν and the impact of the unit revenue conversion rate of the regeneration utilization θ on each steady-state decision variable and steady-state profit are the same.

5.3. Comparative Analysis based on Recycling Channels

Based on Lemma 1 and Lemma 3, a comparison of the steady-state equilibrium outcomes under the same utilization mode but across different recycling channels leads to the following conclusions:

Proposition 3. When PB-CLSC adopts the echelon utilization pattern, it can be observed that:

$w^{MEB} > w^{TEB}$; $p^{MEB} > p^{TEB}$; $r^{MEB} > r^{TEB}$; $V_M^{MEB} > V_M^{TEB}$; $V_R^{MEB} > V_R^{TEB}$; $D_r^{MEB} > D_r^{TEB}$, when $\lambda < \eta\nu$, otherwise $D_r^{TEB} > D_r^{MEB}$.

Proposition 3 indicates that for decision variables such as the wholesale price, selling price, and recycling price of power batteries, as well as the profits of manufacturers and retailers, the steady-state values under the manufacturer-led recycling channel are higher than those under the third-party recycling scenario when the echelon utilization mode is adopted. However, with regard to recycling volume, when $\lambda > \eta\nu$, the volume in the third-party recycling scenario exceeds that in the manufacturer-led scenario. This occurs because a larger λ implies a stronger influence of battery

life on recycling demand. In such cases, consumers place greater emphasis on the remaining battery life when making recycling decisions. Although the recycling price in the third-party channel is lower than that in the manufacturer-led scenario, the average remaining capacity of collected batteries tends to be lower under third-party collection. As a result, consumer willingness to return used batteries increases significantly, leading to higher overall recycling volumes.

Furthermore, based on Lemma 2 and Lemma 4, by comparing the steady-state equilibrium results under the regeneration utilization mode with different recycling channels, we can draw the following conclusions:

Proposition 4. When the PB-CLSC adopts regeneration utilization mode, it can be observed that:

$w^{MRB} > w^{TRB}$; $p^{MRB} > p^{TRB}$; $r^{MRB} > r^{TRB}$; $V_M^{MRB} > V_M^{TRB}$; $V_R^{MRB} > V_R^{TRB}$; $D_r^{MRB} > D_r^{TRB}$, when $\lambda < \eta\nu$, otherwise $D_r^{TRB} > D_r^{MRB}$.

Proposition 4 indicates that when the PB-CLSC adopts the regeneration utilization mode, the equilibrium outcomes—including the wholesale price, retail price, recycling price, manufacturer's profit, and retailer's profit—are superior under the manufacturer-led recycling channel compared to the third-party recycling channel. However, when λ exceeds a certain threshold ($\lambda > \eta\nu$), the volume of power battery recycling under the third-party recycling scenario surpasses that under the manufacturer-led scenario, which is consistent with the conclusion of Proposition 3.

6. CONCLUDING REMARKS

6.1. Research Conclusion

(1) Through the sensitivity analysis of key parameters in the previous text, it can be found that as the influence coefficient α meaning the goodwill of power batteries on their demand increases, the steady-state profits and the optimal decision-making levels of all entities in the PB-CLSC will significantly improve, indicating that the brand effect plays an important role in the long-term development of the PB-CLSC. Meanwhile, the increase of the influence coefficient β meaning the power battery price on its demand will suppress consumers' demand for power batteries, thereby reducing the steady-state profits of all entities. Additionally, the influence coefficient η meaning the recycling price of retired power batteries on the recycling demand and the influence coefficient λ meaning the power battery life on the recycling demand have an interactive effect on the optimal decision-making levels of all entities in the PB-CLSC: when the product of η and ν is greater than λ ($\eta\nu > \lambda$), the optimal decision-making levels of all entities will increase as η and ν increase; conversely, when $\eta\nu < \lambda$, the optimal decision-making levels of all entities will decrease as η and ν increase. Overall, in the current power battery market, consumers' sensitivity to the recycling price of retired power batteries is generally higher than their concern for the remaining battery life. At the same time, the impact of the unit revenue θ of regeneration utilization on the steady-state profits of all entities is not monotonic: when θ is low, it is insufficient to cover the remanufacturing cost, and the steady-state profits of all entities will decrease as θ increases; however, when θ increases to a certain extent, the steady-state profits of all entities will increase as θ increases, and the advantages of the regeneration utilization model will then be reflected.

(2) From the perspective of optimal decision-making, in terms of maximizing profits, for the steady-state profits of battery manufacturers, the manufacturer's recycling situation is better than that of third-party recyclers in both the echelon utilization mode and the regeneration utilization mode. However, for battery retailers, when the echelon utilization mode is adopted, the steady-state profit under the third-party recycler's recycling situation is better than that under the manufacturer's recycling situation. As for third-party recyclers, only when the impact of battery recycling prices on

their recycling demand is low and the impact of battery lifespan on recycling demand is high, will their steady-state profits reach the optimum in the regeneration utilization situation. From an environmental perspective, in terms of the amount of retired battery recycling, the recycling volume in the echelon utilization mode is higher than that in the regeneration utilization mode under both the manufacturer's and third-party recycler's recycling channels. Regarding the remaining lifespan of batteries, regardless of whether the echelon utilization mode or the regeneration utilization mode is adopted, the remaining lifespan of batteries under the manufacturer's recycling situation is higher than that under the third-party recycler's recycling situation.

6.2. Management Implications

(1) Under the current market environment, all entities in the PB-CLSC need to fully utilize blockchain technology.

The research conclusion shows that under the two recycling channels in the current market for retired power batteries, the optimal steady-state profits of each subject and the recycling volume of retired power batteries are both better under the echelon utilization model than under the regeneration utilization model. The reason for this phenomenon is that on the one hand, the technical barriers for harmless regeneration treatment of retired power batteries are high and the cost is large; on the other hand, consumers' environmental awareness is constantly increasing. For the regeneration treatment model of power batteries, the core lies in breaking down the batteries and extracting core raw materials such as lithium, cobalt, and nickel after sorting. Firstly, the structure of power batteries is complex, making their disassembly and crushing difficult. Secondly, the current mainstream sorting and purification processes mainly include "wet smelting" and "dry metallurgy", both of which have technical shortcomings: "wet smelting" requires a large amount of strong acids and strong alkalis to dissolve the batteries, and the resulting wastewater is difficult to treat; "dry metallurgy" removes organic matter through high temperatures, but this method has extremely high energy consumption and is also difficult to control the exhaust gas. Finally, to reduce the impact on the environment, a large amount of environmental protection facilities are needed for the regeneration treatment of batteries, further increasing the operation and maintenance costs. Therefore, in order to carry out the regeneration treatment of retired power batteries more economically, effectively, and environmentally friendly, enterprises need to invest a large amount of funds in technological research and development to improve the treatment process. As for consumers, in recent years, with the call of the government's "low-carbon policy", their environmental awareness has been increasing. When making decisions on the recycling of retired power batteries, they not only consider economic factors but also whether the treatment mode after battery recycling will have an impact on the environment. Even though blockchain technology enables consumers to trace the entire life cycle of power batteries, the solid mindset that regeneration treatment will cause irreversible damage to the environment has been deeply rooted in consumers' minds due to the emergence of "small workshops" of non-compliant recyclers in recent years. Therefore, they tend to prefer echelon utilization for retired power batteries. This suggests that for power battery manufacturers like CATL and BYD, on the one hand, they should increase investment in technological research and development for the regeneration treatment process of power batteries to reduce costs while ensuring the environmental friendliness of the process; on the other hand, they should fully leverage the role of blockchain to make consumers clearly understand that their regeneration treatment methods for retired power batteries are environmentally friendly.

(2) The goodwill of power battery enterprises has a "double-edged sword" attribute.

Data shows that in the past five years, incidents of spontaneous combustion and explosion of new energy vehicle batteries have occurred frequently, intensifying consumers' risk perception. For leading battery manufacturers like CATL, they have developed a series of high-quality products such as the "Qilin Battery" through technological innovation, and have accumulated a large number of

highly loyal consumers through large-scale installation verification and vertical integration with the new energy vehicle industry, earning consumer recognition and brand reputation. In reality, when consumers choose new energy vehicles, models equipped with CATL batteries are often their first choice, and there is even a phenomenon of "no CATL, no buy". In such a market environment, leading enterprises like CATL and BYD have built "moat-like" barriers in the battery industry through technological research and development, large-scale production, and global layout. Many small and medium-sized battery enterprises find it difficult to survive in this environment and will eventually fall into a vicious cycle of "low brand reputation → low-price strategy → low profit → low R&D investment → even lower brand reputation → even lower price". From a macro perspective, this pattern is not conducive to the long-term healthy development of the PB-CLSC. This suggests that the management department should, on the one hand, encourage leading enterprises to continuously carry out technological research and development to maintain their core competitiveness; on the other hand, it should also introduce corresponding preferential policies to support small and medium-sized enterprises with less competitive power to develop in the difficult market environment, thereby promoting the long-term sustainable development of the PB-CLSC. For battery manufacturers, in the current battery market, consumers' purchase decisions are more inclined to consider the brand reputation of different battery manufacturers. The optimal steady-state profits of battery manufacturers, retailers, and third-party recyclers increase significantly with the increase of the influence coefficient of battery brand reputation on demand. This indicates that consumers have shifted from "functional satisfaction" to "value recognition", and the competition among battery manufacturers has shifted from the previous "price war" to "ecological war". Specifically, battery manufacturers with higher brand reputation are more likely to win consumers' favor and gain core competitive advantages. The reasons for this phenomenon are related to factors such as consumers' increasing safety anxiety and risk perception.

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