Decision-making of power battery closed-loop supply chain considering corporate social responsibility and echelon utilization

Kuiyang Hu and Qiang Hou
School of Management, Shenyang University of Technology, Shenyang, China

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Abstract

Purpose – The purpose of this paper is to optimize strategic decisions and profit distribution among members of the power battery closed-loop supply chain (CLSC), considering both competition and cooperation dynamics.
Design/methodology/approach – This study employs the noncooperative-cooperative biform game approach to examine strategy optimization and profit distribution among CLSC members for electric vehicle (EV) power batteries. The model integrates manufacturers' corporate social responsibility (CSR) considerations and competitive recycling dynamics between recyclers and echelon utilization enterprises. Numerical simulations are employed to evaluate how key parameters influence optimal decisions and profit distribution.
Findings – Excessive competition in recycling reduces the supply chain's operational efficiency and negatively affects profits. Recyclers and echelon utilization enterprises should reduce competitive pressures. Higher echelon utilization rates improve supply chain efficiency and promote retired battery recycling. Manufacturers and echelon utilization firms should prioritize investments in utilization technologies and operational productivity. Furthermore, optimizing input costs while balancing CSR investments can enhance mutual benefits among supply chain members.
Originality/value – This paper applies the noncooperative-cooperative biform game to advance theoretical research on power battery CLSC, investigating the interplay between cooperation and competition among supply chain members. The study provides managerial insights for optimizing recycling competition and CSR investment strategies, offering practical value for coordinating stakeholder interests in the power battery CLSC with echelon utilization.

Keywords Closed-loop supply chain, Power battery, Echelon utilization, Corporate social responsibility, Noncooperative-cooperative biform game

Paper type Research paper

1. Introduction

The rapid advancement of new energy technology and the growing public awareness of energy conservation and environmental protection have led to a significant surge in the sales of new energy vehicles (NEVs) in recent years. Since 2015, China has emerged as the world's largest market for NEVs. In 2024, the sales volume of NEVs reached 12.866 million units, representing a year-on-year increase of 35.5%, according to data released by the China Association of Automobile Manufacturers (CAAM). By 2030, electric vehicle sales are projected to surpass 80 million units (Zhang *et al.*, 2023a). Power batteries, which are core components of NEVs, typically have a lifespan of five to eight years. Due to the increase in NEV sales, the number of retired power batteries has significantly increased, with an expected

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total of 1.9 million tonnes by 2030 (Tan *et al.*, 2023). The large-scale retirement of power batteries has made their recycling and reuse increasingly more urgent.

Typically, a power battery must be replaced with a new one when its capacity drops to 70–80% of its initial value, at which point the old battery is considered retired. Although the electrolyte from retired batteries contains harmful substances such as nickel, cobalt, manganese, and fluorine, improper handling may release toxic gases that pose risks to human health and the environment upon contact with water or acid. Conversely, direct disposal of raw materials from old batteries (e.g. cobalt and lithium, which are valuable metals) would lead to significant resource waste. Retired power batteries can be effectively managed through two methods: echelon utilization and dismantling for reuse. Echelon utilization involves converting retired batteries into reusable products through disassembly, residual capacity testing, screening, and reconfiguration when their capacity ranges from 30 to 80% of the initial value. These products are widely deployed in industries such as communication base stations and energy storage power stations (Akhil *et al.*, 2020). Dismantling and reuse refer to extracting metals such as nickel, cobalt, lithium, manganese, and others through crushing, disassembly, and melting when a battery's capacity is below 30%. Retired power batteries undergo a closed-loop process termed "power battery recycling—echelon utilization—dismantling and reuse," which is crucial for safeguarding the economy, conserving resources, and protecting the environment while also enhancing resource utilization and promoting sustainable development (Zhang *et al.*, 2020).

Motivated by the dual drivers of recycling demand and the value of echelon utilization, the power battery industry has formed a multi-stakeholder competitive structure characterized by complex stakeholder interactions. Currently, the market is dominated by three primary types of recycling entities: (1) retailer-based distribution-side recyclers; (2) third-party professional recyclers such as Brunp Recycling and GEM Co., Ltd.; and (3) echelon utilization enterprises that function as both consumers and producers, such as China Tower Corporation. Significantly, leading power battery manufacturers, including BYD and CATL, are rapidly expanding into echelon utilization for retired batteries. CATL, through its subsidiary Brunp Recycling, has established a full lifecycle closed-loop system covering battery design, production, usage, echelon utilization, and recycling and resource regeneration. Meanwhile, BYD operates an echelon utilization facility within its industrial park, processing 12,000 tonnes of end-of-life batteries in 2024. Its Blade Battery echelon products have been deployed in the Guangxi 10 MW Energy Storage Power Station and retrofit projects for low-speed electric vehicles in collaboration with Green Energy Universe. The diversification of recyclers, combined with manufacturers' vertical integration into echelon utilization operations, has intensified heterogeneous competition and conflicting interests among stakeholders across the supply chain. This dynamic landscape, however, reveals a critical challenge: the lack of effective coordination mechanisms to balance the dynamic interplay of cooperation and competition among manufacturers, recyclers, and echelon utilization enterprises. Existing theoretical frameworks have not yet adequately addressed this complexity, particularly when CSR considerations are integrated into strategic decision-making.

While existing research has predominantly focused on recycling channel decision-making (Sun *et al.*, 2022; Wu *et al.*, 2024), existing studies have not fully addressed the operational strategies of manufacturers like CATL and BYD who simultaneously act as producers and echelon utilization providers. Operational practices of power battery manufacturers in echelon utilization, though preliminarily explored (Gu *et al.*, 2021; Zhao *et al.*, 2024), have not been sufficiently contextualized within frameworks that address how their integration reshapes competitive dynamics and profit allocation, particularly when CSR considerations are integrated into strategic decision-making. Notably, despite growing recognition of CSR's strategic importance in sustainable development (Yi *et al.*, 2024), its role in influencing strategic decisions within power battery CLSCs—specifically in balancing cooperative echelon utilization and competitive recycling—remains under-researched. Existing studies have highlighted CSR's impacts on corporate competitiveness through resource efficiency

(Sangari *et al.*, 2023; Sana, 2023), yet modeling CSR-influenced profit allocation mechanisms in multi-stakeholder contexts remains an open area for investigation (Tian *et al.*, 2022).

The analysis presented above forms the basis for this paper's exploration of three major issues:

1. When echelon utilization businesses and recyclers compete in end-of-life power battery recycling channels, how will they coordinate their interests?
2. In light of CSR, how does power battery manufacturers' participation in echelon utilization impact various supply chain participants, and how can manufacturers maximize profits?
3. How should supply chain participants optimize strategies and distribute profits amidst competitive and collaborative dynamics among power battery manufacturers, recyclers, and echelon utilization enterprises?

The remainder of this paper is organized as follows. Section 2 reviews relevant literature. Section 3 identifies research questions and develops hypotheses. Section 4 constructs a biform game model for the CLSC, deriving equilibrium strategies and profits. Section 5 analyzes parametric effects on equilibria. Section 6 performs numerical simulations of competition intensity, echelon utilization ratio, CSR sensitivity, and cost coefficients. Section 7 presents research findings, managerial implications, and future research directions.

2. Literature review

The literature is divided into three main sections: (1) power battery echelon utilization CLSCs, (2) CSR in supply chain management, and (3) noncooperative-cooperative biform game applications in supply chain management.

2.1 Power battery echelon utilization CLSCs

Research on power battery echelon utilization CLSCs has primarily focused on carbon emission cap-and-trade policies, subsidy mechanisms, and strategic interactions among echelon utilization firms, manufacturers, and recyclers. For example, Liu and Ma (2021) analyzed how subsidy levels and allocation strategies influence power battery CLSCs with a focus on the echelon utilization market. Zhang *et al.* (2022) examined recycling under carbon trading policies and investigated decarbonization strategies adopted by retailers, recyclers, and secondary users. Hou *et al.* (2023) further explored equilibrium strategies for manufacturers, recyclers, and secondary users, incorporating fairness considerations into supply chain game theory. Zhang *et al.* (2024a) evaluated CLSC models with and without manufacturer-led echelon utilization operations to determine optimal participation strategies. Gu *et al.* (2021) assessed the impact of government subsidies on a two-stage CLSC involving governmental bodies, secondary consumers, and manufacturers. Zhang *et al.* (2024c) demonstrated that hybrid subsidy policies significantly enhance recycling rates and secondary market demand. However, two aspects remain understudied in current research: (1) the operational realities of power battery manufacturers and (2) the interplay between competitive and cooperative dynamics among supply chain participants.

2.2 CSR in supply chain management

Existing studies on the impact of CSR on supply chain management primarily examine pricing strategies and recovery rate optimization under manufacturer-led CSR initiatives. Panda *et al.* (2017) analyzed recycling channel coordination mechanisms in a CSR-driven supply chain, emphasizing incentive alignment among stakeholders. Tang *et al.* (2023) investigated how revenue-sharing contracts and two-part tariff pricing affect CSR-driven product pricing and recovery rate decisions to enhance supply chain coordination. Sana (2020) integrated CSR into a supply chain inventory decision framework, developing competitive newsvendor models for green and non-green products under government subsidies and taxation policies. Wang *et al.* (2020) empirically demonstrated that CSR investments increase market share, reduce consumer prices, and boost profit margins in supply chains with intense competition. Sana (2021) constructed decentralized and centralized supply chain decision models to analyze price competition between green and conventional manufacturers under CSR constraints. The study proposed market strategies for green quality optimization through equilibrium pricing. Liu *et al.* (2022) developed dual-channel recycling supply chain models incorporating and excluding CSR integration, comparing their operational and environmental impacts. Raj *et al.* (2020) examined supplier and purchaser decision-making under isolated and integrated CSR and green production scenarios to identify trade-offs between economic and sustainability objectives. Yi *et al.* (2024) developed a tripartite Stackelberg game model involving CSR-driven manufacturers, e-commerce platforms, and recyclers, demonstrating that moderate CSR commitments can optimize manufacturers' profitability. While existing research has extensively examined CSR implementation in supply chains, the specific implications for strategic decision-making and profit allocation in dual-channel recycling product recycling systems remain under-explored when manufacturers adopt CSR practices.

2.3 Noncooperative-cooperative biform game applications in supply chain management

Traditional cooperative or non-cooperative game theory has struggled to capture the hybrid nature of simultaneous collaboration and competition inherent in supply chain interactions. Brandenburger and Stuart (2007) pioneered the biform game theory, later extending it to non-cooperative-cooperative biform games to model the interplay of collaborative and competitive behaviors among supply chain participants. Huang and Li (2024) applied this framework to analyze strategy optimization and profit allocation mechanisms among manufacturers, retailers, and recyclers within government-regulated deposit-refund systems. Zheng and Li (2023) employed the noncooperative-cooperative biform game framework to examine ecological efficiency investment incentives between competing manufacturers and suppliers offering technological investments in green manufacturing. Nan *et al.* (2025) developed a biform game model to analyze carbon emission reduction technology collaboration between competing manufacturers in blockchain-enabled low-carbon markets. Their framework leverages blockchain transparency to address coordination challenges under output rivalry. While these applications demonstrate theoretical promise, their implementation in CLSCs for NEV power batteries requires further investigation, particularly in coordinating the interplay of cooperative and competitive dynamics among echelon utilization enterprises, recyclers, and manufacturers.

2.4 Research gap and contribution

Building on the systematic literature review and comparative analysis summarized in Table 1, three key limitations are identified in current research on CLSCs for power battery recycling: First, existing studies have not fully addressed profit-sharing coordination between recyclers and echelon utilization enterprises in competitive recycling channels (Sun *et al.*, 2022; Wu *et al.*, 2024). Second, research on CSR has not systematically analyzed supply chain decision-making when manufacturers engage in echelon utilization operations (Yi *et al.*, 2024). Third, traditional single-game frameworks struggle to reconcile the inherent tensions between market competition in recycling channels and cooperative profit allocation (Yu and Hou, 2023; Zhao *et al.*, 2024).

To address these gaps, this study aims to provide the following contributions: First, the proposed CLSC model integrates market competition between recyclers and echelon utilization enterprises with manufacturers' echelon utilization-related operational decisions, thereby enhancing practical relevance. Second, incorporating CSR into competitive recycling channel analysis enables the identification of coordination mechanisms for socially

Table 1. Comparison with existing literature

Author(s)	CLSC	Echelon utilization	CSR	Game-theoretic methods	Other
Liu and Ma (2021)	✓	✓		Stackelberg game	Subsidy
Hou *et al.* (2023)	✓	✓		Differential game	Fair concerns
Zhang *et al.* (2024a)	✓	✓		Stackelberg game, Nash game	Cap-and-trade policy
Zhao *et al.* (2024)		✓		Stackelberg game	Disassembly design
Tang *et al.* (2023)	✓		✓	Nash bargaining	Revenue sharing contract
Liu *et al.* (2022)	✓		✓	Stackelberg game	Pricing decision
Yi *et al.* (2024)	✓		✓	Stackelberg game	Green innovation
Pal and Sana (2022)	✓			Stackelberg game, Nash game	Dual-channel supply chain
Barman *et al.* (2024)	✓			Stackelberg game	Sales effort
Pal *et al.* (2024)	✓			Stackelberg game, Nash game	Green investment
Li *et al.* (2023)	✓			Biform game	Deposit refund
Zheng and Li (2023)				Biform game	Eco-efficient innovation
Nan *et al.* (2025)				Biform game	Blockchain technology
This paper	✓	✓	✓	Biform game	Echelon utilization market

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responsible manufacturers. Third, the introduction of the non-cooperative-cooperative biform game framework overcomes the limitations of traditional single-game approaches. During the non-cooperative phase, the model simulates recycling channel competition. In the cooperative phase, Shapley value-based profit allocation facilitates equitable distribution. This dual-phase framework offers analytical tools for coordinating multi-stakeholder relationships while explicitly considering CSR-driven pricing and allocation strategies of manufacturers. Compared to existing literature, these theoretical advances extend the CLSC research paradigm for competitive recycling scenarios and provide practical implications for industry stakeholders.

3. Problem description and assumptions

The CLSC system examined in this study comprises a single power battery manufacturer, recyclers, and echelon utilization enterprises to investigate supply chain optimization under CSR constraints. In the forward supply chain, the manufacturer produces new batteries using both virgin materials and recycled materials, which are then distributed to the electric vehicle market.

Notably, the manufacturer engages in echelon utilization operations by repurposing qualified retired batteries for secondary applications such as energy storage systems while maintaining its primary production activities. This production process follows the extended producer responsibility (EPR) principle, where the manufacturer adopts CSR-driven operational strategies that include a dual-sourcing procurement approach: virgin materials for primary production and recycled materials obtained through reverse logistics channels.

Concurrently, the reverse supply chain utilizes a tiered processing mechanism for retired power batteries. Following echelon utilization screening that identifies technically viable batteries for secondary applications, non-viable units are subjected to professional dismantling to recover metallic resources. In this system, traditional recyclers are responsible for collection and transportation operations, while echelon utilization enterprises focus on repurposing activities and then transfer residual materials back to the manufacturer. The complete operational workflow of this CLSC system is illustrated in Figure 1.

To clarify the research question, the relevant symbols and their definitions are summarized in Table 2.

Based on the research objectives, the following assumptions are formulated:

Assumption 1. Similar to Savaskan *et al.* (2004), we posit that power batteries produced by the manufacturer using virgin and recycled materials are homogeneous, and a uniform pricing strategy is adopted in the consumer market.

Assumption 2. Based on consumer behavior theory, the market demand for power batteries is jointly influenced by the selling price p and the manufacturer's CSR effort level θ. Drawing on Yao *et al.* (2021) and Sinayi and Rasti-Barzoki (2018), we define the demand function as: $Q = a - \beta p + \lambda\theta$, where a denotes the market size, β represents the price sensitivity coefficient, and λ captures consumer responsiveness to CSR efforts.

Assumption 3. Reflecting the increasing marginal cost of CSR investments (Modak *et al.*, 2018), the manufacturer's CSR cost function is modeled as a convex quadratic function: $C(\theta) = \frac{1}{2}\eta\theta^2$, where η is the CSR effort cost coefficient. Higher values of η indicate greater implementation costs.

Assumption 4. Building on Huang *et al.* (2013), recycling investment costs are modeled as quadratic functions of collection rates to reflect increasing marginal recycling costs, where the recyclers' and echelon utilization enterprises' costs are defined as $I_c = \sigma\tau_c^2$ and $I_t = \sigma\tau_t^2$, respectively. The collection rates $\tau_i(i = \{c, t\})$ are determined by the relationship $\tau_i = \sqrt{I_i^*/\sigma}$, where σ represents the recycling cost coefficient. Drawing from Savaskan *et al.* (2004) and Zheng *et al.* (2018), the effective recycling investment I_i^* for each participant depends not only on their investment I_i but also on competitive interactions with rivals: $I_i = I_i^* + \alpha_i I_j, i, j \in \{c, t\}, i \neq j$, where $\alpha_i (0 \leq \alpha_i < 1)$ quantifies the intensity of competition between recyclers and echelon utilization enterprises. Unlike studies emphasizing asymmetric competition (Li *et al.*, 2023), this work assumes symmetric

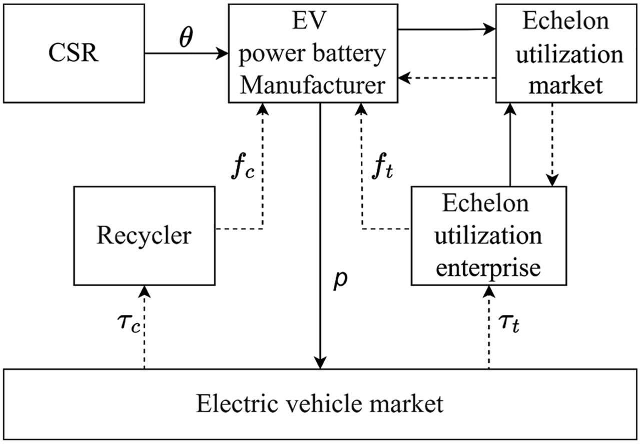

Figure 1. The CLSC operation model. **Source(s):** Created by authors

Table 2. Parameters of the model

Symbol	Description
Variables	
c_m	Unit production cost of new power batteries using virgin materials
c_o	Unit production cost of remanufactured power batteries using recycled materials
Δ	Unit cost saving from using recycled materials ($\Delta = c_m - c_o$)
a	The base market potential for power batteries
β	Consumer price sensitivity coefficient
λ	Consumer sensitivity to manufacturer's CSR efforts
η	CSR cost coefficient
σ	Recycling cost coefficient for collectors
α	Intensity of recycling competition between recyclers and echelon utilization enterprises
c_c	Unit collection price offered by recyclers to consumers
c_t	Unit collection price offered by echelon utilization enterprises to consumers
φ	Proportion of retired batteries suitable for echelon utilization
Decision variables	
p	Unit selling price of new power batteries
θ	Manufacturer's CSR effort level
τ_c	Collection rate by recyclers
τ_t	Collection rate by echelon utilization enterprises
f_c	Unit transfer price of retired batteries from recyclers to manufacturer
f_t	Unit transfer price of retired batteries from echelon utilization enterprises to manufacturer
Functions	
Q	Market demand function for power batteries
$C(\theta)$	Manufacturer's CSR cost function
I_c, I_t	Recycling investment costs for Recyclers and echelon utilization enterprises
π_m, π_c, π_t	Profits of manufacturers, recyclers, and echelon utilization enterprises

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competition intensity $(\alpha_c = \alpha_t = \alpha)$ to streamline the analysis while preserving core mechanisms. Consequently, the recycling cost functions are defined as:

$$I_c = \frac{\sigma\left(\tau_c^2 + \alpha\tau_t^2\right)}{1 - \alpha^2}, I_t \frac{\sigma\left(\tau_t^2 + \alpha\tau_c^2\right)}{1 - \alpha^2}.$$

Assumption 5. To capture battery capacity degradation, the revenue from echelon utilization is defined as $U = \upsilon\widetilde{L}$, where $\widetilde{L}$ (remaining capacity) follows a normal distribution with mean μ_L and variance σ_L^2. Here, υ denotes the profit coefficient per unit of echelon utilization, representing the net profit gained from repurposing one retired battery. The expected net profit per retired battery is $u = \upsilon\mu_L$ (Li, 2020).

Assumption 6. The echelon utilization rate $\varphi(0 < \varphi < 1)$ is the same for both the manufacturer and echelon utilization enterprises.

Assumption 7. The manufacturer's unit cost saving from using recycled materials is given by $\Delta = c_m - c_o$ (Zhang *et al.*, 2024b). To ensure economic viability and incentivize participation, the following constraints are imposed: $c_c < f_c < \Delta + \varphi u$, $c_t < f_t < \Delta$. These inequalities enhance the model by Zhang *et al.* (2024b) by including echelon utilization revenue (denoted as φu) as a critical threshold for recycling incentives.

Assumption 8. The manufacturer and echelon utilization enterprises have identical echelon utilization technologies and costs. Unlike traditional third-party recycling systems (Yu and Hou, 2023; Xiao *et al.*, 2024), echelon utilization enterprises face channel risks due to underdeveloped reverse supply chains. This assumption emphasizes the unique operational challenges in emerging CLSC ecosystems when compared to mature recycling markets.

4. Construction and solution of the noncooperative-cooperative biform game

This section constructs a noncooperative-cooperative biform game model to examine strategic interactions among three key stakeholders: (1) a power battery manufacturer M implementing CSR initiatives through echelon utilization; (2) a recycler C; and (3) an echelon utilization enterprise T competing in the reverse supply chain. The model specifically addresses optimal strategy formulation and profit distribution mechanisms within this tripartite structure.

In the non-cooperative phase, the recycler C and echelon utilization enterprise T strategically determine their collection rates (τ_c, τ_t), thereby forming a competitive scenario. In the cooperative phase, coalition members (the manufacturer M, the recycler C, and the echelon utilization enterprise T) jointly optimize the CSR effort level θ, the price of new power batteries p, and the transfer prices of retired batteries (f_c, f_t), under any competitive scenario (τ_c, τ_t).

The Shapley value mechanism is then applied to allocate profits among the manufacturer M, recycler C, and echelon utilization enterprise T based on their marginal contributions to the coalition value. The allocated profits for the recycler C and echelon utilization enterprise T serve as payoff functions in the non-cooperative phase, enabling the derivation of the Nash equilibrium collection rates (τ_c^*, τ_t^*).

Finally, the equilibrium collection rates are fed back into the cooperative phase to generate globally optimal strategies and profit distributions for all participants through iterative game coordination. The iterative game process, as illustrated in Figure 2, proceeds through the following stages.

4.1 Formulation and solution of coalitional characteristic functions in the cooperative game

Under the cooperative game framework, coalition members—the manufacturer M, recycler C, and echelon utilization enterprise T—jointly optimize the CSR effort level θ, the price of new power batteries p, and the transfer prices of retired batteries f_c and f_t to maximize coalition profits. The total coalition profit is allocated among participants through the Shapley value mechanism based on their marginal contributions.

We first derive the profit functions for each member of the CLSC based on the aforementioned assumptions.

The profit function for the manufacturer M is formulated by:

$$\pi_m = [p - c_m + \tau_c(\varphi u + \Delta - f_c) + \tau_t(\Delta - f_t)](a - \beta p + \lambda\theta) - \frac{1}{2}\eta\theta^2 \tag{1}$$

The profit function for the recycler C is formulated by:

$$\pi_c = \tau_c(f_c - c_c)(a - \beta p + \lambda\theta) - \frac{\sigma\left(\tau_c^2 + \alpha\tau_t^2\right)}{1 - \alpha^2} \tag{2}$$

The profit function for the echelon utilization enterprise T is formulated by:

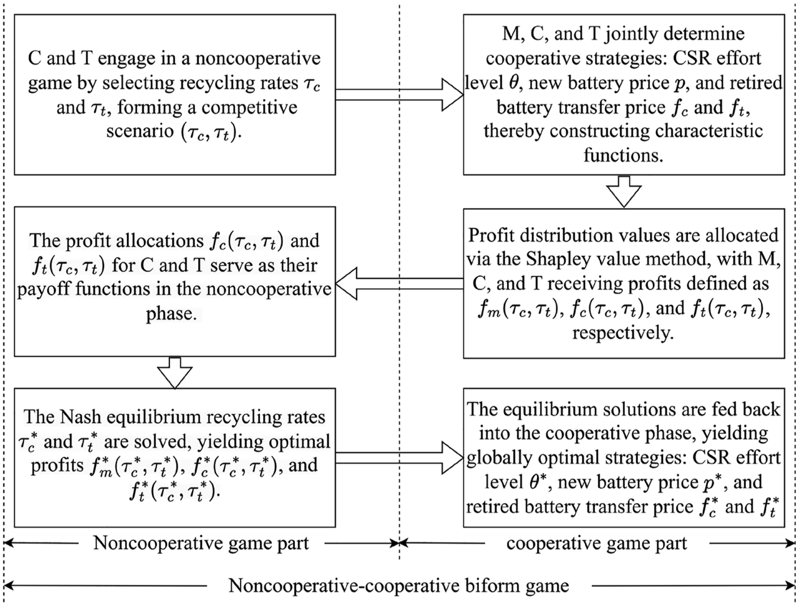


Figure 2. Noncooperative-cooperative biform game solution framework. **Source(s):** Created by authors

$$\pi_t = \tau_t(\varphi u + f_t - c_t)(a - \beta p + \lambda\theta) - \frac{\sigma\left(\tau_t^2 + \alpha\tau_c^2\right)}{1 - \alpha^2} \tag{3}$$

Following the non-cooperative-cooperative biform game sequence, a coalition $S \in \{\text{M}, \text{C}, \text{T}\}$ is formed for any given competitive scenario (τ_c, τ_t). The possible coalitions are: $\{\varnothing\}, \{\text{M}\}, \{\text{C}\}, \{\text{T}\}, \{\text{M}, \text{C}\}, \{\text{M}, \text{T}\}, \{\text{C}, \text{T}\}, \{\text{M}, \text{C}, \text{T}\}$. The characteristic function $v(\tau_c, \tau_t)(S)$ for all coalitions is determined using the von Neumann–Morgenstern approach (minimax theorem). For the empty coalition: $v(\tau_c, \tau_t)(\varnothing) = 0$.

Lemma 1. For any competitive scenario (τ_c, τ_t), the characteristic function values of all non-empty coalitions can be defined as follows:

$$v(\tau_c, \tau_t)(\{\text{M}\}) = \frac{\eta(a - \beta c_m)^2}{2\left(2\eta\beta - \lambda^2\right)} \tag{4}$$

$$v(\tau_c, \tau_t)(\{\text{C}\}) = -\frac{\sigma\left(\tau_c^2 + \alpha\tau_t^2\right)}{1 - \alpha^2} \tag{5}$$

$$v(\tau_c, \tau_t)(\{\text{T}\}) = -\frac{\sigma\left(\tau_t^2 + \alpha\tau_c^2\right)}{1 - \alpha^2} \tag{6}$$

$$v(\tau_c, \tau_t)(\{\text{M}, \text{C}\}) = \frac{\eta[a - \beta c_m + \beta\tau_c(\varphi u + \Delta - c_c)]^2}{2\left(2\eta\beta - \lambda^2\right)} - \frac{\sigma\left(\tau_c^2 + \alpha\tau_t^2\right)}{1 - \alpha^2} \tag{7}$$

$$v(\tau_c,\tau_t)(\{\mathrm{M},\mathrm{T}\}) = \frac{\eta[a-\beta c_m+\beta\tau_t(\varphi u+\Delta-c_t)]^2}{2(2\eta\beta-\lambda^2)} - \frac{\sigma(\tau_t^2+\alpha\tau_c^2)}{1-\alpha^2} \tag{8}$$

$$v(\tau_c,\tau_t)(\{\mathrm{C},\mathrm{T}\}) = -\frac{\sigma(\tau_c^2+\alpha\tau_t^2)}{1-\alpha^2} - \frac{\sigma(\tau_t^2+\alpha\tau_c^2)}{1-\alpha^2} \tag{9}$$

$$\begin{aligned} v(\tau_c,\tau_t)(\{\mathrm{M},\mathrm{C},\mathrm{T}\}) = {} & \frac{\eta[a-\beta c_m+\beta\tau_c(\varphi u+\Delta-c_c)+\beta\tau_t(\varphi u+\Delta-c_t)]^2}{2(2\eta\beta-\lambda^2)} \\ & -\frac{\sigma(\tau_c^2+\alpha\tau_t^2)}{1-\alpha^2} - \frac{\sigma(\tau_t^2+\alpha\tau_c^2)}{1-\alpha^2} \end{aligned} \tag{10}$$

Proof. See Appendix A.1. Proof of Lemma 1.

The cooperative game $v(\tau_c,\tau_t)$ is characterized by all coalitions and their characteristic function values formed by the players: the manufacturer M, recycler C, and echelon utilization enterprise T. The characteristic function $v(\tau_c,\tau_t)(S)$ represents the maximum profit the coalition S can secure when non-members $(Z\backslash S)$ act adversarially to minimize the gains of S, which safeguards against real-world competitive risks. For any competitive scenario (τ_c,τ_t), the characteristic function $v(\tau_c,\tau_t)$ of the cooperative game satisfies the following conditions:

$$v(\tau_c,\tau_t)(S)+v(\tau_c,\tau_t)(Y) \leq v(\tau_c,\tau_t)(S\cup Y)+v(\tau_c,\tau_t)(S\cap Y) \tag{11}$$

Where $S\subseteq Z$, $Y\subseteq Z$, and $Z=\{\mathrm{M},\mathrm{C},\mathrm{T}\}$. This super additivity condition ensures that collaboration strictly dominates fragmentation, as merging coalitions S and Y always yields higher joint profits than the sum of their separate operations minus overlap costs. Such cooperation, under dual-channel recycling competition for retired power batteries, enhances the combined profits of the manufacturer M, the recycler C, and the echelon utilization enterprise T. This Pareto improvement indicates that supply chain members have inherent incentives to form stable alliances.

Based on cooperative game theory, the game $v(\tau_c,\tau_t)$ formed by the three parties is convex, and the Shapley value method ensures a fair profit allocation within the CLSC coalition.

The Shapley value is calculated as follows:

$$S_i(v(\tau_c,\tau_t)) = \sum_{i\in S\subseteq Z}\frac{(|S|-1)!(3-|S|)!}{3!}[v(\tau_c,\tau_t)(S)-v(\tau_c,\tau_t)(S\backslash i)](i=m,c,t) \tag{12}$$

Where $|S|$ denotes the number of players in the coalition S. The weighting factor $\frac{(|S|-1)!(3-|S|)!}{3!}$ reflects the probability of the coalition S forming, and the marginal contribution of participants i joining the coalition S is given by $[v(\tau_c,\tau_t)(S)-v(\tau_c,\tau_t)(S\backslash i)]$, which quantifies the additional value that player i brings to the coalition S.

Using the Shapley value, the profit allocation for each member of the CLSC is derived as follows.

The profit allocated to the manufacturer M is:

$$f_m(\tau_c,\tau_t)=\frac{\eta(a-\beta c_m)^2}{6\left(2\eta\beta-\lambda^2\right)}+\frac{\eta[a-\beta c_m+\beta\tau_c(\varphi u+\Delta-c_c)]^2}{12\left(2\eta\beta-\lambda^2\right)}+\frac{\eta[a-\beta c_m+\beta\tau_t(\varphi u+\Delta-c_t)]^2}{12\left(2\eta\beta-\lambda^2\right)}$$
$$+\frac{\eta[a-\beta c_m+\beta\tau_c(\varphi u+\Delta-c_c)+\beta\tau_t(\varphi u+\Delta-c_t)]^2}{6\left(2\eta\beta-\lambda^2\right)} \tag{13}$$

The profit allocated to the recycler C is:

$$f_c(\tau_c,\tau_t)=-\frac{\eta(a-\beta c_m)^2}{12\left(2\eta\beta-\lambda^2\right)}+\frac{\eta[a-\beta c_m+\beta\tau_c(\varphi u+\Delta-c_c)]^2}{12\left(2\eta\beta-\lambda^2\right)}-\frac{\eta[a-\beta c_m+\beta\tau_t(\varphi u+\Delta-c_t)]^2}{6\left(2\eta\beta-\lambda^2\right)}$$
$$+\frac{\eta[a-\beta c_m+\beta\tau_c(\varphi u+\Delta-c_c)+\beta\tau_t(\varphi u+\Delta-c_t)]^2}{6\left(2\eta\beta-\lambda^2\right)}-\frac{\sigma\left(\tau_c^2+\alpha\tau_t^2\right)}{1-\alpha^2} \tag{14}$$

The profit allocated to the echelon utilization enterprise T is:

$$f_t(\tau_c,\tau_t)=-\frac{\eta(a-\beta c_m)^2}{12\left(2\eta\beta-\lambda^2\right)}-\frac{\eta[a-\beta c_m+\beta\tau_c(\varphi u+\Delta-c_c)]^2}{6\left(2\eta\beta-\lambda^2\right)}+\frac{\eta[a-\beta c_m+\beta\tau_t(\varphi u+\Delta-c_t)]^2}{12\left(2\eta\beta-\lambda^2\right)}$$
$$+\frac{\eta[a-\beta c_m+\beta\tau_c(\varphi u+\Delta-c_c)+\beta\tau_t(\varphi u+\Delta-c_t)]^2}{6\left(2\eta\beta-\lambda^2\right)}-\frac{\sigma\left(\tau_t^2+\alpha\tau_c^2\right)}{1-\alpha^2} \tag{15}$$

The mathematical relationships in Equations (4)–(6) and (13)–(15): $f_m(\tau_c,\tau_t) \geq v(\tau_c,\tau_t)(\{M\}), f_c(\tau_c,\tau_t) \geq v(\tau_c,\tau_t)(\{C\}), f_t(\tau_c,\tau_t) \geq v(\tau_c,\tau_t)(\{T\})$ demonstrate that under the Shapley value allocation mechanism in any competitive scenario, the profit allocations obtained by the manufacturer M, recycler C, and echelon utilization enterprise T through coalition cooperation strictly dominate their maximum payoffs under independent operations. This result satisfies both individual rationality and collective rationality conditions in cooperative games, ensuring fairness in profit allocation and stability of the coalition.

From a supply chain synergy perspective, the tripartite cooperation holds significant managerial value: the Shapley value mechanism precisely quantifies each member's contribution, ensuring Pareto improvement in individual payoffs while achieving optimal collective benefits for the coalition. By establishing an equitable profit-sharing rule, this framework effectively facilitates the strategic transition of supply chain members from noncooperative competition to synergistic symbiosis, providing theoretical underpinnings for resource integration and sustainable development in the power battery recycling industry.

4.2 Noncooperative game solution and profit allocation

In the noncooperative game phase, the recycler C and echelon utilization enterprise T, acting as independent decision-makers, determine their optimal retired battery recycling rates τ_c and τ_t to maximize individual profits. The profit allocations $f_c(\tau_c,\tau_t)$ and $f_t(\tau_c,\tau_t)$, derived from the cooperative game phase via the Shapley value method, are assigned as the payoff functions in the noncooperative game, from which the equilibrium solutions are solved.

Lemma 2. The optimal recycling rates for the recycler C and echelon utilization enterprise T are given by:

$$\tau_c^*=\frac{3k_2(a-\beta c_m)\mathrm{A}\left(12\sigma k_1-k_2\beta\mathrm{B}^2\right)}{144\sigma^2k_1^2-36\sigma k_1k_2\beta\left(\mathrm{A}^2+\mathrm{B}^2\right)+5k_2^2\beta^2\mathrm{A}^2\mathrm{B}^2} \tag{16}$$

$$\tau_t^* = \frac{3k_2(a-\beta c_m)\mathrm{B}\left(12\sigma k_1 - k_2\beta \mathrm{A}^2\right)}{144\sigma^2 k_1^2 - 36\sigma k_1 k_2 \beta\left(\mathrm{A}^2+\mathrm{B}^2\right) + 5k_2^2\beta^2\mathrm{A}^2\mathrm{B}^2} \tag{17}$$

Where $\mathrm{A} = \varphi u + \Delta - c_c$, $\mathrm{B} = \varphi u + \Delta - c_t$; $k_1 = 2\eta\beta - \lambda^2$, $k_2 = (1-\alpha^2)\eta\beta$.
Proof. See Appendix A.2. Proof of Lemma 2.

The optimal recycling rates τ_c^* and τ_t^* of the recycler C and the echelon utilization enterprise T form the optimal competitive scenario (τ_c^*, τ_t^*) in the noncooperative game.

Substituting the optimal competitive scenario (τ_c^*, τ_t^*) from Equations (16) and (17) into the expressions for the optimal power battery sales price and CSR effort level (Equations (A.12) and (A.13), respectively), the manufacturer's optimal sales price p^* and CSR effort level θ^* are derived as:

$$\begin{aligned} p^* = \Big\{&144\sigma^2 k_1^2\left[a\eta + c_m\left(\eta\beta - \lambda^2\right)\right] - 36a\sigma k_1^2 k_2\left(\mathrm{A}^2+\mathrm{B}^2\right) + k_2^2\beta\mathrm{A}^2\mathrm{B}^2\Big[5a\eta\beta + \\ &(6a-\beta c_m)\left(\eta\beta-\lambda^2\right)\Big]\Big\}\Big/\left\{k_1\left[144\sigma^2k_1^2 - 36\sigma k_1k_2\beta\left(\mathrm{A}^2+\mathrm{B}^2\right)+5k_2^2\beta^2\mathrm{A}^2\mathrm{B}^2\right]\right\}\end{aligned} \tag{18}$$

$$\begin{aligned}\theta^* = \left\{\lambda(a-\beta c_m)\left\{144\sigma^2 {k_1}^2 - k_2^2\beta^2\mathrm{A}^2\mathrm{B}^2\right\}\right\}\Big/\Big\{k_1\Big[144\sigma^2k_1^2 - \\ 36\sigma k_1k_2\beta\left(\mathrm{A}^2+\mathrm{B}^2\right)+5k_2^2\beta^2\mathrm{A}^2\mathrm{B}^2\Big]\Big\}\end{aligned} \tag{19}$$

Substituting the manufacturer's optimal sales price p^* and CSR effort level θ^* (Equations (18) and (19)) into the CLSC's power battery demand function $Q = a - \beta p + \lambda\theta$, the optimal market demand is obtained as:

$$Q^* = \frac{\eta\beta(a-\beta c_m)\left(144\sigma^2{k_1}^2 - k_2^2\beta^2\mathrm{A}^2\mathrm{B}^2\right)}{k_1\left[144\sigma^2k_1^2 - 36\sigma k_1k_2\beta\left(\mathrm{A}^2+\mathrm{B}^2\right)+5k_2^2\beta^2\mathrm{A}^2\mathrm{B}^2\right]} \tag{20}$$

Substituting the optimal recycling rates of the recycler and echelon utilization enterprise (Equations (16) and (17)) into Equations (13)–(15), the optimal profits for the manufacturer M, recycler C, and echelon utilization enterprise T are derived as:

$$\begin{aligned} f_m^*\left(\tau_c^*, \tau_t^*\right) = \Big\{&\eta(a-\beta c_m)^2\{2\left[144\sigma^2k_1^2 - 36\sigma k_1k_2\beta\left(\mathrm{A}^2+\mathrm{B}^2\right)+5k_2^2\beta^2\mathrm{A}^2\mathrm{B}^2\right]^2 \\ &+\left(144\sigma^2k_1^2 - 36\sigma k_1k_2\beta\mathrm{B}^2 + 2k_2^2\beta^2\mathrm{A}^2\mathrm{B}^2\right)^2 + \left(144\sigma^2k_1^2 - 36\sigma k_1k_2\beta\mathrm{A}^2 + \right. \\ &\left.2k_2^2\beta^2\mathrm{A}^2\mathrm{B}^2\right)^2 + 2\left(144\sigma^2k_1^2 - k_2^2\beta^2\mathrm{A}^2\mathrm{B}^2\right)^2\}\Big\}\Big/\Big\{12k_1\Big[144\sigma^2k_1^2 - \\ &36\sigma k_1k_2\beta\left(\mathrm{A}^2+\mathrm{B}^2\right)+5k_2^2\beta^2\mathrm{A}^2\mathrm{B}^2\Big]^2\Big\}\end{aligned} \tag{21}$$

$$\begin{aligned} f_c^*\left(\tau_c^*, \tau_t^*\right) = \Big\{&9\eta(a-\beta c_m)^2\left(12\sigma k_1k_2\beta\mathrm{A}^2 - k_2^2\beta^2\mathrm{A}^2\mathrm{B}^2\right)\Big[96\sigma^2k_1^2 - 4\sigma k_1k_2\beta \times \\ &\left(3\mathrm{A}^2+2\mathrm{B}^2\right) + k_2^2\beta^2\mathrm{A}^2\mathrm{B}^2\Big]\Big\}\Big/\left\{4k_1\left[144\sigma^2k_1^2 - 36\sigma k_1k_2\beta\left(\mathrm{A}^2+\mathrm{B}^2\right)+5k_2^2\beta^2\times\mathrm{A}^2\mathrm{B}^2\right]^2\right\} \\ &-\Big\{9\sigma k_2\eta\beta(a-\beta c_m)^2\Big[\mathrm{A}^2\left(12\sigma k_1 - k_2\beta\mathrm{B}^2\right)^2 + \alpha\mathrm{B}^2\Big(12\sigma k_1 - \\ &k_2\beta\mathrm{A}^2\Big)^2\Big]\Big\}\Big/\left\{\left[144\sigma^2k_1^2 - 36\sigma k_1k_2\beta\left(\mathrm{A}^2+\mathrm{B}^2\right)+5k_2^2\beta^2\mathrm{A}^2\mathrm{B}^2\right]^2\right\}\end{aligned} \tag{22}$$

$$\begin{aligned} f_t^*\left(\tau_c^*,\tau_t^*\right) = {} & \Big\{9\eta(a-\beta c_m)^2\left(12\sigma k_1k_2\beta\mathrm{B}^2-k_2^2\beta^2\mathrm{A}^2\mathrm{B}^2\right)\Big[96\sigma^2k_1^2-4\sigma k_1k_2\beta\Big(2\mathrm{A}^2 \\ & +3\mathrm{B}^2\Big)+k_2^2\beta^2\mathrm{A}^2\mathrm{B}^2\Big]\Big\}\Big/\Big\{4k_1\left[144\sigma^2k_1^2-36\sigma k_1k_2\beta\left(\mathrm{A}^2+\mathrm{B}^2\right)+5k_2^2\beta^2\mathrm{A}^2\mathrm{B}^2\right]^2\Big\} \\ & -\Big\{9\sigma k_2\eta\beta(a-\beta c_m)^2\Big[\mathrm{B}^2\left(12\sigma k_1-k_2\beta\mathrm{A}^2\right)^2+\alpha\mathrm{A}^2\left(12\sigma k_1-k_2\beta\mathrm{B}^2\right)^2\Big]\Big\}\Big/ \\ & \Big\{\left[144\sigma^2k_1^2-36\sigma k_1k_2\beta\left(\mathrm{A}^2+\mathrm{B}^2\right)+5k_2^2\beta^2\mathrm{A}^2\mathrm{B}^2\right]^2\Big\} \end{aligned} \tag{23}$$

By substituting the recycler's optimal recycling rate τ_c^*, manufacturer's optimal sales price p^*, and CSR effort level θ^* (Equations (16), (18), and (19)) into the recycler's profit function π_c (Equation (2)), and simultaneously solving with recycler's optimally allocated profit $f_c(\tau_c^*, \tau_t^*)$ under the cooperative game, the equilibrium price for the recycler to sell retired power batteries to the manufacturer is derived as:

$$f_c^* = \frac{288\sigma^2k_1^2(\mathrm{A}+2c_c)-12\sigma k_1k_2\beta\mathrm{A}\left(3\mathrm{A}^2+2\mathrm{B}^2\right)+k_2^2\beta^2\mathrm{A}^2\mathrm{B}^2(3\mathrm{A}-4c_c)}{4\left(144\sigma^2k_1^2-k_2^2\beta^2\mathrm{A}^2\mathrm{B}^2\right)} \tag{24}$$

Similarly, the equilibrium price for the echelon utilization enterprise to sell retired power batteries to the manufacturer is derived as:

$$f_t^* = \frac{288\sigma^2k_1^2(2\Delta-\mathrm{B})-12\sigma k_1k_2\beta\mathrm{B}\left(2\mathrm{A}^2+3\mathrm{B}^2\right)+k_2^2\beta^2\mathrm{A}^2\mathrm{B}^2(7\mathrm{B}-4\Delta)}{4\left(144\sigma^2k_1^2-k_2^2\beta^2\mathrm{A}^2\mathrm{B}^2\right)} \tag{25}$$

5. Equilibrium analysis

Based on the computational results in Section 4, this subsection analyzes the conditions for the existence of a unique equilibrium solution and examines the impacts of key parameters—retired battery recycling competition intensity α, echelon utilization ratio φ, consumer sensitivity to CSR efforts λ, and CSR cost coefficient η—on the equilibrium pricing strategies of CLSC members. The following corollaries are derived.

Corollary 1. The noncooperative-cooperative biform game solution of the CLSC, $((\theta^*, p^*), (\tau_c^*, f_c^*), (\tau_t^*, f_t^*);\ (f_m^*, f_c^*, f_t^*))$, is unique if the parameters satisfy $\eta\beta > \lambda^2$, $a > \beta c_m$, and σ is sufficiently large.

Proof. See Appendix A.3. Proof of Corollary 1.

Corollary 2. $\frac{\partial \tau_c^*}{\partial \alpha} < 0, \frac{\partial \tau_t^*}{\partial \alpha} < 0, \frac{\partial p^*}{\partial \alpha} > 0, \frac{\partial \theta^*}{\partial \alpha} < 0, \frac{\partial Q^*}{\partial \alpha} < 0, \frac{\partial f_c^*}{\partial \alpha} > 0, \frac{\partial f_t^*}{\partial \alpha} > 0.$

Proof. See Appendix A.4. Proof of Corollary 2.

As the recycling competition intensity α between the recycler and echelon utilization enterprise increases, systemic adjustments arise in operational costs, resource acquisition efficiency, and pricing strategies across the supply chain. The intensified competition directly raises the marginal operational costs for both parties, compelling them to reduce recycling scales to mitigate cost pressures. The decline in recycled material supply compels manufacturers to turn to relatively costlier virgin materials, which exerts an upward pressure on unit production costs to a notable extent. To counteract these pressures, manufacturers adopt a dual cost-transfer strategy: transferring production costs through price increases while reducing CSR investments to protect profit margins, which further suppresses market demand. To address persistent material shortages, manufacturers adjust reverse supply chain incentives by increasing acquisition prices, thereby stabilizing operations and ensuring a baseline supply of recycled materials.

Corollary 3. $\frac{\partial \tau_c^*}{\partial \varphi} > 0, \frac{\partial \tau_t^*}{\partial \varphi} > 0, \frac{\partial p^*}{\partial \varphi} < 0, \frac{\partial \theta^*}{\partial \varphi} > 0, \frac{\partial Q^*}{\partial \varphi} > 0, \frac{\partial f_c^*}{\partial \varphi} > 0, \frac{\partial f_t^*}{\partial \varphi} < 0.$

Proof. See Appendix A.5. Proof of Corollary 3.

A higher echelon utilization ratio φ enhances the economic returns and lifecycle value of recycled materials, thereby incentivizing recyclers and echelon utilizers to expand recycling scales to compete for retired power battery resources. Manufacturers leverage the cost savings from recycled materials and the benefits of echelon utilization to strategically reduce product prices and intensify CSR investments, thereby stimulating market demand growth. However, cost pressures from the recycling sector propagate through the reverse supply chain, compelling recyclers to raise acquisition prices to maintain profit margins. Concurrently, echelon utilizers face conflicting interests with manufacturers due to operational costs, compelling them to lower transaction prices to maintain cooperation.

Corollary 4. (1) $\frac{\partial \tau_c^*}{\partial \lambda} > 0, \frac{\partial \tau_t^*}{\partial \lambda} > 0, \frac{\partial p^*}{\partial \lambda} > 0, \frac{\partial \theta^*}{\partial \lambda} > 0, \frac{\partial Q^*}{\partial \lambda} > 0;$

(2) When $k_1 > 2, \frac{\partial f_c^*}{\partial \lambda} < 0, \frac{\partial f_t^*}{\partial \lambda} < 0.$

Proof. See Appendix A.6. Proof of Corollary 4.

Consumers' sensitivity to CSR λ drives dynamic adjustments in the CLSC via the demand function. Through demand expansion, manufacturers significantly increase CSR investment levels and enhance the potential value of recycled materials, thereby incentivizing recyclers and echelon utilizers to expand resource recovery scales. However, when production efficiency meets the condition $k_1 = 2\eta\beta - \lambda^2 > 2$, manufacturers' bargaining power is strengthened, compelling recyclers to accept lower transfer prices to sustain cooperation. In the terminal market, the internalization of CSR costs raises product prices, while consumers' value recognition of CSR drives simultaneous sales growth through the advantages of demand elasticity, forming a short-term equilibrium of rising volume and price.

Corollary 5. (1) $\frac{\partial \tau_c^*}{\partial \eta} < 0, \frac{\partial \tau_t^*}{\partial \eta} < 0, \frac{\partial \theta^*}{\partial \eta} < 0, \frac{\partial Q^*}{\partial \eta} < 0$; (2) When $a + \beta c_m < a\beta k_2(\mathrm{A}^2 + \mathrm{B}^2)$, $\frac{\partial p^*}{\partial \eta} < 0.$

Proof. See Appendix A.7. Proof of Corollary 5.

When the manufacturer's CSR effort cost coefficient η increases, the marginal cost of fulfilling social responsibilities increases significantly, compelling firms to reduce CSR investment levels. The decline in CSR investments triggers a demand suppression effect via the demand function. As consumers perceive diminished product value due to weakened CSR performance, it leads to sustained market demand contraction. The reduced demand for recycled materials lowers the potential returns for recyclers and echelon utilizers, prompting them to rationally scale down recycling activities, thereby exacerbating resource circulation inefficiencies and environmental risks. When the market base is small and cost sensitivity is high (i.e. $a + \beta c_m < a\beta k_2(\mathrm{A}^2 + \mathrm{B}^2)$), the contraction of market demand constrains the manufacturer's ability to pass through CSR costs, ultimately forcing price reductions to retain market share and triggering a "cost-demand double suppression" vicious cycle.

From a managerial perspective, manufacturers need to optimize CLSC efficiency through coordinated pricing mechanisms and technology-driven strategies. To counter the recycling rate decline caused by intensified competition, the dynamic adjustment of transfer prices can balance recyclers' profits and resource acquisition efficiency. To enhance echelon utilization, manufacturers should prioritize investments in battery sorting and residual value assessment technologies and reduce recycled material costs, thereby stimulating demand growth through price transmission. Consumers' CSR sensitivity can be converted into brand premiums through green certifications but must be complemented by differentiated pricing strategies to avoid market exclusion due to high prices. To address high CSR costs, manufacturers should collaborate with governments and industries to promote policy support (e.g. tax relief, R&D subsidies), thereby lowering the marginal cost of compliance and sustaining a virtuous cycle between CSR investments and market demand.

6. Numerical analysis

This section uses numerical examples to analyze the impacts of key parameters—recycling competition intensity α, echelon utilization ratio φ, consumer sensitivity to CSR effort level λ, and CSR effort cost coefficient η—on the equilibrium strategies and profits of supply chain members. Based on non-negativity constraints, relevant assumptions, and empirical plausibility, the parameter values are referenced from studies by Tang *et al.* (2018) and Zhang *et al.* (2023b): $a = 250$, $\beta = 4$, $c_m = 14$, $c_o = 7$, $u = 4$, $\sigma = 400$, $\alpha = 0.5$, $\eta = 500$, $c_c = 2$, $c_t = 3$, $\varphi = 0.5$ and $\lambda = 16$.

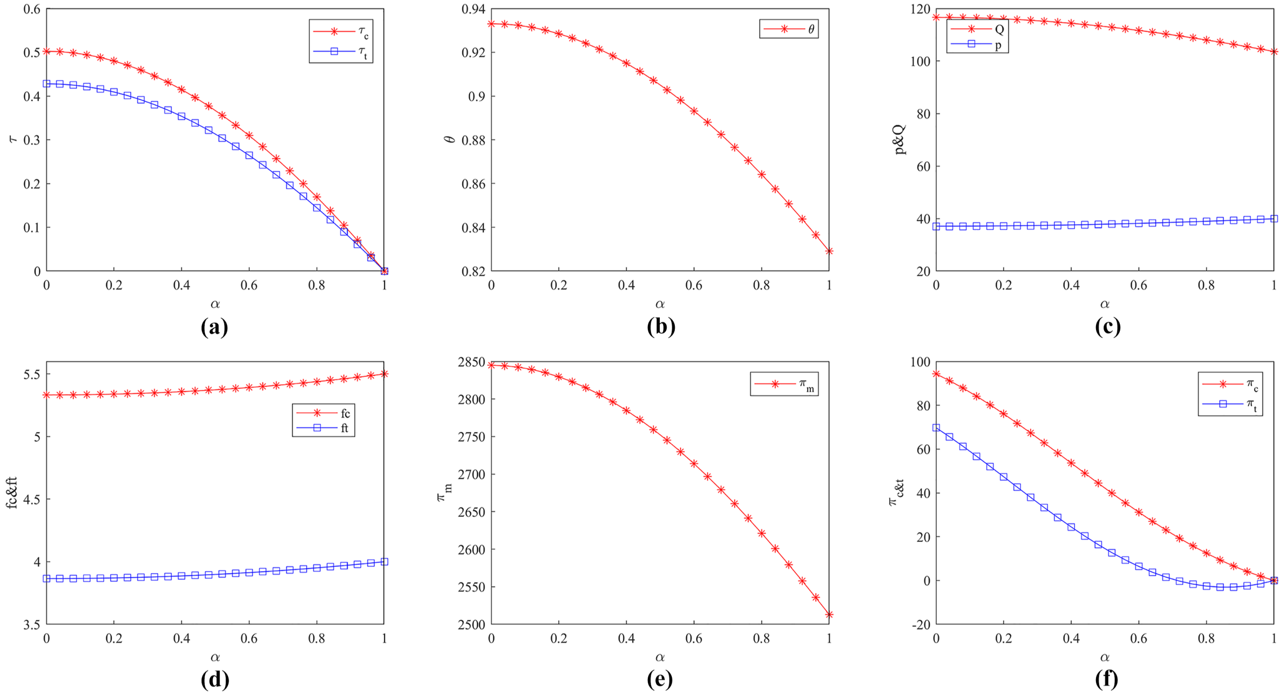
6.1 Analysis of the recycling competition intensity

Assuming all other factors remain constant, Figure 3 illustrates the impact of the recycling competition intensity α on decision-making and profit distribution among supply chain members, aligning with Corollary 2. Furthermore, as α increases, the profits of all CLSC members decline.

Figure 3 reveals the systematic impact of the recycling competition intensity α on the decisions and profits of CLSC members. As shown in Figure 3(a), the recycling rates of recyclers and echelon utilization enterprises exhibit nonlinear declines with α, with recyclers' rates decreasing significantly faster. When α approaches 1, both rates converge to zero, indicating that extreme competition halts recycling activities. This phenomenon stems from the dual cost pressures under intensified competition: (1) recyclers and echelon utilization enterprises must invest more resources to compete for recycling channels, thereby increasing marginal costs; (2) manufacturers cap excessive increases in transfer prices, thereby suppressing their recycling rates.

Figure 3(b) further shows that manufacturers' CSR effort levels decline with increasing α, with the slope of the curve steepening, reflecting how competition forces firms to prioritize short-term profits over long-term CSR commitments. In Figure 3(c), power battery prices rise continuously, but market demand sharply contracts due to price sensitivity and weakened CSR performance, forming a vicious cycle where cost pass-through triggers demand suppression. Despite partial cost offsetting through price hikes, manufacturers' reliance on costlier virgin materials due to recycled material shortages further exacerbates demand erosion. Figure 3(d) indicates that recyclers' and echelon utilization enterprises' transaction prices rise marginally but are constrained by manufacturers' bargaining power, resulting in shrinking profit margins.

Figures 3(e)–(f) confirm that the profits of manufacturers, recyclers, and echelon utilization enterprises decline continuously with increasing α. As α increases, manufacturers' profits decrease gradually, while recyclers' and echelon utilization enterprises' profits decline more rapidly, collectively indicating systemic inefficiency. When $\alpha > 0.7$, echelon utilization enterprises' profits drop to zero, and they may even exit the market, driven by the dual pressures of competition and cost structure: echelon utilization enterprises bear higher unit processing costs while facing manufacturers' suppression of transfer prices. Recyclers, lacking value-added operations, experience the most significant profit declines due to their complete reliance on manufacturers. The erosion of manufacturers' profits highlights the complexity of supply chain power dynamics. Although price hikes partially offset costs, recycled material shortages force reliance on costlier alternatives, thereby compressing marginal profits. Concurrently, the shrinkage of demand erodes economies of scale, further compressing profit margins.



(a) (b) (c) (d) (e) (f)

Figure 3. Impact of competition intensity on supply chain decisions and profits. **Source(s):** Created by authors

6.2 Analysis of the echelon utilization ratio

Assuming all other factors remain constant, the impact of the echelon utilization rate φ on the decisions and profits of supply chain members is depicted in Figure 4, which is consistent with Corollary 3. Furthermore, as φ increases, the profits of all CLSC members rise.

Figure 4 illustrates the structural effects of the echelon utilization ratio φ on the decisions and profits of the CLSC. As shown in Figure 4(a), the recycling rates of recyclers and echelon utilization enterprises increase synchronously with φ, exhibiting similar growth rates. This phenomenon arises from the two-fold incentives of φ on recycling economics: a higher φ enhances the regenerative value of retired batteries, motivating recyclers and echelon utilization enterprises to expand recycling scales to compete for resources. However, echelon utilization enterprises' slower growth rate stems from their additional processing costs (e.g. testing, repackaging), resulting in a balanced state driven by value incentives yet constrained by costs.

Figures 4(b)–(c) further demonstrate that manufacturers, as core participants in echelon utilization, activate the market through two-pronged strategies: reducing product prices and intensifying CSR efforts. The increase in φ enables manufacturers to integrate internal echelon utilization resources capturing higher value-added that provides room for price reductions. Simultaneously, enhanced CSR efforts strengthen consumer recognition of sustainable products, unleashing latent demand. The synergy between price reductions and CSR improvements propels the market into a virtuous cycle of cost optimization, demand expansion, and economies of scale.

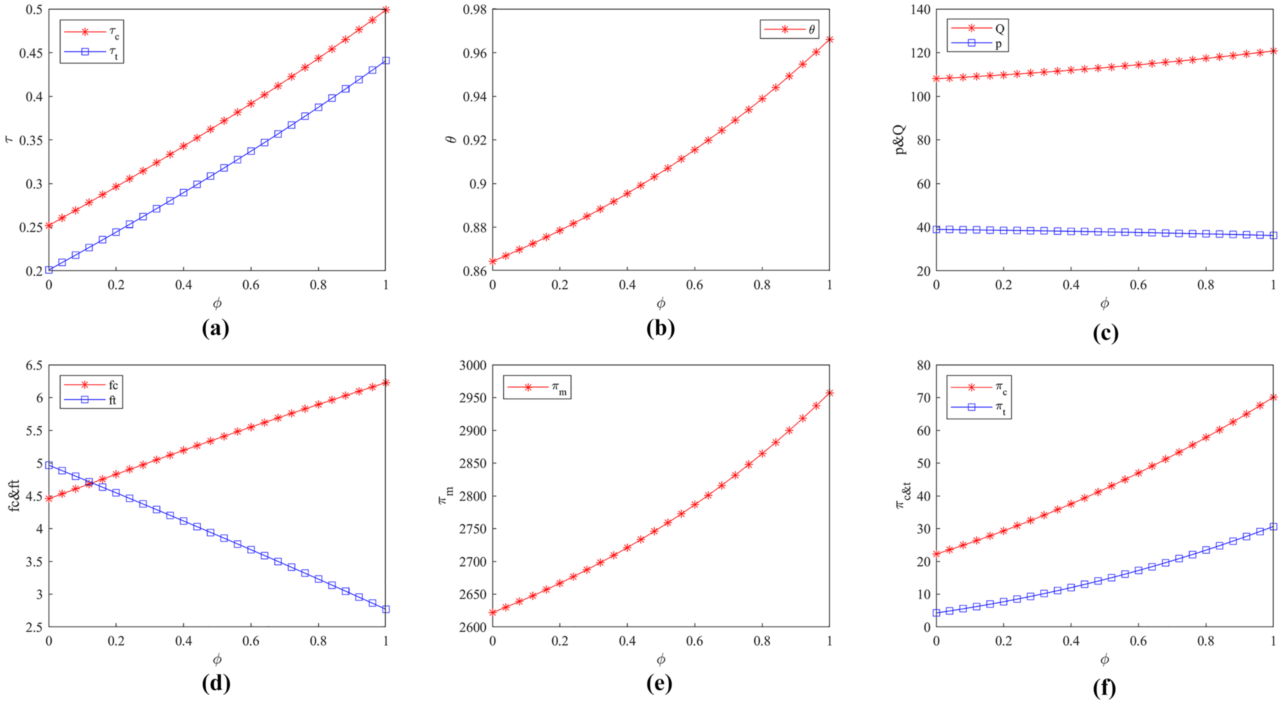
Figure 4(d) reveals price divergence in the recycling sector: recyclers' transaction prices rise with φ, while echelon utilization enterprises' prices decline. This contrast originates from manufacturers' strategic procurement preference: under high φ, manufacturers prioritize purchasing untreated batteries from recyclers, granting them bargaining power. Echelon utilization enterprises, to sustain cooperation, are forced to lower prices to offset their cost disadvantages. This price divergence underscores manufacturers' strategic dominance over the supply chain through balanced internal resource integration and external procurement.

Figures 4(e)–(f) confirm that profits of all supply chain members rise with φ, yet manufacturers' profit growth significantly outpaces that of other members. Recyclers achieve significant profit increases through scale expansion and moderate price hikes. Echelon utilization enterprises' profit growth remains constrained by cost pressures and declining transfer prices, despite partial offsetting through value-added operations. Manufacturers, benefiting from demand growth and the value of echelon utilization, steadily enhance profits.

6.3 Analysis of the consumer sensitivity to CSR effort level and CSR effort cost coefficient

(1) Assuming all other factors remain constant, the impact of consumers' sensitivity coefficient to CSR efforts λ on the decisions of supply chain members is depicted in Figure 5, aligning with Corollary 4.

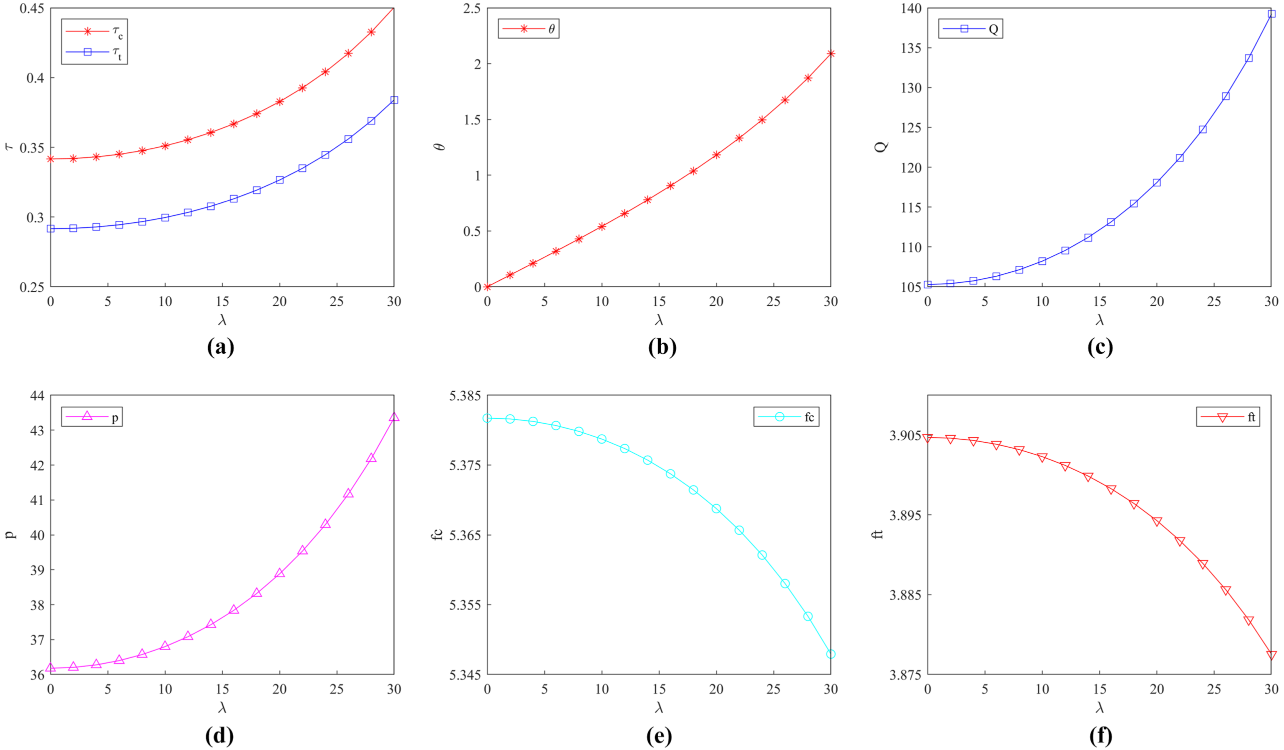
Figure 5 reveals the system-wide impact of consumers' CSR sensitivity coefficient λ on CLSC decisions. As shown in Figure 5(a), the recycling rates of recyclers and echelon utilization enterprises increase synchronously with λ, exhibiting similar growth rates. This phenomenon stems from the two-fold drivers of heightened consumer sensitivity: a higher λ directly incentivizes manufacturers to escalate CSR efforts, strengthening consumer recognition of sustainable products and thereby stimulating market demand. The demand expansion compels manufacturers to expand recycled material procurement, prompting recyclers and echelon utilization enterprises to enhance recycling rates to capture market share. Although the growth rates of recycling rates are similar, echelon utilization enterprises' slower increase is slightly constrained by their higher processing costs.



(a) **(b)** **(c)**

(d) **(e)** **(f)**

Figure 4. Impact of echelon utilization rate on supply chain decisions and profits. **Source(s):** Created by authors



(a) (b) (c)

(d) (e) (f)

Figure 5. Impact of CSR sensitivity coefficient on supply chain members' decisions. **Source(s):** Created by authors

Figures 5(b)–(c) further demonstrate that manufacturers' CSR effort levels and market demand rise significantly with λ. The strategic essence lies in a positive feedback loop where CSR investments drive demand expansion, which in turn generates profit feedback to sustain CSR commitments. An elevated λ makes consumers willing to pay a premium, and manufacturers amplify market appeal through intensified CSR commitments. Economies of scale from demand expansion further reduce CSR costs, enabling sustained CSR escalation. Notably, when λ surpasses a critical threshold, the growth of Q accelerates markedly, reflecting the increased marginal effect of green premiums on demand post the sensitivity threshold.

In Figure 5(d), product prices rise continuously with λ, alongside synchronous demand growth. This paradox arises from the restructuring of consumer payment willingness: increased λ partially offsets price elasticity through green premiums, shifting consumer focus to sustainability attributes over absolute prices. Manufacturers achieve two-fold objectives: maximizing profits through premium pricing while securing market dominance via demand-driven scale by precisely balancing the marginal returns of p and θ.

Figures 5(e)–(f) show that recyclers' and echelon utilization enterprises' transaction prices decline with λ. This reflects a shift in supply chain power dynamics: despite demand-driven growth in recycled material procurement, manufacturers leverage CSR-enhanced brand authority to suppress recycling sectors' bargaining power. To retain procurement shares, recyclers, and echelon utilization enterprises are forced to marginally lower prices in exchange for volume growth, forming a trade-off logic prioritizing volume growth over price maintenance.

(2) Assuming all other factors remain constant, the impact of the manufacturer's CSR effort cost coefficient η on the decisions of supply chain members is depicted in Figure 6, aligning with Corollary 5.

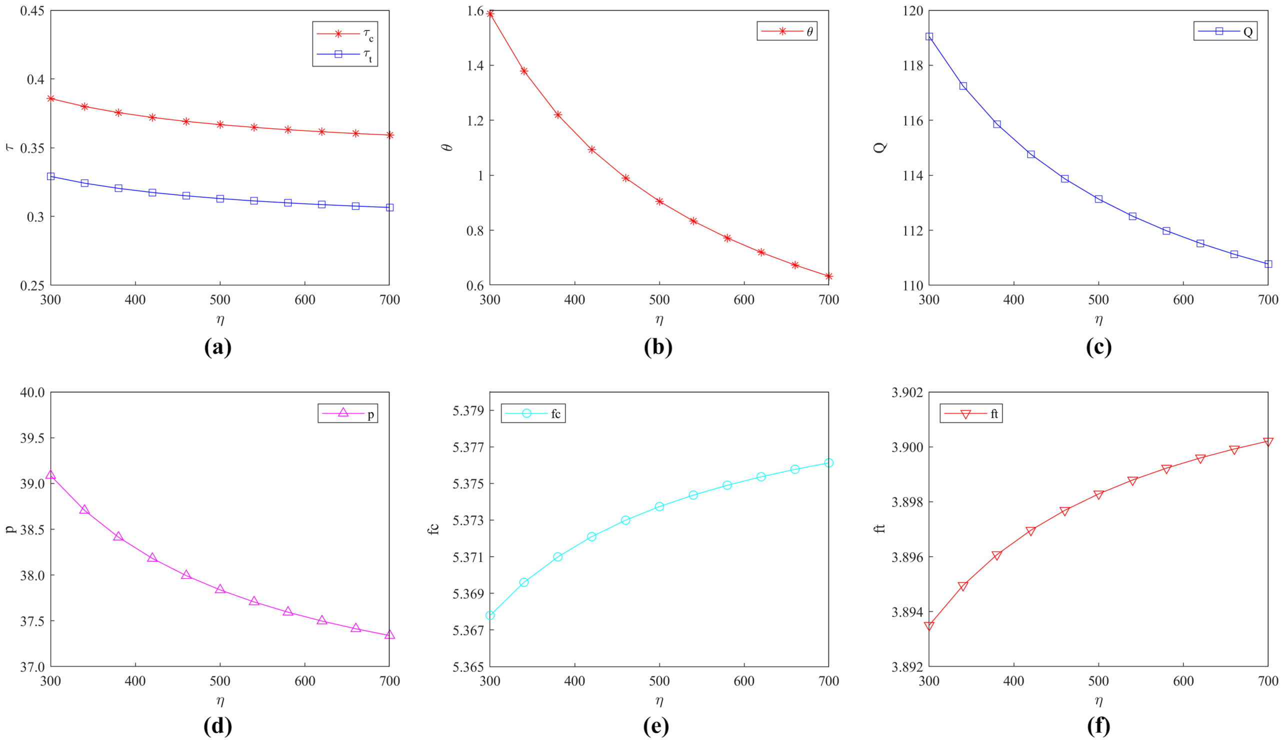
Figure 6 reveals the systematic impact of the manufacturer's CSR effort cost coefficient η on CLSC decisions. As shown in Figure 6(a), the recycling rates of recyclers and echelon utilization enterprises decline with increasing η. This phenomenon stems from the increasing marginal cost effect of CSR investments: a higher η directly constrains the manufacturer's capacity to invest in green technology R&D and recycling transparency enhancement, eroding consumer perception of product sustainability. The erosion of consumer trust triggers market demand contraction, compelling manufacturers to reduce recycled material procurement, which further suppresses recycling activities.

In Figures 6(b)–(d), the manufacturer's CSR effort level decreases nonlinearly with η, accompanied by synchronous declines in market demand and product prices. This is rooted in a two-fold cost squeeze: (1) Weakened CSR efforts diminish consumer willingness to pay, forcing price reductions to stimulate demand; (2) CSR cost pressures compress profit margins, further curtailing sustainable investments.

Figures 6(e)–(f) show that recyclers' and echelon utilization enterprises' transaction prices inversely rise with η. This counterintuitive trend reflects recycling sectors' survival tactics: despite declining volumes due to demand contraction, recycling companies marginally raise prices to cover fixed operational costs. However, increased prices exacerbate manufacturers' procurement cost burdens, further suppressing recycling orders and creating a negative feedback loop of cost pass-through, order loss, and renewed cost pass-through.

(3) Assuming all other factors remain constant, the joint effects of consumers' CSR sensitivity coefficient λ and the manufacturer's CSR effort cost coefficient η on the profits of supply chain members are depicted in Figure 7.

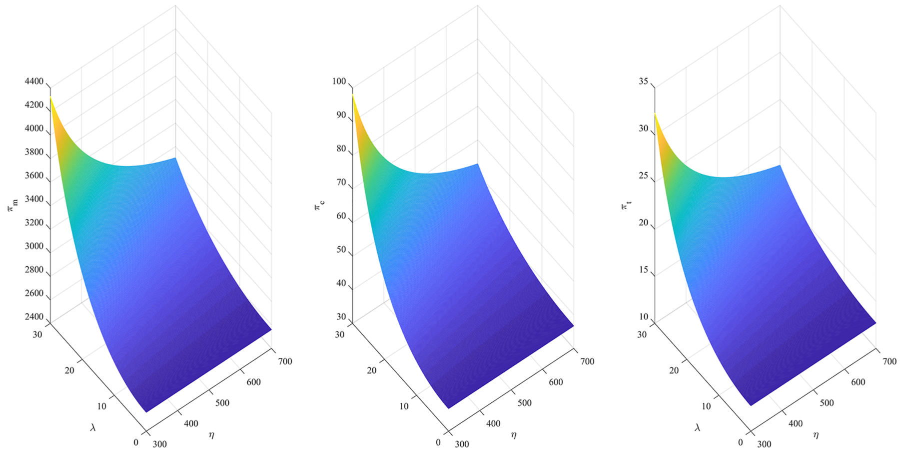
Figure 7 illustrates the effects of consumers' CSR sensitivity coefficient λ and the manufacturer's CSR cost coefficient η on supply chain profits. As shown in Figure 7(a), the



(a) **(b)** **(c)**

(d) **(e)** **(f)**

Figure 6. Impact of manufacturer’s CSR effort cost coefficient on supply chain decisions. **Source(s):** Created by authors



(a) **(b)** **(c)**

Figure 7. Impact of manufacturer's CSR cost coefficient and consumer CSR sensitivity coefficient on supply chain members' profits. **Source(s):** Created by authors

manufacturer's profit increases markedly as λ rises. Enhanced consumer willingness to pay for CSR attributes enables the manufacturer to moderately raise prices while sustaining market demand. Concurrently, enhanced recycling rates reduce production costs. When η increases, the decline in profit exhibits diminishing marginal returns, as the manufacturer mitigates cost pressures through price reductions and optimized CSR efficiency. Figure 7(b) indicates that recyclers' profits increase progressively with λ, as the expansion of recycling volumes offsets the impact of declining transfer prices. When η rises, recyclers mitigate profit contraction by marginally raising prices and aligning with the manufacturer's pricing strategy. Figure 7(c) demonstrates that echelon utilization enterprises' profits increase with λ, driven by increased material availability and value-added benefits from echelon utilization. When η increases, echelon utilization enterprises similarly stabilize profits through moderate price adjustments and strategic alignment with the manufacturer's strategy.

7. Conclusion

This study constructs a CLSC model comprising a power battery manufacturer, a recycler, and an echelon utilization enterprise. Using the noncooperative-cooperative biform game approach, we investigate the optimal strategies and profit distribution among these stakeholders under manufacturer-led CSR initiatives and recycling competition dynamics. Numerical simulations analyze the effects of recycling competition intensity, echelon utilization rate, consumer sensitivity to CSR efforts, and CSR cost coefficients on supply chain performance. The main findings reveal that (1) increased recycling competition intensity leads to decreased recovery rates of retired power batteries, reduced CSR effort levels from manufacturers, higher sales prices, diminished consumer demand, and profit reductions for all supply chain members. This suggests that excessive recycling competition may negatively impact supply chain sustainability. Notably, when the competition coefficient exceeds a critical threshold (e.g. $\alpha > 0.7$), echelon utilization enterprises may exit the market due to deteriorating profitability. This finding underscores the importance for policymakers to consider competition intensity when formulating market stabilization policies. (2) The recovery rate of retired power batteries, manufacturers' CSR effort levels, consumer demand, and profits of all supply chain members are positively correlated with the echelon utilization rate. This indicates that improving echelon utilization efficiency can significantly enhance overall supply chain performance. Consequently, both manufacturers and echelon utilization businesses should continuously enhance their R&D capabilities and technological competencies to maximize the value of echelon utilization. (3) Higher consumer sensitivity to CSR efforts positively impacts retired power battery rates, manufacturers' CSR commitment, product pricing, and profitability across the supply chain. This highlights the crucial role of consumer awareness in driving sustainable supply chain development. Conversely, increasing CSR cost coefficients generates adverse effects. Therefore, manufacturers can achieve mutually beneficial outcomes for all stakeholders by strategically enhancing CSR investments while optimizing related costs.

This study provides managerial insights for advancing the sustainable development of power battery CLSCs. (1) For manufacturers, establishing a synergistic "CSR-echelon utilization" strategic framework is crucial for enhancing competitiveness. By optimizing recycled material production processes—such as reducing disassembly costs through modular battery designs—and adopting advanced residual value assessment technologies (e.g. AI-powered battery health diagnostics), manufacturers can achieve cost efficiency and capture green premiums driven by consumer preferences. (2) For recyclers and echelon utilization enterprises, differentiated market positioning is a key strategy to resolve competitive dilemmas. Specialized division of labor based on regional demand patterns (e.g. prioritizing urban fast-charging networks versus rural energy storage systems) or battery technology types (e.g. LFP vs. NCM batteries) reduces efficiency losses from homogeneous competition, while long-term pricing agreements with manufacturers stabilize revenue streams. (3) For policymakers, a dynamic and adaptive regulatory framework is essential. This includes macro-level interventions such as setting regional competition intensity thresholds (e.g. capping recycler density in high-demand urban areas), meso-level support through technical certifications for high-efficiency echelon utilization enterprises, and micro-level standardization of battery residual value testing protocols. This multi-tiered governance model aligns environmental benefits with economic value across the supply chain, fostering a sustainability ecosystem guided by policy, driven by innovation, and sustained through industry collaboration.

This study focuses on the CLSC model where power battery manufacturers assume CSR responsibilities through a noncooperative-cooperative biform game framework. Future research could explore the dynamics of the supply chain when recyclers or echelon utilization businesses assume CSR obligations, as well as investigate more complex competitive-collaborative relationships among supply chain members.

Data availability

No data was used for the research described in the article.

Supplementary material

The supplementary material for this article can be found online.

References

Akhil, G., Liu, Y., Liang, G. and Darwin, B.P. (2020), "Development of recycling strategy for large stacked systems: experimental and machine learning approach to form reuse battery packs for secondary applications", *Journal of Cleaner Production*, Vol. 412, 137379, doi: 10.1016/j.jclepro.2020.124152.

Barman, A., Das, R., De, P.K. and Sana, S.S. (2024), "Pricing policies for a competitive dual-channel supply chain with green investment and sales effort under revenue-sharing contract", *RAIRO – Operations Research*, Vol. 58 No. 5, pp. 3985-4012, doi: 10.1051/RO/2024158.

Brandenburger, A. and Stuart, H. (2007), “Biform games”, *Management Science*, Vol. 53 No. 4, pp. 537-549, doi: 10.1287/mnsc.1060.0591.

Gu, X.Y., Zhou, L., Huang, H.F., Huang, X.T. and Petros, I. (2021), “Electric vehicle battery secondary use under government subsidy: a closed-loop supply chain perspective”, *International Journal of Production Economics*, Vol. 234, 108035, doi: 10.1016/j.ijpe.2021.108035.

Hou, Q., Liu, J.W. and Bao, W.T. (2023), “A closed-loop supply chain game model considering manufacturers’ fair concern and cascade utilization”, *Systems Engineering*, No. 2, pp. 1-11, available at: http://kns.cnki.net/kcms/detail/43.1115.n.20220824.1703.008.html

Huang, C.X. and Li, D.F. (2024), “Research on closed-loop supply chain pricing and profit distribution based on noncooperative-cooperative biform game and deposit return to recyclers”, *Chinese Journal of Management Science*, Vol. 32 No. 2, pp. 166-177, doi: 10.16381/j.cnki.issn1003-207x.2021.2244.

Huang, M., Song, M., Lee, L.H. and Ching, W.K. (2013), “Analysis for strategy of closed-loop supply chain with dual recycling channel”, *International Journal of Production Economics*, Vol. 144 No. 2, pp. 510-520, doi: 10.1016/j.ijpe.2013.04.002.

Li, X. (2020), *Collection Decisions of Electric Vehicle Battery Closed-Loop Supply Chain under Different Policies*, Beijing Jiaotong University, Beijing, pp. 41-42.

Li, D.F., Wei, L.X. and Li, M.Q. (2023), “Noncooperative-cooperative biform game approach for dual channel recycling competition and profit allocation of closed-loop supply chain under deposit return to manufacturer”, *Systems Engineering-Theory and Practice*, Vol. 43 No. 11, pp. 3241-3264, doi: 10.12011/SETP2023-0055.

Liu, J.J. and Ma, J.L. (2021), “Research on reverse subsidy mechanism of power battery closed-loop supply chain considering cascade utilization”, *Industrial Engineering and Management*, Vol. 26 No. 3, pp. 80-88, doi: 10.19495/j.cnki.1007-5429.2021.03.011.

Liu, S., Chen, D.Y. and Yao, M.F. (2022), “Research on CSR investment model and coordination strategy of dual-channel recycling closed-loop supply chain”, *Management Review*, Vol. 34 No. 10, pp. 245-257, doi: 10.14120/j.cnki.cn11-5057/f.2022.10.001.

Modak, M.N., Kazemi, N. and Cárdenas-Barrón, L.E. (2018), “Investigating structure of a two-echelon closed-loop supply chain using social work donation as a corporate social responsibility practice”, *International Journal of Production Economics*, Vol. 207, pp. 19-33, doi: 10.1016/j.ijpe.2018.10.009.

Pal, B. and Sana, S.S. (2022), “Game-theoretic analysis in an environment-friendly competitive closed-loop dual-channel supply chain with recycling”, *Operations Management Research*, Vol. 15 Nos 3-4, pp. 627-646, doi: 10.1007/S12063-021-00221-Z.

Nan, J.X., Wu, X.Y. and Zhang, M.J. (2025), “Production competition and emission reduction technology cooperation between manufacturers under the low-carbon market based on blockchain technology”, *Chinese Journal of Management Science*, Vol. 33 No. 6, pp. 360-368, doi: 10.16381/j.cnki.issn1003-207x.2023.1421.

Pal, B., Mandal, A. and Sana, S.S. (2024), “A closed-loop green supply chain with retailers’ competition and product recycling in the green environment under the cap-and-trade policy”, *Green Finance*, Vol. 6 No. 1, pp. 117-161, doi: 10.3934/GF.2024006.

Panda, S., Modak, M.N. and Cárdenas-Barrón, E.L. (2017), “Coordinating a socially responsible closed-loop supply chain with product recycling”, *International Journal of Production Economics*, Vol. 188, pp. 11-21, doi: 10.1016/j.ijpe.2017.03.010.

Raj, A., Modak, M.N., Kelle, P. and Singh, B. (2020), “Analysis of a dyadic sustainable supply chain under asymmetric information”, *European Journal of Operational Research*, Vol. 289 No. 2, pp. 582-594, doi: 10.1016/j.ejor.2020.07.042.

Sana, S.S. (2020), “Price competition between green and non green products under corporate social responsible firm”, *Journal of Retailing and Consumer Services*, Vol. 55, 102118, doi: 10.1016/j.jretconser.2020.102118.

Sana, S.S. (2021), “A structural mathematical model on two echelon supply chain system”, *Annals of Operations Research*, Vol. 315 No. 2, pp. 1-29, doi: 10.1007/S10479-020-03895-Z.

Sana, S.S. (2023), "The effects of green house gas costs on optimal pricing and production lotsize in an imperfect production system", *RAIRO – Operations Research*, Vol. 57 No. 4, pp. 2209-2230, doi: 10.1051/ro/2023115.

Sangari, N., Mirzaeian Khamseh, P. and Sana, S.S. (2023), "Green concept of neuromarketing based on a systematic review using the bibliometric method", *Green Finance*, Vol. 5 No. 3, pp. 392-430, doi: 10.3934/GF.2023016.

Savaskan, R.C., Bhattacharya, S. and Wassenhove, L.N.V. (2004), "Closed-loop supply chain models with product remanufacturing", *Management Science*, Vol. 50 No. 2, pp. 239-252, doi: 10.1287/mnsc.1030.0186.

Sinayi, M. and Rasti-Barzoki, M. (2018), "A game theoretic approach for pricing, greening, and social welfare policies in a supply chain with government intervention", *Journal of Cleaner Production*, Vol. 196, pp. 1443-1458, doi: 10.1016/j.jclepro.2018.05.212.

Sun, Q.Q., Chen, H., Long, R.Y., Li, Q.W. and Huang, H. (2022), "Comparative evaluation for recycling waste power batteries with different collection modes based on Stackelberg game", *Journal of Environmental Management*, Vol. 312, 114892, doi: 10.1016/J.JENVMAN.2022.114892.

Tan, Q., Li, J., Yang, L. and Xu, G. (2023), "Cascade use potential of retired traction batteries for renewable energy storage in China under carbon peak vision", *Journal of Cleaner Production*, Vol. 412, 137379, doi: 10.1016/j.jclepro.2023.137379.

Tang, Y.Y., Zhang, Q., Li, Y.M., Wang, G. and Li, Y. (2018), "Recycling mechanisms and policy suggestions for spent electric vehicles' power battery-a case of Beijing", *Journal of Cleaner Production*, Vol. 186, pp. 388-406, doi: 10.1016/j.jclepro.2018.03.043.

Tang, J., Li, B.Y., Gong, B.G., Liu, Z. and Zhu, X.D. (2023), "Decision and coordination of the retailer recycling closed-loop supply chain considering corporate social responsibility", *Chinese Journal of Management Science*, Vol. 31 No. 11, pp. 228-237, doi: 10.16381/j.cnki.issn1003-207x.2020.1809.

Tian, T.L., Zheng, C.Y., Yang, L.G., Luo, X.C. and Lu, L. (2022), "Optimal recycling channel selection of power battery closed-loop supply chain considering corporate social responsibility in China", *Sustainability*, Vol. 14 No. 24, 16712, doi: 10.3390/SU142416712.

Wang, Z.Z., Wang, M.Z. and Liu, W.W. (2020), "To introduce competition or not to introduce competition: an analysis of corporate social responsibility investment collaboration in a two-echelon supply chain", *Transportation Research Part E: Logistics and Transportation Review*, Vol. 133 No. 1, pp. 1-18, doi: 10.1016/j.tre.2019.11.006.

Wu, W.Q., Li, M., Zhang, M., Wang, Y.Q., Wang, L.K. and You, Y. (2024), "Electric vehicle battery closed-loop supply chain pricing and carbon reduction decisions under the carbon cap-and-trade and reward-penalty policies", *Process Safety and Environmental Protection*, Vol. 192, pp. 1467-1482, doi: 10.1016/J.PSEP.2024.10.121.

Xiao, M., Xu, C. and Xie, F. (2024), "Research on the impact of information sharing and government subsidy on competitive power battery recycling", *Journal of Cleaner Production*, Vol. 467, 142989, doi: 10.1016/J.JCLEPRO.2024.142989.

Yao, M.F., Yan, Y.L. and Liu, S. (2021), "Recycling and pricing decisions for closed-loop supply chain considering corporate social responsibility investment under government's subsidy", *Operations Research and Management Science*, Vol. 30 No. 6, pp. 69-76, doi: 10.12005/orms.2021.0182.

Yi, Y.X., He, X.W., Li, Y.Q. and Li, C. (2024), "Decision-making in a green trade-ins closed-loop supply chain under financial constraints and corporate social responsibility (CSR)", *Computers and Industrial Engineering*, Vol. 197, 110626, doi: 10.1016/J.CIE.2024.110626.

Yu, S. and Hou, Q. (2023), "A closed-loop power battery supply chain differential game model considering echelon utilization under a cost subsidy", *Kybernetes*, Vol. 52 No. 8, pp. 2826-2846, doi: 10.1108/K-07-2021-0544.

Zhang, H.M., Huang, J.Y., Hu, R.H., Zhou, D.Q., Haroon, R.K. and Ma, C.X. (2020), "Echelon utilization of waste power batteries in new energy vehicles: review of Chinese policies", *Energy*, Vol. 206, 118178, doi: 10.1016/j.energy.2020.118178.

Zhang, C., Tian, Y.X. and Han, M.H. (2022), "Recycling mode selection and carbon emission reduction decisions for a multi-channel closed-loop supply chain of electric vehicle power battery under cap-and-trade policy", *Journal of Cleaner Production*, Vol. 375, 134060, doi: 10.1016/j.jclepro.2022.134060.

Zhang, C., Li, H. and Tian, Y.X. (2023a), "Manufacturer's carbon abatement strategy and selection of spent power battery collecting mode based on echelon utilization and cap-and-trade policy", *Computers and Industrial Engineering*, Vol. 177, 109079, doi: 10.1016/j.cie.2023.109079.

Zhang, C., Chen, Y.X. and Tian, Y.X. (2023b), "Collection and recycling decisions for electric vehicle end-of-life power batteries in the context of carbon emissions reduction", *Computers and Industrial Engineering*, Vol. 175, 108869, doi: 10.1016/j.cie.2022.108869.

Zhang, C., Tian, Y.X. and Li, C.C. (2024a), "Echelon utilization decision of an EV power battery manufacturer under cap-and-trade policy", *Control and Decision*, Vol. 39 No. 6, pp. 2051-2059, doi: 10.13195/j.kzyjc.2022.1506.

Zhang, C., Tian, Y.X. and Cui, M.Y. (2024b), "Selection of hybrid channel recycling modes and carbon emission reduction decisions for the electric vehicle battery manufacturer", *Chinese Journal of Management Science*, Vol. 32 No. 6, pp. 184-195, doi: 10.16381/j.cnki.issn1003-207x.2022.2221.

Zhang, W.S., Zhu, L., Liu, X.Y., Wang, W. and Song, H.F. (2024c), "Optimal strategies in electric vehicle battery closed-loop supply chain considering government subsidies and echelon utilization", *Journal of Energy Storage*, Vol. 99, 113341, doi: 10.1016/j.est.2024.113341.

Zhao, S.L., Liu, H.C., Zhou, Q. and Xia, X.Q. (2024), "How the external environment affects the equilibrium decisions and profits of battery and EV manufacturers?", *Journal of Cleaner Production*, Vol. 434, 139838, doi: 10.1016/j.jclepro.2023.139838.

Zheng, X.X. and Li, D.F. (2023), "A new biform game-based investment incentive mechanism for eco-efficient innovation in supply chain", *International Journal of Production Economics*, Vol. 258, 108795, doi: 10.1016/j.ijpe.2023.108795.

Zheng, B.R., Yang, C. and Yang, J. (2018), "Manufacturer's optimal alliance strategy in closed-loop supply chains in the presence of competing recycling channels", *Systems Engineering-Theory and Practice*, Vol. 38 No. 6, pp. 1479-1491, doi: 10.12011/1000-6788(2018)06-1479-13.

Corresponding author
Qiang Hou can be contacted at: houqiang@sut.edu.cn