

Research on Coordination Mechanism Design of Closed-Loop Supply Chain for New Energy Vehicle Power Batteries

Yonglong Wang*, Meili Song, and Jirong Cai

School of Business Administration, Chongqing Technology and Business University,
Chongqing 400067, China

*Corresponding Author

Abstract

Taking the power battery closed-loop supply chain system composed of new energy vehicle manufacturers, automobile retailers and echelon utilization enterprises as the research background, this paper constructs a centralized decision-making model and a decentralized decision-making model based on Stackelberg game led by new energy vehicle manufacturers, and investigates the design of coordination mechanisms for the power battery closed-loop supply chain. The results reveal that the decentralized decision-making model fails to coordinate the power battery closed-loop supply chain due to the existence of double marginalization effect. By contrast, the proposed coordination mechanism combining recycling service cost-sharing and two-part tariff can not only effectively coordinate the supply chain, but also achieve Pareto improvement in the profits of all members within the closed-loop supply chain.

Keywords

Power Battery Closed-Loop Supply Chain; Supply Chain Coordination; New Energy Vehicles.

1. Introduction

Driven by the dual imperatives of the "Dual Carbon" goals and industrial low-carbon transformation, new energy vehicles (NEVs), as a flagship solution for energy conservation and emission reduction in the transportation sector, have emerged as a linchpin for alleviating China's energy and environmental pressures and advancing high-quality development of the automobile industry [1]. Power batteries constitute the core component of NEVs, with an average service life of approximately eight years, after which they enter echelon utilization or material regeneration recycling [2]. The *Interim Measures for the Administration of the Recycling and Utilization of Power Batteries for New Energy Vehicles* stipulates that NEV manufacturers bear the primary responsibility for power battery recycling, and relevant enterprises shall fulfill corresponding obligations across all recycling and utilization links to ensure efficient utilization and environmentally sound disposal of retired power batteries [3]. Nevertheless, the practical recycling and utilization chain is beset by multiple bottlenecks. By the end of 2023, the standardized recycling rate of NEV power batteries in China remained below 25%, with the majority of spent batteries diverted to unregulated enterprises operating within an unstandardized grey market [4]. In addition, fragmented coordination across all links of the power battery recycling industry chain prevents the formation of an integrated, functional industrial ecosystem [5]. An in-depth analysis of these dilemmas reveals that divergent interest demands among stakeholders and the absence of effective coordination mechanisms constitute the core underlying constraints. Against this backdrop, this paper systematically investigates the collaborative governance of closed-loop supply chain systems for NEV power batteries,

aiming to offer actionable references for elevating the standardized recycling rate of retired power batteries and facilitating effective coordination among all supply chain participants.

Extant literature has conducted comprehensive research on NEV power batteries from diverse theoretical perspectives. The first research stream focuses on recycling channel selection for spent NEV power batteries. For instance, Li [6] compared decision-makers' preference rankings for three recycling channel configurations: recycling by electric vehicle manufacturers and retailers, recycling by electric vehicle manufacturers and third-party recyclers, and recycling by electric vehicle retailers and third-party recyclers. Wang et al. [7] conducted a comparative analysis of two recycling channel models-power battery manufacturers paired with third-party recyclers, and the tripartite alliance of power battery manufacturers, NEV manufacturers and third-party recyclers-to examine their respective impacts on the profitability of power battery manufacturers. Zhang et al. [8] quantified the profit margins obtained by power battery manufacturers under four recycling channel frameworks: manufacturer-retailer joint recycling, manufacturer-third-party joint recycling, retailer-third-party joint recycling, and tripartite joint recycling involving manufacturers, retailers and third-party recyclers. Targeting four recycling scenarios including decentralized non-alliance recycling, manufacturer-retailer alliance recycling, manufacturer-third-party alliance recycling, and retailer-third-party alliance recycling, Bai et al. [9] analyzed the channel selection inclinations of all supply chain participants and end consumers.

The second strand centers on policy research concerning NEV power batteries. Tang et al. [10] and Zhang et al. [11] analyzed how reward-penalty mechanisms for power batteries affect the recycling rate of retired batteries. Zhang et al. [12] evaluated social welfare under policy interventions including subsidies, deposit-refund schemes, and reward-penalty policies, where social welfare consists of economic benefits, environmental gains, consumer surplus and government surplus. Wang et al. [13] discussed factors influencing the recycling decisions of battery manufacturers and automobile manufacturers, as well as the conditions under which both parties choose to conduct recycling, under two scenarios: no government intervention and the implementation of subsidy-penalty policies. Zhang et al. [14] analyzed how different subsidy targets affect supply chain members' optimal operational decisions and profits across four cases: zero subsidies, subsidies for retailers, subsidies for manufacturers, and subsidies for third-party recyclers. Wu and Zhang [15] investigated the optimal decisions of the power battery recycling supply chain under three subsidy strategies (subsidies for battery manufacturers, subsidies for recyclers, and subsidies for consumers) within a cap-and-trade carbon policy framework.

The third strand addresses coordination issues of power battery supply chains. Liu et al. [16] verified that both two-part tariff contracts and revenue-sharing contracts can coordinate remanufacturing supply chains composed of battery suppliers and automobile manufacturers when bilateral irrational preferences exist. Taking a closed-loop recycling supply chain of retired power batteries consisting of battery producers, automobile manufacturers, consumers and the government as the research object, Liu et al. [17] demonstrated that the hybrid contract combining recycling cost-sharing and revenue-sharing can effectively coordinate supply chain operations. Based on a closed-loop supply chain formed by automobile manufacturers and third-party recyclers, Wu and Zhang [18] analyzed the coordination efficiency of cost-profit sharing contracts. Zhou et al. [19] constructed a closed-loop supply chain system covering the government, battery manufacturers, battery retailers and third-party recyclers, and explored the feasibility of bilateral cost-sharing contracts for supply chain coordination. Ding [20] examined a closed-loop supply chain consisting of NEV manufacturers and power battery suppliers, and discussed the effectiveness of recycling cost-sharing mechanisms in supply chain coordination.

This paper differentiates itself from existing literature in three main aspects: (1) Distinct composition of participants in the closed-loop power battery supply chain. On the basis of References [16–20], this paper constructs a closed-loop supply chain involving NEV manufacturers, automobile retailers and echelon utilization enterprises, and establishes a full-lifecycle closed-loop system covering the chain: new power batteries → new energy vehicles → retired battery recycling → echelon utilization of retired batteries → material regeneration of retired batteries. In the forward supply chain, automobile manufacturers sell NEVs to automobile retailers, who further distribute vehicles to end consumers. In the reverse supply chain, NEV manufacturers cooperate with automobile retailers to collect retired power batteries. Collected batteries are allocated to either echelon utilization (batteries reaching the end of echelon service life will subsequently enter regeneration recycling) or direct material regeneration recycling according to their residual quality. (2) A novel coordination mechanism integrating recycling service cost-sharing and two-part tariff is designed to resolve interest conflicts among supply chain participants. Under specific threshold conditions, Pareto improvement can be achieved in the profits of all stakeholders. (3) Extended assumptions for the baseline model. Building on References [16–20], this paper incorporates two additional practical factors into the model: the impact of automobile manufacturers' recycling service investments (including battery replacement costs, recycling purchase prices, recycling network layout, door-to-door collection services, digital trading platform construction, etc.) on total recycled battery volume; and the influence of sales efforts invested by echelon utilization enterprises on market demand for secondary echelon batteries.

2. Problem Description and Model Assumptions

2.1. Problem Description

This paper investigates a closed-loop power battery supply chain system consisting of a new energy vehicle manufacturer (denoted as M), an automobile retailer (denoted as R), and an echelon utilization enterprise (denoted as T). The new energy vehicle manufacturer acts as the Stackelberg leader in the supply chain game [9,20]. As illustrated in Figure 1, the operational process is divided into a forward supply chain and a reverse supply chain. In the forward supply chain, the manufacturer produces new energy vehicles at a unit production cost c and wholesales them to the retailer at a unit wholesale price w ; the retailer further sells vehicles to end consumers at a unit retail price p . In the reverse supply chain, once power batteries reach their end of service life, the manufacturer collaborates with the retailer to conduct collection, inspection and preliminary processing of retired power batteries. Qualified retired batteries available for echelon utilization are sold to the echelon utilization enterprise at unit price w_t , and the enterprise resells such secondary batteries to the echelon energy storage market at unit price p_m . After the echelon-used batteries expire again, they will be delivered for material regeneration recycling. Meanwhile, the manufacturer directly conducts regeneration treatment on unqualified scrapped batteries recovered from the market, generating a net profit f per unit scrapped battery. Specifically, θ ($0 < \theta < 1$) represents the proportion of collected retired batteries suitable for echelon utilization, and the remaining proportion $1 - \theta$ refers to scrapped batteries only eligible for regeneration recycling [14]. A practical industrial example is China FAW Group. Relying on its subsidiary Fuaao Smart Energy Technology Co., Ltd. and Hongqi 4S stores, FAW undertakes the collection of retired power batteries. After battery testing and regrouping, FAW carries out two types of resource disposal: on the one hand, it cooperates with Shijiazhuang Kelin Electric Co., Ltd. to build a virtual power plant energy storage station adopting echelon-used batteries in Changchun; on the other hand, it establishes joint ventures with enterprises such as Zhejiang Huayou Recycling Technology Co., Ltd. to construct a lithium

battery waste regeneration project with an annual processing capacity of 10,000 tons. Against the above operational background, this paper designs coordination mechanisms for the closed-loop supply chain of new energy vehicle power batteries.

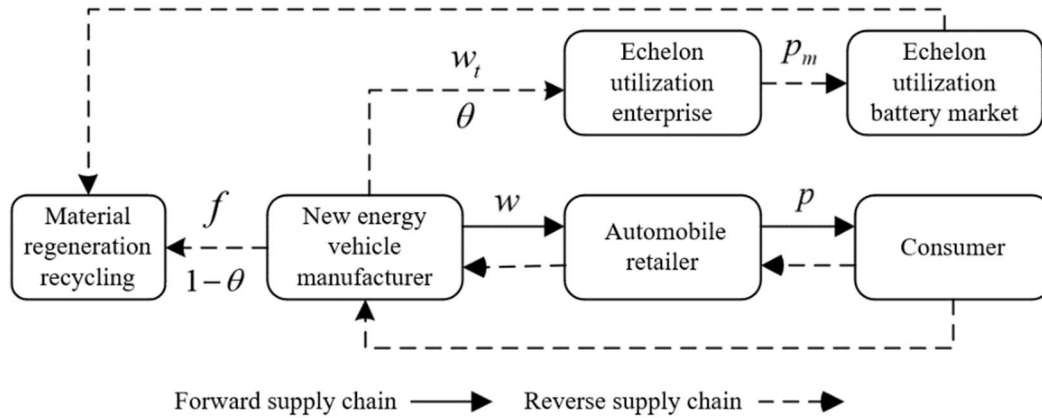


Figure 1. Schematic of the Closed-Loop Power Battery Supply Chain

2.2. Model Assumptions

The model in this paper is established based on the following assumptions:

Assumption 1: The market demand for new energy vehicles is a linear function of retail price p , denoted as $Q = a - p$ [14,17–21], where a represents the potential market demand for new energy vehicles.

Assumption 2: Drawing on the research of References [2,8,9,15,17,18,21], the total quantity of retired power batteries collected by the automobile manufacturer is defined as $Q_n = b + \beta e_r + \omega$. Among them, b represents the quantity of retired power batteries voluntarily returned by environmentally conscious vehicle owners; e_r denotes the recycling service level for retired power batteries jointly invested by the automobile manufacturer and retailer (including battery replacement costs, battery recycling acquisition prices, recycling network layout, door-to-door collection services, construction of digital trading platforms, etc.), and all costs $e_r^2 / 2$ incurred by recycling services are borne solely by the automobile manufacturer; β refers to consumers’ sensitivity coefficient to battery recycling services; ω is the residual value of retired power batteries.

Assumption 3: The retail price of echelon-reused power batteries is set as $p_m = m - \theta Q_n + e_i$ [22]. m represents the potential market scale of echelon-reused batteries; e_i denotes the sales effort invested by echelon utilization enterprises (such as market promotion, channel development, etc.), with corresponding sales effort cost expressed as $e_i^2 / 2$ [22]; θ stands for the proportion of collected retired batteries that are qualified for echelon utilization.

Assumption 4: To simplify the model without altering core research conclusions, the production cost of new energy vehicles is neglected $c = 0$ [16].

Superscripts A , B and C are adopted to represent the centralized decision-making model, decentralized decision-making model and coordination mechanism model, respectively. Subscripts M , R , T and S correspond to the automobile manufacturer, automobile retailer, echelon utilization enterprise and the whole closed-loop supply chain, separately. Definitions of all other symbolic variables are summarized in Table 1.

Table 1. Notations and Definitions

Notations	Definitions
w	wholesale price of new energy vehicles
w_t	unit selling price of retired power batteries from automobile manufacturers to echelon utilization enterprises
c_t	unit processing cost of retired batteries available for echelon utilization borne by automobile manufacturers
p	retail price of new energy vehicles
p_m	retail price of echelon-reused retired power batteries in the echelon utilization market
f	net profit per unit scrapped power battery from material regeneration for automobile manufacturers
θ	proportion of retired power batteries eligible for echelon utilization
Q	market demand for new energy vehicles
Q_n	total collection quantity of retired power batteries by automobile manufacturers
e_r	recycling service level of automobile manufacturers
e_t	sales effort level of echelon utilization enterprises
a	potential market demand for new energy vehicles
b	quantity of retired power batteries voluntarily returned by environmentally conscious vehicle owners
β	consumers' sensitivity coefficient to retired battery recycling services
ω	residual value of retired power batteries
m	potential market scale of echelon-reused power batteries
x	cost-sharing ratio of automobile manufacturers' recycling service costs undertaken by echelon utilization enterprises
K_1	lump-sum payment from automobile retailers to automobile manufacturers
K_2	lump-sum payment from automobile retailers to echelon utilization enterprises
π_j^i	profit of i under model $j, i \in \{A, B, C\}, j \in \{M, R, T, S\}$

3. Model Formulation

3.1. Centralized Decision-Making Model

Under the centralized decision-making framework, the automobile manufacturer, automobile retailer and echelon utilization enterprise act as an integrated decision-making entity. The optimal retail price p^{A*} of new energy vehicles, sales effort level e_t^{A*} and recycling service level e_r^{A*} are derived via centralized optimization to maximize the total profit of the entire closed-loop supply chain system. At this time, the total profit of the closed-loop supply chain is expressed as Eq. (1):

$$\pi_s^A = pQ + [f(1 - \theta) + (p_m - c_t)\theta]Q_n - \frac{1}{2}e_r^2 - \frac{1}{2}e_t^2 \tag{1}$$

In Equation (1), the first term stands for the revenue generated from new energy vehicle sales; the second term denotes the revenue obtained from the material regeneration of scrapped retired power batteries; the third term represents the revenue from the echelon utilization of qualified retired power batteries; the fourth term refers to the recycling service cost borne by

the automobile manufacturer; the fifth term is the sales effort cost incurred by the echelon utilization enterprise.

Based on Equation (1), the first-order conditions of π_S^A with respect to p , e_r and e_t can be derived as follows:

$$\frac{\partial \pi_S}{\partial p} = a - 2p = 0 \tag{2}$$

$$\frac{\partial \pi_S}{\partial e_r} = m\beta\theta - f\beta(\theta - 1) - \beta\theta c_t - e_r - 2\beta\theta^2(b + \omega + \beta e_r) + \beta\theta e_t = 0 \tag{3}$$

$$\frac{\partial \pi_S}{\partial e_t} = \theta(b + \omega + \beta e_r) - e_t = 0 \tag{4}$$

The Hessian matrix of π_S^A is given by:

$$A_3 = \begin{bmatrix} -2 & 0 & 0 \\ 0 & -1 - 2\beta^2\theta^2 & \beta\theta \\ 0 & \beta\theta & -1 \end{bmatrix}$$

The leading principal minors of Hessian matrix A_3 are $|A_1| = \frac{\partial^2 \pi_S}{\partial p^2} = -2$, $|A_2| = 2 + 4\beta^2\theta^2 > 0$ and $|A_3| = -2 - 2\beta^2\theta^2 < 0$, respectively. Therefore, π_S^A is jointly concave with respect to p , e_r and e_t . By simultaneously solving Equations (2)–(4), the unique optimal solution $\{p^{A*}, e_r^{A*}, e_t^{A*}\}$ that maximizes π_S^A can be obtained. The above analysis yields Proposition 1.

Proposition 1. (1) π_S^A is jointly concave in p , e_r and e_t . (2) There exists a unique optimal

solution $\{p^{A*}, e_r^{A*}, e_t^{A*}\}$ satisfying $e_r^{A*} = -\frac{\beta[f(\theta - 1) + \theta^2(b + \omega) - \theta m + \theta c_t]}{1 + \beta^2\theta^2}$,

$e_t^{A*} = \frac{\theta(b + f\beta^2 - f\beta^2\theta + m\beta^2\theta + \omega - \theta\beta^2 c_t)}{1 + \beta^2\theta^2}$, $p^{A*} = \frac{a}{2}$. (3) The profit of the closed-loop supply

chain equals $\pi_S^{A*} = p^{A*}Q + [f(1 - \theta) + (p_m - c_t)\theta]Q_n - \frac{1}{2}(e_r^{A*})^2 - \frac{1}{2}(e_t^{A*})^2$.

3.2. Decentralized Decision-Making Model

Under the decentralized decision-making framework, all stakeholders within the closed-loop supply chain make independent decisions to maximize their respective individual profits. As the automobile manufacturer acts as the dominant player in the closed-loop supply chain, the game follows a typical Stackelberg leader-follower game structure. Accordingly, the profit functions of the automobile manufacturer, automobile retailer and echelon utilization enterprise are formulated as follows:

$$\pi_M^B = wQ + w_r\theta Q_n + f(1 - \theta)Q_n - \frac{1}{2}e_r^2 \tag{5}$$

$$\pi_R^B = (p - w)Q \tag{6}$$

$$\pi_T^B = (p_m - w_t - c_t)\theta Q_n - \frac{1}{2}e_t^2 \tag{7}$$

By solving $\frac{\partial \pi_R^B}{\partial p} = a - 2p + w = 0$ and $\frac{\partial \pi_T^B}{\partial e_t} = \theta(b + \omega + \beta e_r) - e_t = 0$ separately, we obtain

$p^{B*} = \frac{a + w}{2}$ and $e_t^{B*} = \theta(b + \omega + \beta e_r)$. Substitute the expressions of p^{B*} and e_t^{B*} into Equation

(5) to solve for $\frac{\partial \pi_M^B}{\partial e_r} = \beta(f - f\theta + \theta w_t) - e_r = 0$, and $e_r^{B*} = \beta(f - f\theta + \theta w_t)$ can be derived.

Finally, substitute e_r^{B*} into the expression of e_t^{B*} , and further substitute the optimal values of e_r^{B*} , p^{B*} and e_t^{B*} into Equations (5)–(7), which yields Proposition 2.

Proposition 2. Under decentralized decision-making, there exists a unique optimal decision $\{p^{B*}, e_r^{B*}, e_t^{B*}\}$ that maximizes π_M^B , π_R^B and π_T^B . The corresponding optimal values are

$p^{B*} = \frac{a + w}{2}$, $e_t^{B*} = \theta[b + \omega + \beta^2(f - f\theta + \theta w_t)]$ and $e_r^{B*} = \beta(f - f\theta + \theta w_t)$; the optimal profits of each participant and the whole closed-loop supply chain are expressed as follows:

$$\pi_M^{B*} = \frac{1}{2}w(a - w) - \frac{1}{2}\beta^2(f - f\theta + \theta w_t)^2 + (f - f\theta + \theta w_t)[b + \omega + \beta^2(f - f\theta + \theta w_t)]$$

$$\pi_R^{B*} = \frac{(a - w)^2}{4}$$

$$\pi_T^{B*} = \frac{1}{2}\theta[b + \omega + \beta^2(f - f\theta + \theta w_t)]\{2(m - c_t - w_t) - \theta[b + \omega + \beta^2(f - f\theta + \theta w_t)]\}$$

$$\begin{aligned} \pi_S^{B*} &= \frac{1}{4}(a - w)^2 + \frac{1}{2}(a - w)w - \frac{1}{2}\beta^2(f - f\theta + \theta w_t)^2 + (f - f\theta + \theta w_t)[b + \omega + \beta^2(f - f\theta + \theta w_t)] \\ &+ \frac{1}{2}\theta[b + \omega + \beta^2(f - f\theta + \theta w_t)]\{2(m - c_t - w_t) - \theta[b + \omega + \beta^2(f - f\theta + \theta w_t)]\} \end{aligned}$$

Assume that $e_r^{B*} = e_r^{A*}$, then we can solve and derive

$$m = \frac{[f(1 - \theta) + \theta w_t](1 + \beta^2\theta^2) - f(1 - \theta) + \theta^2(b + \omega) + \theta c_t}{\theta}$$

. Substitute m into

$$e_t^{A*} = \frac{\theta(b + f\beta^2 - f\beta^2\theta + m\beta^2\theta + \omega - \theta\beta^2c_t)}{1 + \beta^2\theta^2}, \text{ and we obtain } e_t^{A*} - e_t^{B*} = \frac{f(\theta - 1)\beta^2\theta^2}{1 + \beta^2\theta^2} \neq 0.$$

Consequently, there exists no scenario where both A and B can hold simultaneously, which leads to Proposition 3.

Proposition 3. The optimal recycling service input level and sales effort input level under the decentralized decision-making framework cannot coincide with those obtained in the centralized decision-making model at the same time. Hence, decentralized decision-making fails to realize the coordination of the closed-loop supply chain for power batteries.

3.3. Decentralized Decision-Making Model

To address the poor coordination arising from conflicting objectives among supply chain participants under decentralized decision-making, a novel coordination mechanism named "recycling service cost-sharing and two-part tariff" is designed to restructure the coordination relationship within the closed-loop supply chain. This coordination mechanism is denoted as (x, w, K_1, K_2) , with detailed rules elaborated as follows: 1) Since the automobile manufacturer bears a huge burden of recycling service costs independently, the echelon utilization enterprise undertakes a proportion $x(0 < x < 1)$ of the manufacturer's recycling service costs to secure a larger supply of retired power batteries, thereby incentivizing the manufacturer to elevate its recycling service level. For practical illustration, Zhejiang Huayou Recycling Technology Co., Ltd., a real-world echelon utilization enterprise, has delivered critical support to BMW Group in the retired power battery recycling business. 2) The automobile retailer provides lump-sum payments K_1 and K_2 to the automobile manufacturer and the echelon utilization enterprise respectively to subsidize retired battery collection and subsequent echelon utilization activities. As a practical case, Hyundai's Canadian dealership network consistently supports Hyundai Motor's retired power battery recycling and echelon utilization programs. Under the "recycling service cost-sharing plus two-part tariff" mechanism, the profit functions of each supply chain participant are formulated as follows:

$$\pi_M^C = wQ + w_t\theta Q_n + f(1-\theta)Q_n - \frac{(1-x)}{2}e_r^2 + K_1 \tag{8}$$

$$\pi_R^C = (p-w)(a-p) - (K_1 + K_2) \tag{9}$$

$$\pi_T^C = (p_m - w_t - c_t)\theta Q_n - \frac{1}{2}e_t^2 - \frac{x}{2}e_r^2 + K_2 \tag{10}$$

The solution procedure is consistent with the above analysis, from which Proposition 4 can be derived.

Proposition 4. Under the coordination mechanism model, there exists a unique optimal decision $\{p^{C*}, e_r^{C*}, e_t^{C*}\}$ that maximizes π_M^C , π_R^C and π_T^C . The corresponding optimal values of

$$\{p^{C*}, e_r^{C*}, e_t^{C*}\} \text{ are } e_t^{B*} = \theta(b+w) + \frac{\theta\beta f(1-\theta) + \theta^2\beta w_t}{1-x}, \quad p^{C*} = \frac{a+w}{2} \text{ and } e_r^{C*} = \frac{\beta f(1-\theta) + \beta\theta w_t}{1-x}.$$

The optimal profit functions of each participant and the entire closed-loop supply chain are expressed as:

$$\pi_M^{C*} = w(a - p^{C*}) + [\theta w_t + (1-\theta)f](b + \beta e_r^{C*} + \omega) - \frac{(1-x)}{2}(e_r^{C*})^2 + K_1$$

$$\pi_R^{C*} = (p^{C*} - w)(a - p^{C*}) - (K_1 + K_2)$$

$$\pi_T^{C*} = \theta[m - \theta(b + \beta e_r^{C*} + \omega) + e_t^{C*} - w_t - c_t](b + \beta e_r^{C*} + \omega) - \frac{1}{2}(e_t^{C*})^2 - \frac{x}{2}(e_r^{C*})^2 + K_2$$

$$\pi_S^{C*} = p^{C*}(a - p^{C*}) + [f(1-\theta) + \theta(m - c_t)](b + \beta e_r^{C*} + \omega) + \theta(b + \beta e_r^{C*} + \omega)e_t^{C*} - \theta^2(b + \beta e_r^{C*} + \omega)^2 - \frac{1}{2}(e_r^{C*})^2 - \frac{1}{2}(e_t^{C*})^2$$

Proposition 5. If parameter (x, w, K_1, K_2) satisfies Equation (11), then $p^{C^*} = p^{A^*}$, $e_r^{C^*} = e_r^{A^*}$ and $e_t^{C^*} = e_t^{A^*}$ hold. Under this condition, the proposed mechanism can achieve the coordination of the closed-loop supply chain for power batteries, and the profits of the automobile manufacturer, automobile retailer and echelon utilization enterprise are given by Equation (12).

$$\begin{cases} w = 0 \\ x = \frac{2f\theta - 2f - m\theta + b\theta^2 - f\beta^2\theta^2 + f\beta^2\theta^3 + \theta^2\omega + \theta c_t - (\theta + \beta^2\theta^3)w_t}{f(\theta - 1) + \theta[\theta(b + \omega) - m] + \theta c_t} \end{cases} \tag{11}$$

$$\begin{cases} \pi_M^{C^*} = A\pi_S^{A^*} + K_1 \\ \pi_R^{C^*} = B\pi_S^{A^*} - (K_1 + K_2) \\ \pi_T^{C^*} = (1 - A - B)\pi_S^{A^*} + K_2 \end{cases} \tag{12}$$

$$\begin{cases} A = \frac{[\theta w_t + (1 - \theta)f](b + \beta e_r^{A^*} + \omega) + w(a - p^{A^*}) - \frac{(1 - x)}{2}(e_r^{A^*})^2}{\pi_S^{A^*}} \\ B = \frac{(p^{A^*} - w)(a - p^{A^*})}{\pi_S^{A^*}} \end{cases} \tag{13}$$

Table 2. Calculation Results under Different Models

Model	p	e_r	e_t	π_M	π_R	π_T	π_S
Centralized Decision-Making	15	3.53	6.88	—	—	—	300.39
Decentralized Decision-Making	20	1.39	5.98	118.78	100	53.89	272.67
Coordination Mechanism	15	3.53	6.88	$46.27 + K_1$	$225 - K_1 - K_2$	$39.12 + K_2$	300.39

Proposition 6. When the closed-loop supply chain of power batteries achieves coordination, if the lump-sum payments K_1 and K_2 satisfy Equation (14), then $\pi_M^{C^*} > \pi_M^{B^*}$, $\pi_R^{C^*} > \pi_R^{B^*}$ and $\pi_T^{C^*} > \pi_T^{B^*}$ hold. In this case, the profits of the automobile manufacturer, automobile retailer and echelon utilization enterprise can realize Pareto improvement.

$$\begin{cases} \max\{\pi_M^{B^*} - A\pi_S^{A^*}, 0\} < K_1 \\ < [B\pi_S^{A^*} - \pi_R^{B^*} - \max\{\pi_T^{B^*} - (1 - A - B)\pi_S^{A^*}, 0\}] \\ \max\{\pi_T^{B^*} - (1 - A - B)\pi_S^{A^*}, 0\} < K_2 < B\pi_S^{A^*} - \pi_R^{B^*} - K_1 \end{cases} \tag{14}$$

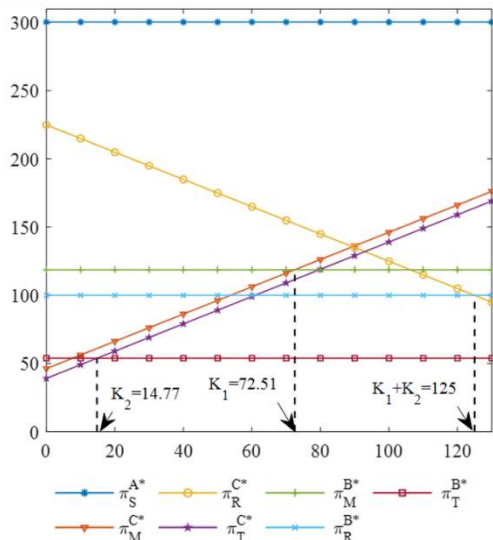


Figure 2. Impacts of Lump-Sum Payment K_1 or K_2 on Profits

4. Conclusion

This paper investigates the design of coordination mechanisms for a closed-loop power battery supply chain composed of new energy vehicle manufacturers, automobile retailers and echelon utilization enterprises. It first identifies the baseline conditions for realizing supply chain coordination, then analyzes the coordination performance of the decentralized decision-making model. Drawing on practical power battery operation cases of BMW and Hyundai, a novel coordination mechanism integrating recycling service cost-sharing and two-part tariff is established. The main research findings are summarized as follows:

- 1) Affected by the double marginalization effect, the closed-loop power battery supply chain under decentralized decision-making fails to coordinate the operational decisions of all participants. By contrast, the proposed recycling service cost-sharing and two-part tariff mechanism can effectively coordinate the supply chain and achieve global optimization of the entire closed-loop system. Meanwhile, Pareto improvement can be realized for the profits of all supply chain members.
- 2) Under decentralized decision-making, the automobile manufacturer acts as the Stackelberg leader pursuing maximum individual profit. The manufacturer bears all costs of recycling service investment, yet the corresponding benefits are shared by retailers and echelon utilization enterprises, which tends to lead to insufficient recycling service input. Similarly, the marginal revenue generated by the sales efforts of echelon utilization enterprises is partially captured by manufacturers, making their sales effort level lower than the optimal benchmark under centralized decision-making. In centralized decision-making, the profits of the three parties are internalized. All benefits from echelon utilization and material regeneration brought by recycling services accrue to the whole supply chain, and all marginal gains from sales efforts are retained by the integrated system. Accordingly, both the recycling service level and sales effort level are higher under centralized decision-making. Such disparities stem from the persistence of double marginalization in decentralized scenarios and its elimination under centralized decision-making.

Acknowledgments

This work was supported by the Social Science Planning Project of Chongqing(2024NDYB075), and the Humanities and Social Sciences Research Project of Chongqing Municipal Education Commission (25SKGH135; 23SKGH159).

References

- [1] Jia, J. X., & Zhao, X. K. (2022). Battery endurance and recycling strategies of a new energy vehicle supply chain under government subsidies. *Journal of Systems Engineering*, 37, 330–343.
- [2] Jiao, J. L., Pan, Z. T., et al. (2024). Selection of power battery recycling model considering economic benefits of reuse and emission efficiency. *Chinese Journal of Management Science*, 32, 201–213.
- [3] Anonymous. (2018). Interpretation of the Interim Measures for the Administration of Recycling and Utilization of Power Batteries for New Energy Vehicles. *Resources Economization & Environmental Protection*, 4, 3–5.
- [4] China Finance Economic Journal. (2025, March 27). [Web page]. https://www.cfej.net/ztl/lmjt/202503/t20250327_1104847.shtml
- [5] People.cn. (2024, July 22). [Web page]. https://paper.people.com.cn/zgnybwap/html/2024-07/22/content_26071600.htm
- [6] Li, X. (2022). Collection mode choice of spent electric vehicle batteries: Considering collection competition and third-party economies of scale. *Scientific Reports*, 12, 6691. <https://doi.org/10.1038/s41598-022-10758-9>
- [7] Wang, Y., Zhang, Z., et al. (2023). Collaborative decision-making based on effort level: power battery recycling alliance. *Procedia Computer Science*, 221, 1155–1161.
- [8] Jiao, J., Pan, Z., & Li, J. (2024). Selection of power battery recycling model considering economic benefits of reuse and emission efficiency. *Chinese Journal of Management Science*, 32, 201–213.
- [9] Bai, Y. H., Peng, L., & Cheng, J. H. (2025). The selection of the combined recycling mode of used power batteries considering the recycling target responsibility. *Operations Research and Management Science*. <https://link.cnki.net/urlid/34.1133.G3.20250928.1424.006>
- [10] Tang, Y., Zhang, Q., Li, Y., et al. (2018). Recycling mechanisms and policy suggestions for spent electric vehicles' power battery -A case of Beijing. *Journal of Cleaner Production*, 186, 388–406. <https://doi.org/10.1016/j.jclepro.2018.03.156>
- [11] Zhang, Q., Tang, Y., Bunn, D., et al. (2021). Comparative evaluation and policy analysis for recycling retired EV batteries with different collection modes. *Applied Energy*, 303, 117614. <https://doi.org/10.1016/j.apenergy.2021.117614>
- [12] Zhang, M., Wu, W., & Song, Y. (2023). Study on the impact of government policies on power battery recycling under different recycling models. *Journal of Cleaner Production*, 413, 137492. <https://doi.org/10.1016/j.jclepro.2023.137492>
- [13] Liu, Y., Zhong, L., & Tong, P. (2023). Research on Recovery Decision of Waste Power Battery under Subsidy-Penalty Policy. *Chinese Journal of Management Science*, 31, 90–102.
- [14] Chuan, Z., & Yu, C. (2021). Decision and coordination of cascade utilization power battery closed-loop supply chain with economies of scale under government subsidies. *Operations Research and Management Science*, 30, 72.
- [15] Wu, W., & Zhang, M. (2025). Decision-making analysis of power battery recycling under carbon cap-and-trade mechanism and subsidy policy. *Chinese Journal of Management Science*, 33, 340–354.
- [16] Liu, Z., Hui, W., Liu, C. Y., et al. (2024). Optimal decisions and coordination of power battery remanufacturing supply chain under irrational preferences. *Journal of Systems & Management*, 33, 29.
- [17] Liu, J., Xue, J. W., & Zhang. (2022). Contract coordination of power battery collecting channels under the government carbon tax and recycling subsidy. *Science and Technology Management Research*, 42, 160–168.
- [18] Anonymous. (2024). Pricing and Coordination Strategy of Power Battery Closed-loop Supply Chain Under Policy. *Industrial Engineering and Management*, 29, 147–158.
- [19] Zhou, X., Qiu, J., & Liu, Y. (2025). Contractual Coordination Strategies for the Power Battery Recycling Supply Chain Under Different Subsidy Policies. *Scientific Decision Making*, 6, 185–198.
- [20] Ding, J. F. (2025). Closed-loop Supply Chain Decisions and Coordination of New Energy Vehicle Power Battery under Cost-sharing Contract. *Industrial Engineering and Management*, 30, 63–74.

- [21] Chong, D. S., Sun, N., & Shao, S. R. (2020). Closed-loop Supply Chain of Vehicle Power Battery under Multiple Leading Modes. *Mathematics in Practice and Theory*, 50, 68–74.
- [22] Cachon, G. P., & Lariviere, M. A. (2005). Supply chain coordination with revenue-sharing contracts: strengths and limitations. *Management Science*, 51, 30–44.
<https://doi.org/10.1287/mnsc.1040.0297>