Heliyon 10 (2024) e38597

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

Power battery modular innovation investment strategies with government subsidy policies

Juanjuan Liu [a], Bin Du [b], Jing Xue [a], Weisi Zhang [b,*]

[a] *School of Economics & Management, Shanghai Maritime University, Shanghai, 201306, China*
[b] *Logistics Research Center, Shanghai Maritime University, Shanghai, 201306, China*

A R T I C L E I N F O

Keywords:
Closed-loop supply chain
Government subsidies
Power batteries
Tiered utilization
Innovation investment
Supply chain coordination

A B S T R A C T

This paper investigates the closed-loop supply chain decisions of battery manufacturers considering innovation investments and different subsidy methods provided by the government. The analysis encompasses four scenarios: whether battery manufacturers engage in innovation investments and whether the government opts for technology R&D subsidies or production subsidies. The study finds that innovation investments by battery manufacturers can enhance the modularization level of batteries. The reward or penalty measures for recycling quality imposed on automobile manufacturers elevate the quality of battery recycling, and also increase the wholesale price of batteries and the retail price of automobiles. After implementing R&D and production subsidies, both the modularization level of batteries and the profits of supply chain members exceed those without subsidies, though these subsidies do not affect the quality of battery recycling. R&D subsidies more effectively promote innovation capacity and product quality among battery manufacturers, whereas production subsidies more significantly boost the profits of both battery manufacturers and automobile manufacturers. Therefore, subsidy measures should be tailored according to different stages of the power battery industry's development. Regardless of whether battery manufacturers invest in innovation or whether the government provides subsidies, collaboration between battery manufacturers and automobile manufacturers is essential to coordinate the closed-loop supply chain. The research findings offer valuable guidance for formulating subsidy policies in the new energy vehicle industry across different periods, and also provide theoretical insights for decision-making behaviors among related enterprises.

1. Introduction

As the scarcity of fossil fuels intensifies globally and as governments worldwide increasingly prioritize environmental concerns, new energy vehicles (NEVs) have become a major trend in the automotive industry's green transformation and innovative development. This shift is evidenced by significant growth in both the scale and sales of NEVs. Concomitantly, the industry of power batteries, which are integral to NEVs, has experienced rapid growth. However, the challenge of properly disposing of a large volume of retired power batteries is critical. Improper disposal not only results in resource waste but also poses environmental risks. Currently, China is approaching a peak period for the retirement of used power batteries, with an expected annual scrapping volume of up to 800,000 tons

* Corresponding author.
E-mail address: wszhang@shmtu.edu.cn (W. Zhang).

https://doi.org/10.1016/j.heliyon.2024.e38597
Received 15 May 2024; Received in revised form 25 September 2024; Accepted 26 September 2024
Available online 28 September 2024

by 2025 [1]. Such trends have significantly heightened the focus on power battery recycling, underscoring the necessity for effective management and sustainable solutions.

Although the market for recycling power batteries is vast, China's retired power battery industry is still in the nascent stages of recycling and reuse, presenting numerous risks and challenges. Currently, there are two main pathways for repurposing retired power batteries: firstly, the cascaded utilization of batteries with a capacity degradation level between 20% and 80 % [2], and secondly, the regeneration and reuse of batteries unfit for cascaded utilization. The progression of battery technology offers a sustainable development path for the transportation industry [3]. Currently, the regeneration and reuse of power batteries primarily encounter significant technical challenges. The processes of recycling and regenerating spent power batteries are gradual and necessitate substantial technological advancements, which are currently inadequate. This deficiency in progress leads to elevated costs for recycling and remanufacturing, consequently resulting in a low reuse rate of retired power batteries. Therefore, investigating power battery modular innovation investment strategies with government subsidy policies is an essential topic.

With the rapid development of the new energy vehicle industry in recent years [4], the disposal of used batteries has become a critical issue. In light of this background, there remains significant research potential in the recycling of used power batteries. Accordingly, this paper establishes a Closed-Loop Supply Chain (CLCS) model consisting of battery manufacturers and electric vehicle manufacturers to study the collection and remanufacturing strategies in supplier and manufacturer recycling models. We consider factors such as battery capacity at the time of recycling, corporate R&D, and government subsidies. Within this framework, the Stackelberg game is employed as the research method, with battery manufacturers designated as leaders, while automobile manufacturers as followers. Building on relevant theoretical foundations and current practical challenges, we delineate the following research questions.

(1) How do centralized and decentralized decisions specifically impact the quality of retired battery recycling and the profitability of the closed-loop supply chain?
(2) What is the specific impact of increased investment in technological R&D on the profits of the closed-loop supply chain, and how does this impact manifest in the product value creation and competitive enhancement of battery manufacturers?
(3) How do different government subsidy strategies affect the modularity level of power batteries and the profits of battery manufacturers and automobile manufacturers, particularly which is more effective: government R&D subsidies or production subsidies?
(4) How does the use of the K-S solution to coordinate the profits of closed-loop supply chain members perform under various government subsidy scenarios, and how does it ensure optimal cooperation among supply chain members?

Therefore, this study primarily focuses on the modular design of power batteries and investments in enhancing battery recycling quality. We have established a closed-loop supply chain model for power batteries, analyzing various government subsidy scenarios and methods. Our analysis identifies two main types of government subsidy strategies for power battery modular innovation investments: technology investment subsidies and production volume subsidies. Technology investment subsidies, exemplified by policies in Germany and South Korea, primarily support battery technology research and innovation. Conversely, production volume subsidies, as implemented in China and the USA, aim to incentivize large-scale battery production. These strategies facilitate technological advancement and the scaling of the battery industry. This research emphasizes the impact of battery manufacturers' innovative investments, recycling quality incentive measures, and government subsidy strategies on the closed-loop supply chain of power batteries.

The main findings of the research are as follows. When battery manufacturers engage in technological innovation, it effectively improves the quality and quantity of recycled power batteries and increases the overall profit of the supply chain. When manufacturers lack sufficient R&D funds, the government should provide interest subsidies. If both the government and manufacturers aim to achieve a certain level of new energy vehicle technology, the government should offer free green credit [5]. Conversely, our study finds that if the goal is to enhance new energy vehicle technology, the government should adopt R&D subsidy strategies; if the goal is to generate more economic benefits, production subsidies are more appropriate. Furthermore, we find that centralized decision-making yields better economic benefits compared to decentralized decision-making during the recycling process, consistent with the findings of literature [6].

This study proposes a new theoretical model that incorporates product recycling quality and tiered utilization in the battery recycling process, while also considering corporate R&D innovation and various government subsidy strategies. It reveals several important conclusions in the power battery recycling process, providing guidance for related enterprises in their decision-making. Additionally, it explains the impacts of different government subsidy models and offers answers on selecting the appropriate subsidy strategy under different goals and stages. This study further enriches the research in the field of battery recycling and promotes its development.

The remainder of this paper is organized as follows. Section 2 provides an overview of the related literature. Section 3 details the model description and research assumptions. In Section 4, the decision model without government subsidies is analyzed. Section 5 examines the decision model under different government subsidies. Section 6 presents a comparison and analysis of the models. Section 7 offers numerical analysis. Finally, Section 8 concludes with findings and implications.

2. Literature review

The substantial environmental and economic advantages of the tiered utilization and recycling remanufacturing of retired power batteries have captured the interest of the academic community extensively. This study extends the discussion on urban planning strategies critical for mitigating climate change, particularly emphasizing transport planning policies as effective methods to address climate impacts. These strategies are vital in amplifying the benefits derived from the innovative reuse and remanufacturing of retired power batteries, demonstrating the synergy between sustainable urban mobility plans and efficient battery lifecycle management. Drawing on discussions from Ref. [7], which highlight the advantages of reusing retired batteries and propose to strengthen innovative design in battery design to enhance the environment and the economy to help the benefits [8]. summarized that after retired power batteries are recycled, the first step is to carry out gradient utilization, and then material recycling treatment is the best technical route, which is of considerable necessity and practical significance in terms of economy, resources and environment [9]. proposed to use the recycling rate of used products as an endogenous variable to satisfy the set goals and to provide OEMs with optimal remanufacturing strategies based on reverse operating costs and new product manufacturing costs with and without recycling provisions. Since the quality level of OEMs not only affects their own production costs but also the recovery costs of independent remanufacturers. Therefore [10], studied independent remanufacturers' cooperation with OEMs through technology licensing or R&D joint venture mechanisms to reduce costs and compare the performance between cooperative models [11]. demonstrated that power battery recycling and remanufacturing can increase supply chain profits and suggested that focusing on factors such as battery quality and cost is key to realizing the remanufacturing of retired batteries. The results of [12] suggested that battery recycling and reuse can help to reduce raw material consumption and thus environmental impacts compared to new battery manufacturing, but there may not be an economic benefit to be gained [13]. studied a closed-loop supply chain consisting of manufacturers, retailers, and third-party recyclers. Based on different channel structures, a Stackelberg game model is developed to explore the optimal decision of product price, recycling quality level and recycling quantity [14]. investigated the effects of carbon trading policies, power battery range and advertising effects on the choice of recycling channels for manufacturer recycling, retailer recycling and mixed recycling [15]. showed that the manufacturing cost of new batteries and the quality level of used batteries are key factors influencing the performance of the recycled battery supply chain, and that remanufacturing costs and subsidies can act as proxies for coordination among supply chain members, thereby improving the efficiency of the recycling supply chain [16]. investigated the recycling model selection and carbon emission reduction decision of closed-loop supply chain of power battery under carbon cap-and-trade policy, and the positive effect of recycling by ladder utilizers to alleviate the pressure of recycling.

In the context of green sustainable development and national dual carbon goals, corporate innovation investment strategies have attracted widespread attention [17]. set firms to reduce carbon footprints in the supply chain through product innovation and design, and use game theory methods to study the effects of supply chain cost-sharing contracts on the level of product greening, product prices and members' profits [18]. studied the value of process and product innovation in supply chains under different dominant structures, suggested that manufacturers should be leaders in investing in product innovation and need to invest more in innovation [19]. constructed a cooperative and non-cooperative model to study the impact of process innovation on remanufacturing, and the results showed that process innovation can effectively improve remanufacturing performance, as well as increase the manufacturer's recycling rate [20]. investigated product design and its impact on the operations of a two-level closed-loop supply chain and showed that while remanufacturing does not necessarily improve profitability, adjusting product design strategies can help to curb losses if profitability is affected [21]. construct a closed-loop supply chain containing manufacturers and retailers modeled with loss aversion characteristics, aiming to investigate the impact of loss aversion on the recycling quality decisions of supply chain members [22]. study to enhance the efficiency of product eco-design and collection in a closed-loop supply chain, where manufacturers and retailers cooperate with each other through responsibility sharing, and comparatively analyze the impact of the responsibility sharing ratio on the optimal eco-design.

Manufacturers' product R&D decisions are influenced by both market conditions and government subsidy incentives [22]. compared the effects of government policies on subsidies for recycling companies, consumer subsidies, and subsidies for both recycling companies and consumers. They found that without government subsidies, the market cannot ensure high returns for either party. However, government subsidies for recycling companies and consumers can maximize social welfare at the lowest government cost [23]. proposed a tripartite game model for low-carbon innovation in power battery recycling. By simulating the evolutionary process through parameter allocation and exploring parameter sensitivity and comparative effects, they found that government incentive measures play a crucial role in encouraging manufacturers and recyclers to engage in low-carbon innovation [24]. studied the impact of environmental subsidies on the incentives of manufacturing firms to invest in emission-reducing technologies, comparing manufacturer subsidies with consumer subsidies. They found that technology subsidies to manufacturers increase the level of green inputs and reduce carbon emissions, while subsidies to consumers increase social welfare. In order to promote the secondary utilization of power batteries [25], proposed that the government increase subsidies to secondary consumers to incentivize the secondary utilization of power batteries [26]. aimed to explore the impact of government regulations on manufacturers' recycling decisions and found that manufacturers' participation in recycling depended on technological innovation and carbon allowances, and that manufacturers preferred carbon tax or cap-and-trade policies [27]. showed that reducing the potential risk of innovation and development of recyclers and cascade utilization enterprises can increase the motivation of both parties to promote the practical improvement of the level of recycling. In addition, increasing the environmental treatment fee for professional battery dismantling enterprises is an effective way to enhance the efficiency of resource utilization [28]. built the bonus-penalty contract based on the product quality criteria provided by suppliers, to study how the contract influences the coordination of supply chain in the context of fairness preference.

Existing research has extensively studied recycling and remanufacturing, innovation investment, and government subsidies. However, there is a lack of research on the impact of corporate innovation investment and government subsidy methods on the closed-loop supply chain of power batteries when considering the tiered utilization of retired power batteries. Most scholars treat recycling quality as an exogenous variable, assuming that product recycling quality is not directly related to corporate recycling efforts or government regulation. In reality, the quality of recycled products is a crucial standard for their entry into recycling and remanufacturing processes. Therefore, it is more reasonable to set the quality of recycled products as an endogenous variable. Based on the above analysis, this paper constructs decision models for closed-loop supply chains under scenarios where battery manufacturers invest in innovation and different government subsidy methods, considering the tiered utilization of power batteries. The study explores the impact of different government subsidy policies on the decisions of closed-loop supply chain members under corporate innovation investment. Table 1 illustrates the differences between this study and related literature.

Reference [6] constructed a closed-loop supply chain and used the Stackelberg model to analyze three pricing strategies related to the automobile battery recycling process under government subsidies. In contrast, this study differentiates itself by introducing the tiered utilization of used batteries and investigating the impact of innovation investment and battery recycling quality on each decision within the closed-loop supply chain. Additionally, we developed two different government subsidy models, comparing the effects of various subsidy schemes to provide valuable insights for government policy-making.

3. Problem description and research assumptions

3.1. Problem description

In the context of enhancing the recycling quality of retired power batteries, this study considers a closed-loop supply chain comprising a sole battery manufacturer, a single automobile manufacturer, and consumers. To elevate the recycling quality of retired power batteries, the battery manufacturer invests in innovative technology, designs the power batteries modularly, and implements quality-based reward and penalty measures for the automobile manufacturer, incentivizing their investment in recycling quality. The government provides technical R&D subsidies or production subsidies to the battery manufacturer for recycling and remanufacturing. In this model, the battery manufacturer sells power batteries to the automobile manufacturer at a wholesale price w, who in turn sells new energy vehicles to consumers at a retail price p. Subsequently, the automobile manufacturer buys back used power batteries from consumers at a recycling price U and sells them to the battery manufacturer and the cascade utilizers at transfer prices h_1 and h_2, respectively. Under the government subsidy scenario, the government provides a subsidy to battery manufacturers. The battery manufacturer then remanufactures using the reclaimed batteries, while cascade utilizers employ them for their sequential usage.

The operational model of the closed-loop supply chain studied in this paper is illustrated in Fig. 1.

3.2. Methodology

This study primarily employs the Stackelberg game approach, where battery manufacturers act as the leaders in the game, and automobile manufacturers are the followers. The optimal decisions under different models are derived using the backward induction method. Mathematical tools and data visualization techniques are utilized for conducting property analysis and numerical analysis.

3.3. Research assumptions and parameter settings

In this study, we construct a closed-loop supply chain centered around the battery manufacturer. The battery manufacturer engages in innovative technology investment (indicated by the level of product modularization representing product design characteristics, leveraging sufficient industry technological infrastructure without altering the battery package's performance, thereby preserving public acceptance), production, and sales, and develops reward and penalty policies for recycling quality. These policies aim to motivate automobile manufacturers to enhance the quality of recycling. The automobile manufacturers are responsible for selling new energy vehicles and recycling retired power batteries. Tiered utilizers reprocess and resell used power batteries suitable for tiered utilization to the tiered utilization market. The battery manufacturer remanufactures those used power batteries that are not suitable for tiered utilization.

The relevant symbols are detailed in Table 2, under the following assumptions:

Assuming 1: All members of the supply chain are ideal decision-makers, aiming to maximize profits, and operate under conditions

Table 1
A brief review of the related literature.

	CLCS	Game theory	R&D	Government subsidies	Recycling or graded utilization
Zhang et al. (2023) [16]	✓	✓			✓
Zhao et al. (2022) [21]	✓	✓			✓
Wu et al. (2018) [10]	✓	✓	✓		✓
Xu et al. (2021) [9]	✓				✓
Chai et al. (2024) [19]	✓	✓	✓		
Liu et al. (2019) [20]	✓		✓		
Wang et al. (2023) [22]	✓	✓	✓		
Li et al. (2024) [29]	✓	✓	✓	✓	
Gu et al. (2021) [25]	✓			✓	✓
This paper	✓	✓	✓	✓	✓

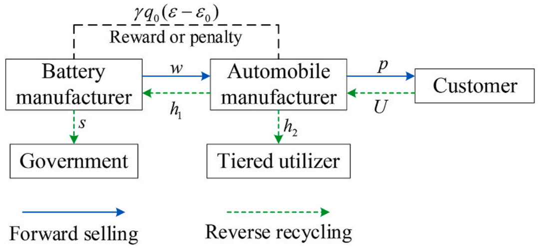

Fig. 1. Operational model of the closed-loop supply chain for power batteries.

of complete information, with a neutral attitude towards risk.

Assuming 2: The model only considers a single cycle of the power battery, and the remanufactured batteries are of the same quality as new batteries, sold at the same market price.

Assuming 3: Similar to the literature [30], the demand function for the new energy vehicle market is represented as $q(p) = a - bp + vk$, where a is the potential maximum market demand, b is the price sensitivity coefficient, and v represents the impact of product modular design level on market demand. The R&D investment cost for product design at modular level k is represented as σk^2. Financial constraints are not considered a primary concern, primarily due to the provision of government subsidies for R&D investment costs.

Assuming 4: Similar to the literature [31,32], the quantity of retired power batteries collected is influenced by the recycling price, $q_0 = m + lU$. Since the recycling price depends on the recycling quality level, the unit recycling price for automobile manufacturers is $U = \zeta\varepsilon$, resulting in $q_0 = m + l\zeta\varepsilon$. For simplicity, let the quantity of retired power batteries be influenced by the recycling quality, denoting $n = l\zeta$, so $q_0 = m + n\varepsilon$, where m is the quantity of retired power batteries voluntarily returned by consumers when the recycling price is zero, l is the sensitivity coefficient of recycling quantity to recycling price, and n is the sensitivity coefficient of recycling quantity to recycling quality.

Assuming 5: Building upon reference [28], improvements are made to incentivize higher recycling quality of retired power batteries. Battery manufacturers implement rewards or penalties for automobile manufacturers based on recycling quality, with a critical threshold for recycling quality denoted as ε_0 and an implementation amount of $\gamma q_0(\varepsilon - \varepsilon_0)$. If the recycling quality of automobile manufacturers falls below the target recycling quality ε_0, they will face economic penalties; conversely, they will receive economic rewards.

Assuming 6: Automobile manufacturers responsible for recycling invest in quality during the retired power battery recycling process, with quality investment cost of $\lambda\varepsilon^2$.

Assuming 7: The remanufacturing cost of retired batteries differs from the manufacturing cost of new batteries, with the unit cost of remanufactured products represented as $c_r = c_m - e\varepsilon - \mu k$, where $c_m > c_r > 0$. When battery manufacturers do not engage in product modular design, $\sigma = 0$.

Assuming 8: Following reference [19], the unit recycling price for automobile manufacturers collecting retired power batteries is $U = \zeta\varepsilon$, where U is the unit cost of collecting retired power batteries from consumers, and the recycling cost increases with higher recycling quality. Battery manufacturers set transfer prices as $h_1 = \theta\varepsilon$ and tiered utilization prices as $h_2 = \rho\varepsilon$, where the transfer prices

Table 2
Basic symbol descriptions.

Symbol	Description
p	Retail price of new energy vehicles
w	Wholesale price of power batteries
c_m	Production cost of new batteries
c_r	Production cost of retired power batteries
ε	Recycling quality
U	Recycling price of retired power batteries by automobile manufacturer
θ	Maximum unit transfer price the battery manufacturer is willing to pay
q_0	Volume of recycled retired power batteries
s_1	Government subsidy for technological R&D
s_2	Government subsidy for production volume
ζ	Maximum unit recycling price the automobile manufacturer is willing to pay
ρ	Maximum unit transfer price the tiered utilizer is willing to pay
f	Proportion of recycled retired power batteries unsuitable for tiered utilization
λ	Quality investment coefficient in the recycling process by automobile manufacturer
π_R	Profit of automobile manufacturer
π_M	Profit of battery manufacturer
π_{SC}	Total profit of the supply chain
e	Battery recycling quality cost subsidy coefficient
μ	Modularity level cost subsidy coefficient
σ	R&D investment cost coefficient

are a function of recycling quality, and higher recycling quality results in higher recycling costs for battery manufacturers and cascaded utilization businesses. To ensure the profitability and recycling incentives of automobile manufacturers and battery manufacturers, it is assumed that $U < h_i, i = 1,2$, meaning $\rho > \theta > \zeta > 0$.

Assuming 9: To guarantee an optimal solution for the model, it is assumed that $e > \rho > \theta > \zeta > 0$, this ensures that used batteries meeting the standards for tiered utilization are prioritized for sale to tiered utilization enterprises to achieve higher economic benefits. It also ensures that the remanufacturing by battery manufacturers can achieve positive economic benefits. $\lambda - n(f\theta + \rho - f\rho - \zeta) > 0$; $b\sigma(1 - s_1) > v^2$, with $0 < f < 1$.

4. Non subsidized supply chain decision making model

4.1. Battery manufacturer without innovation technology investment model

Under decentralized decision-making, battery manufacturer and automobile manufacturer will choose their respective profit-maximizing decisions. The battery manufacturer will first decide the battery wholesale price w based on profit maximization principle, and then automobile manufacturer will determine the car retail price p and the quality level of retired power battery recycling ε to maximize his profit. This results in objective profit maximization functions for battery manufacturer and automobile manufacturer.

$$\max \pi_M(w) = (w - c_m)(q - q_0 f) + (w - c_r)q_0 f - h_1 q_0 f \tag{1}$$

$$\max \pi_R(p, \varepsilon) = (p - w)q - Uq_0 + h_1 q_0 f + h_2 q_0(1 - f) - \lambda\varepsilon^2 \tag{2}$$

Using reverse induction, the automobile manufacturer makes the initial decision. First of all, it is obtained according to the profit function (2) of the automobile manufacturer $\frac{\partial^2 \pi_R}{\partial p^2} = -2b < 0$ and $\begin{vmatrix} \frac{\partial^2 \pi_R}{\partial p^2} & \frac{\partial^2 \pi_R}{\partial p \partial \varepsilon} \\ \frac{\partial^2 \pi_R}{\partial \varepsilon \partial p} & \frac{\partial^2 \pi_R}{\partial \varepsilon^2} \end{vmatrix} = 4b[\lambda - n(f\theta + \rho - f\rho - \zeta)] > 0$, it can be observed that π_R is a concave function with respect to p and ε, indicating the existence of a maximum value. Therefore, by setting $\frac{\partial \pi_R}{\partial p} = 0$ and $\frac{\partial \pi_R}{\partial \varepsilon} = 0$, we can derive the best response functions: $p = \frac{a+bw}{2b}, \varepsilon_1 = \frac{m[f(\theta-\rho)+\rho-\zeta]}{2[\lambda-n(f\theta+\rho-f\rho-\zeta)]}$.

Having obtained p and ε_1, We can now bring them into the profit function (1) of the battery manufacturer and take the derivative with respect to its decision variable w. Similarly, the second derivative is $-b < 0$, confirming concavity. By setting $\frac{\partial \pi_M}{\partial w} = 0$, we can derive the optimal decision for the battery manufacturer $w_1 = \frac{a+bc_m}{2b}$. Substituting w_1 back into the car retail price p, we can obtain the equilibrium retail price for the automobile manufacturer $p_1 = \frac{1}{4}\left(\frac{3a}{b} + c_m\right)$.

Theorem 1. *The equilibrium retail price for the automobile manufacturer is* $p_1 = \frac{1}{4}\left(\frac{3a}{b} + c_m\right)$. *The quality level of retired power battery recycling is given by* $\varepsilon_1 = \frac{m[f(\theta-\rho)+\rho-\zeta]}{2[\lambda-n(f\theta+\rho-f\rho-\zeta)]}$. *The equilibrium wholesale price for the battery manufacturer is* $w_1 = \frac{a+bc_m}{2b}$. *The demand for new energy vehicles is* $D_1 = \frac{1}{4}(a - bc_m + 4kv)$, *and the quantity of retired power battery recycling is* $q_{01} = \frac{1}{2}m\left(1 + \frac{\lambda}{\lambda-n(f\theta+\rho-f\rho-\zeta)}\right)$.

Corollary 1. *In the model without innovative technology investment by the battery manufacturer,* $\frac{\partial p}{\partial c_m} > 0$; $\frac{\partial \varepsilon}{\partial \zeta} < 0$; $\frac{\partial \varepsilon}{\partial f} < 0$; $\frac{\partial \varepsilon}{\partial n} > 0$; $\frac{\partial \varepsilon}{\partial \theta} > 0$; $\frac{\partial \varepsilon}{\partial \rho} > 0$.

The quality of battery recycling increases with the increase in the maximum unit recycling price offered by the tiered utilizer and the battery manufacturer. This is because a higher recycling price from the tiered utilizer and the battery manufacturer motivates the automobile manufacturer to improve battery recycling quality. The battery recycling quality decreases with an increase in the maximum recycling price the automobile manufacturer is willing to pay and the proportion of batteries unsuitable for tiered utilization. The retail price of new energy vehicles increases with the increase in the remanufacturing cost of the battery manufacturer.

Proof: $\frac{\partial p}{\partial c_m} = \frac{1}{4} > 0$; $\frac{\partial \varepsilon}{\partial \zeta} = -\frac{mn(f\theta+\rho-f\rho-\zeta)}{[2[\lambda-n(f\theta+\rho-f\rho-\zeta)]]^2} - \frac{m}{2[\lambda-n(f\theta+\rho-f\rho-\zeta)]} < 0$; $\frac{\partial \varepsilon}{\partial f} = \frac{mn(\theta-\rho)(f\theta+\rho-f\rho-\zeta)}{[2[\lambda-n(f\theta+\rho-f\rho-\zeta)]]^2} + \frac{m(\theta-\rho)}{2[\lambda-n(f\theta+\rho-f\rho-\zeta)]} < 0$; $\frac{\partial \varepsilon}{\partial n} = \frac{m(f\theta+\rho-f\rho-\zeta)^2}{[2[\lambda-n(f\theta+\rho-f\rho-\zeta)]]^2} > 0$; $\frac{\partial \varepsilon}{\partial \theta} = \frac{fmn(f\theta+\rho-f\rho-\zeta)}{[2[\lambda-n(f\theta+\rho-f\rho-\zeta)]]^2} + \frac{fm}{2[\lambda-n(f\theta+\rho-f\rho-\zeta)]} > 0$; $\frac{\partial \varepsilon}{\partial \rho} = \frac{(1-f)mn(f\theta+\rho-f\rho-\zeta)}{[2[\lambda-n(f\theta+\rho-f\rho-\zeta)]]^2} + \frac{(1-f)m}{2[\lambda-n(f\theta+\rho-f\rho-\zeta)]} > 0$.

4.2. Battery manufacturer innovation technology investment model

The battery manufacturer participates in the recycling and remanufacturing of retired power batteries and invests in innovative technologies. This involves the modular design of power batteries and the implementation of reward or penalty measures for recycling quality directed at the automobile manufacturer, thereby encouraging them to enhance the recycling quality level of retired power batteries.

The objective profit maximization functions for the battery manufacturer and automobile manufacturer in this scenario are shown in the following equations (3) and (4) respectively as follows:

$$\max \pi_M(w) = (w - c_m)(q - q_0 f) + (w - c_r)q_0 f - h_1 q_0 f - \sigma k^2 - \gamma q_0(\varepsilon - \varepsilon_0) \tag{3}$$

$$\max \pi_R(p,\varepsilon) = (p-w)q - Uq_0 + h_1 q_0 f + h_2 q_0 (1-f) + \gamma q_0(\varepsilon - \varepsilon_0) - \lambda\varepsilon^2 \tag{4}$$

Theorem 2. *The equilibrium retail price for the automobile manufacturer is given by* $p_2 = \frac{1}{(8b\sigma-\nu^2)B}\left(f\left(n\left(2(\theta-\rho)\left(-6a\sigma-2bc_m+c_m\nu^2\right)-3\gamma\mu\nu n\varepsilon_0\right)-3\mu m\nu(N-2\lambda)\right)+2\left(c_m\left(\nu^2-2b\sigma\right)-6a\sigma\right)(N-\lambda)+3A\right)$, *where the recycling quality level of retired power batteries is* $\varepsilon_2 = \frac{m\gamma-\zeta+f\theta+\rho-f\rho-n\gamma\varepsilon_0}{2[\lambda-n(\gamma-\zeta+f\theta+\rho-f\rho)]}$, *the equilibrium wholesale price for the battery manufacturer is* $w_2 = \frac{-4fn\sigma(\theta-\rho)(a+bc_m)+\left(c_m\nu^2-4\sigma(a+bc_m)\right)(N-\lambda)-f\nu[n(c_m\nu(\rho-\theta)+\gamma\mu n\varepsilon_0)+\mu m(N-2\lambda)]+A}{(8b\sigma-\nu^2)B}$, *and the level of modular design of power batteries is* $k_2 = \frac{a\nu B+b\left(f\left(c_m\nu n(\rho-\theta)+4\lambda\mu m-2\mu mN-2\gamma\mu n^2\varepsilon_0+c_m\nu(N-\lambda)+2A\right.\right.}{(8b\sigma-\nu^2)B}$. *Here,* $A = f^2\mu m\nu n(\rho-\theta)$; $B = \lambda - n(\gamma-\zeta+f\theta+\rho-f\rho)$; $N = n(\gamma-\zeta+\rho)$.

Corollary 2. *In the model with innovation technology investment by the battery manufacturer,* $\frac{\partial w}{\partial\gamma} > 0$; $\frac{\partial p}{\partial\gamma} > 0$; $\frac{\partial\varepsilon}{\partial\gamma} > 0$; $\frac{\partial k}{\partial\gamma} > 0$.

The implementation of reward or penalty measures by the battery manufacturer increases the wholesale price of power batteries and the retail price of new energy vehicles, improving the recycling quality of retired power batteries. This implies that reward and penalty measures increase the retail price of new energy vehicles, thus reducing market demand and the profits of the battery manufacturer. On the other hand, these measures also elevate the modular design level of power batteries, increasing market demand, and therefore the profits of the battery manufacturer. The battery manufacturer can adjust the intensity of reward and penalty to motivate the automobile manufacturer to improve recycling quality.

Proof: When $m\lambda - n\varepsilon_0(\lambda - n(f\theta+\rho-f\rho-\zeta)) > 0$; $2bf\mu + (f-1)\nu > 0$; $f\mu\nu + 4(f-1)\sigma > 0$; $\frac{\partial\varepsilon}{\partial\gamma} = \frac{m\lambda-n\varepsilon_0[\lambda-n(-\zeta+f\theta+\rho-f\rho)]}{2[\lambda-n(\gamma-\zeta+f\theta+\rho-f\rho)]^2} > 0$; $\frac{\partial p}{\partial\gamma} = \frac{n[m\lambda-n\varepsilon_0(\lambda-n(f\theta+\rho-f\rho-\zeta))]\left(3bf\mu\nu+(f-1)\nu^2+4b(f-1)\sigma\right)}{2b\left(8b\sigma-\nu^2\right)[\lambda-n(\gamma-\zeta+f\theta+\rho-f\rho)]^2} > 0$; $\frac{\partial w}{\partial\gamma} = \frac{n[m\lambda-n\varepsilon_0(\lambda-n(f\theta+\rho-f\rho-\zeta))](f\mu\nu+4(f-1)\sigma)}{(8b\sigma-\nu^2)[\lambda-n(\gamma-\zeta+f\theta+\rho-f\rho)]^2} > 0$; $\frac{\partial k}{\partial\gamma} = \frac{n[m\lambda-n\varepsilon_0(\lambda-n(f\theta+\rho-f\rho-\zeta))](2bf\mu+(f-1)\nu)}{(8b\sigma-\nu^2)[\lambda-n(\gamma-\zeta+f\theta+\rho-f\rho)]^2} > 0$.

5. Supply chain decision model under government subsidies

To encourage battery manufacturers to invest in innovative technology development, the government adopts different subsidy methods: 1) subsidizing innovation and development investments, thereby sharing part of the innovation R&D costs with battery manufacturers; 2) subsidizing based on the production volume of power batteries by the battery manufacturer.

5.1. Battery manufacturer innovation technology investment model under government technological R&D subsidy

The government provides technological R&D subsidies to encourage battery manufacturers to innovate and invest in new technologies. The objective profits for the battery manufacturer and automobile manufacturer in this scenario are shown in equations (5) and (6) below, respectively:

$$\max \pi_M(w) = (w-c_m)(q-q_0) + (w-c_r)q_0 f - h_1 q_0 f - (1-s_1)\sigma k^2 - \gamma q_0(\varepsilon-\varepsilon_0) \tag{5}$$

$$\max \pi_R(p,\varepsilon) = (p-w)q - Uq_0 + h_1 q_0 f + h_2 q_0(1-f) + \gamma q_0(\varepsilon-\varepsilon_0) - \lambda\varepsilon^2 \tag{6}$$

Theorem 3. *The retail price for the automobile manufacturer under the government R&D subsidy with the battery manufacturer's innovation technology investment model is given by* $p_3 = \frac{1}{2B(8b\sigma(1-s_1)-\nu^2)}\left(f\left(n\left(2(\theta-\rho)\left(2\sigma(s_1-1)(3a+bc_m)+c_m\nu^2\right)-3\gamma\mu n\nu\varepsilon_0\right)\right.\right.$, *the recycling quality level of retired power batteries is* $\varepsilon_3 = \frac{m(\gamma-\zeta+f\theta+\rho-f\rho)-n\gamma\varepsilon_0}{2\lambda-2n(\gamma-\zeta+f\theta+\rho-f\rho)}$, *the equilibrium wholesale price for the battery manufacturer is* $w_3 = \frac{1}{(8b\sigma(1-s_1)-\nu^2)B}\left(4fn\sigma(s_1-1)(\theta-\rho)(a+bc_m)+(N-\lambda)\left(4\sigma(s_1-1)(a+bc_m)+c_m\nu^2\right)-f\nu(n(c_m\nu(\rho-\theta)+\gamma\mu n\varepsilon_0)+\mu m(N-2\lambda))+A\right)$, *and the level of modular design of power batteries is* $k_3 = \frac{a\nu B+bf(c_m\nu n(\theta-\rho)-2\mu A)+c_m\nu(N-\lambda)+2A}{[8b\sigma(1-s_1)-\nu^2]B}$.

Corollary 3. *In the government R&D subsidy model with the battery manufacturer's innovation technology investment,* $\frac{\partial p}{\partial s_1} > 0$*;* $\frac{\partial\varepsilon}{\partial s_1} = 0$*;* $\frac{\partial w}{\partial s_1} > 0$*;* $\frac{\partial k}{\partial s_1} > 0$.

The level of modular design of power batteries increases with the increase in the government R&D subsidy coefficient. This indicates that government R&D subsidies can effectively encourage battery manufacturers to invest in technology. In an era of technology-driven supply chains, government subsidies can help companies overcome the challenges of technological innovation. However, an increase in the modular design level of power batteries also increases the cost incurred by the battery manufacturer, leading them to raise the wholesale price of power batteries, transferring the increased costs to downstream automobile manufacturers. Automobile manufacturers, to maintain their profits, increase the retail price of new energy vehicles. However, due to increased market demand and sales volume resulting from the higher modular design level of power batteries, the government R&D subsidy can enhance the technological innovation capabilities and product quality of enterprises, benefiting both battery manufacturers and automobile manufacturers in enhancing supply chain value.

Proof: When $2\lambda m > n^2\gamma\varepsilon_0$, $\frac{\partial p}{\partial s_1} = \frac{1}{(8b\sigma(1-s_1)-\nu^2)^2 B}\left(6\nu\sigma(a\nu B) + bf(c_m\nu n(\theta-\rho) - 2\mu A + bc_m\nu(n(\gamma-\zeta+\rho)-\lambda)) + 6\nu\sigma\left(2bf^2\mu mn(\rho-\theta) - (f-1)\nu A\right)\right) > 0$; $\frac{\partial\varepsilon}{\partial s_1} = 0$; $\frac{\partial w}{\partial s_1} = \frac{1}{(8b\sigma(1-s_1)-\nu^2)^2 B}\left(4\nu\sigma(a\nu B) + bf(c_m\nu n(\theta-\rho) - 2\mu A) + bc_m\nu(n(\gamma-\zeta+\rho)-\lambda)) + 4\nu\sigma\left(2bf^2\mu mn(\rho-\theta) - (f-1)\nu A\right)\right) > 0$; $\frac{\partial k}{\partial s_1} = \frac{1}{(8b\sigma(1-s_1)-\nu^2)^2 B(\lambda-n(\gamma-\zeta+f\theta+\rho-f\rho))}(8\nu\sigma(a\nu B) + bf(c_m\nu n(\theta-\rho) - 2\mu A) + bc_m\nu(n(\gamma-\zeta+\rho)-\lambda)) +$

$$8\nu\sigma\Big(2bf^2\mu mn(\rho-\theta)-(f-1)\nu A\Big)\Big)>0.$$

5.2. Battery manufacturer innovation technology investment model under government production subsidy

To encourage battery manufacturers to innovate technologically, the government provides subsidies based on the production volume of batteries. The objective profit maximization functions for the battery manufacturer and automobile manufacturer are shown in equations (7) and (8) below:

$$\max \pi_M(w)=(w-c_m)(q-q_0)+(w-c_r)q_0f-h_1q_0f-\sigma k^2-\gamma q_0(\varepsilon-\varepsilon_0)+s_2q \tag{7}$$

$$\max \pi_R(p,\varepsilon)=(p-w)q-Uq_0+h_1q_0f+h_2q_0(1-f)+\gamma q_0(\varepsilon-\varepsilon_0)-\lambda\varepsilon^2 \tag{8}$$

Theorem 4. *The equilibrium retail price for the automobile manufacturer under government output subsidy with the battery manufacturer's innovation technology investment model is* $p_4=\frac{1}{2(8b\sigma-\nu^2)B}\big(f\big(n\big(2(\theta-\rho)\big((c_m-s_2)\big(\nu^2-2b\sigma\big)-6a\sigma-3\gamma\mu\nu n\varepsilon_0\big)-3\mu m\nu(N-2\lambda)+2(\lambda-N)\big(6a\sigma-(c_m-s_2)\big(\nu^2-2b\sigma\big)\big)+3A\big)$, *the recycling quality level of retired power batteries is* $\varepsilon_4=\frac{m(\gamma-\zeta+f\theta+\rho-f\rho)-n\gamma\varepsilon_0}{2\lambda-2n(\gamma-\zeta+f\theta+\rho-f\rho)}$, *the equilibrium wholesale price for the battery manufacturer is* $w_4=\frac{1}{(8b\sigma-\nu^2)B}\big(-f\big(n\big((\theta-\rho)\big(4a\sigma-(c_m-s_2)\big(\nu^2-4b\sigma\big)\big)+\gamma\mu\nu n\varepsilon_0\big)$, *and the level of modular design of power batteries is* $k_4=\frac{1}{(8b\sigma-\nu^2)B}\big(a\nu B+b\big(f\big(\nu n(c_m-s_2)(\theta-\rho)+4\lambda\mu m-2\mu mN-2\gamma\mu n^2\varepsilon_0+\nu(c_m-s_2)(N-\lambda)+2A\big)$.

Corollary 4. *Under government production subsidy with the battery manufacturer's innovation technology investment model,* $\frac{\partial p}{\partial s_2}<0$; $\frac{\partial \varepsilon}{\partial s_2}=0$; $\frac{\partial w}{\partial s_2}<0$; $\frac{\partial k}{\partial s_2}>0$.

An increase in the government's production subsidy coefficient reduces the wholesale price of power batteries and the retail price of new energy vehicles while increasing the level of modular design of power batteries. This implies that production subsidies not only improve the level of modular design of power batteries but are also beneficial to consumers and automobile manufacturers compared to technological R&D subsidies. Government production subsidies can effectively motivate battery manufacturers to invest in innovative technologies.

Proof: $\frac{\partial p}{\partial s_2}=-\frac{2b\sigma-\nu^2}{8b\sigma-\nu^2}<0$; $\frac{\partial \varepsilon}{\partial s_2}=0$; $\frac{\partial w}{\partial s_2}=-\frac{4b\sigma-\nu^2}{8b\sigma-\nu^2}<0$; $\frac{\partial k}{\partial s_2}=\frac{b\nu}{8b\sigma-\nu^2}>0$.

6. Model comparison

6.1. Comparison of automobile retail prices

Proposition 1. *After the battery manufacturer invests in innovation, the retail price of automobiles is higher than when there is no innovation investment* $p_2>p_1$*; The retail price of automobiles with government subsidies is higher than the retail price of automobiles without government subsidies* $p_3>p_2$*; the retail price of automobiles under government output subsidy is lower than the retail price without subsidy* $p_4<p_2$.

Proposition 1 indicates that the retail price of new energy vehicles under the innovation and R&D investment and reward and penalty measures by the battery manufacturer is higher than the retail price without innovation and reward and penalty measures. This suggests that the innovation technology investment and recycling quality reward and penalty measures by the battery manufacturer impact the retail price of new energy vehicles. The cost of innovation investment by the battery manufacturer is partly passed on to the automobile manufacturer, thus increasing the retail price of automobiles. Government technological R&D subsidies encourage the battery manufacturer to engage in modular design, enhancing product value, and hence increasing the retail price of new energy vehicles. Government production subsidies save cost investments for the battery manufacturer, reducing the retail price of new energy vehicles, motivating consumer consumption, and expanding market demand.

Proof: $p_2-p_1=\frac{3\nu^2B(a-bc_m)-6f\mu\nu mbB-6f\mu\nu b\left(\gamma n^2\varepsilon_0-\lambda m\right)}{4b(8b\sigma-\nu^2)(\lambda-n(\gamma-\zeta+f\theta+\rho-f\rho))}>0$; $p_3-p_2=\frac{1}{B(8b\sigma-\nu^2)(8b(1-s_1)\sigma-\nu^2))}(6s_1\nu\sigma(a\nu B+b(f(n(c_m\nu(\theta-\rho)+2\gamma\mu n\varepsilon_0)+2\mu m(N-2\lambda)+c_m\nu(\lambda-N)+2A)))>0$; $p_4-p_2=-\frac{s_2\left(2b\sigma-\nu^2\right)}{8b\sigma-\nu^2}<0$.

6.2. Comparison of battery recycling quality

Proposition 2. $\varepsilon_2=\varepsilon_3=\varepsilon_4>\varepsilon_1$. *After the battery manufacturer invests in innovative technology, the recycling quality of retired power batteries is higher than when there is no technology investment. Whether the government provides subsidies does not affect the recycling quality.*

Proposition 2 indicates that the recycling quality level after the battery manufacturer implements reward or penalty measures for recycling quality is higher than the level without such measures. This is because, after implementing reward or penalty measures for recycling quality, automobile manufacturers become more proactive in recycling retired batteries. Once the quality level of recycled batteries exceeds the reward threshold set by the battery manufacturer, automobile manufacturers opt to recycle. The recycling quality of retired power batteries improves as the intensity of reward and penalty measures by the battery manufacturer increases. To obtain this reward and avoid penalties, automobile manufacturers naturally increase their investment in recycling quality, thereby enhancing the quality of recycled power batteries. The technological R&D subsidy or production subsidy provided by the government to the battery manufacturer does not affect the recycling quality of retired power batteries.

Proof: $\varepsilon_2 = \varepsilon_3 = \varepsilon_4 = \frac{m(\gamma-\zeta+f\theta+\rho-f\rho)-n\gamma\varepsilon_0}{2\lambda-2n(\gamma-\zeta+f\theta+\rho-f\rho)} > \frac{m[f(\theta-\rho)+\rho-\zeta]}{2[\lambda-n(f\theta+\rho-f\rho-\zeta)]} = \varepsilon_1$.

6.3. Comparison of modular design level of power batteries

Proposition 3. $k_3 > k_2$, $k_4 > k_2$. *The modular design level of batteries by the battery manufacturer is higher under government technological R&D subsidy or production subsidy than when there is no government subsidy.*

Proposition 3 indicates that the method of government subsidy significantly impacts the modular design level of power batteries. Both technological R&D subsidy and production subsidy can enhance the modular design level of power batteries. Government subsidies incentivize battery manufacturers to increase investment in modular technology for their products. The improvement in the modular design level of power batteries expands the market demand for new energy vehicles, meaning the innovation technology investment by the battery manufacturer can enhance their profits. Enterprises will increase their innovation and R&D investment in power batteries when it is profitable.

Proof: $k_3 - k_2 = \frac{1}{B(8b\sigma-\nu^2)[8b(s_1-1)\sigma+\nu^2)]}\Big(8b\sigma s_1\Big(bf(n(c_m\nu(\rho-\theta) + 2\gamma\mu n\varepsilon_0) - a\nu B + 2\mu m(n(\gamma-\zeta+\rho) - 2\lambda)) + bc_m\nu\Big(\lambda - n(\gamma-\zeta+\rho))) + 2bf^2\mu mn(\theta-\rho) + (f-1)\nu A\Big) > 0$, $k_4 - k_2 = \frac{b\nu s_2}{8b\sigma-\nu^2} > 0$.

6.4. Centralized vs. decentralized decision making

6.4.1. Supply chain coordination mechanism

The K-S (Kuhn-Szymanski) solution is a common and reasonable distribution mechanism, whose main principle is to distribute the incremental total profit of the entire closed-loop supply chain under centralized and decentralized decision-making based on the varying contributions of each member enterprise. Drawing from Ref. [33], this study employs a modified K-S coordination mechanism to achieve coordination in the closed-loop supply chain.

The profit difference brought about by centralized and decentralized decisions in the closed-loop supply chain is denoted as: $\Delta =$ Total profit under centralized decision $-$ Total profit under decentralized decision. Compared to decentralized decision-making, the absolute contributions of the battery manufacturer and automobile manufacturer to the closed-loop supply chain under centralized decision-making are $\Delta_M =$ Total profit under centralized decision $- \pi_R^*$ and $\Delta_R =$ Total profit under centralized decision $- \pi_M^*$, respectively. From this, the absolute contribution ratio of the battery manufacturer is calculated as $\rho_M = \frac{\Delta_M}{\Delta_M+\Delta_R}$, and the absolute contribution ratio of the automobile manufacturer is $\rho_R = \frac{\Delta_R}{\Delta_M+\Delta_R}$. Subsequently, the optimal profits for the battery manufacturer, automobile manufacturer, and tiered utilizer are determined as $\pi_M^{**} = \pi_{M1}^* +_\Delta . \rho_M$, $\pi_R^{**} = \pi_{R1}^* +_\Delta . \rho_R$. Following the same method, the profit of each member after coordination in other models are obtained.

6.4.2. Total profit of supply chain under centralized and decentralized decision

Further considering the scenario where the battery manufacturer and automobile manufacturer make centralized decisions, optimal decisions are calculated for different models, yielding respective optimal profit functions. The total profit of the supply chain under decentralized decision-making and centralized decision-making in four different modes can be represented as follows. Without innovation technology investment $\pi = \frac{1}{16}\left(\frac{3(a-bcm)^2}{b} + \frac{4fm^2(e-\theta)\left(\frac{\lambda^2}{(n(-f\theta+(f-1)\rho+\zeta)+\lambda)^2}-1\right)}{n} + \frac{4m^2(-f\theta+(f-1)\rho+\zeta)^2}{n(-f\theta+(f-1)\rho+\zeta)+\lambda}\right)$, $\pi_{sc} = \frac{1}{4}\left(\frac{(a-bcm)^2}{b} - \frac{m^2(ef-f\rho-\zeta+\rho)^2}{efn-n((f-1)\rho+\zeta)-\lambda}\right)$. With innovation technology investment and recycling quality reward and penalty $\pi = p_2q + c_m(-q+fq_0) - q_0(-h_2 + f(c_r+h_2) + U) - {\varepsilon_2}^2\lambda - k_2^2\sigma$, $\pi_{sc} = p_2^*q + c_m(-q+fq_0) - q_0(-h_2 + f(c_r+h_2) + U) - (\varepsilon_2^*)^2\lambda - (k_2^*)^2\sigma$. With government technological R&D subsidy and innovation technology investment $\pi = p_3q + c_m(-q+fq_0) - q_0(-h_2 + f(c_r+h_2) + U) - \varepsilon_3^2\lambda - k_3^2(s_1-1)\sigma$, $\pi_{sc} = p_3^*q + c_m(-q+fq_0) - q_0(-h_2 + f(c_r+h_2) + U) - (\varepsilon_3^*)^2\lambda - (k_3^*)^{2(s_1-1)}\sigma$, $\pi_{sc} = c_m(fq_0-q) - q_0(c_rf + (f-1)h_2 + U) - (k_4^*)^2\sigma + q(p_4^* + s_2) - \lambda(\varepsilon_4^*)^2$. With government production subsidy and innovation Technology Investment $\pi = c_m(fq_0-q) - q_0(c_rf + (f-1)h_2 + U) - k_4^2\sigma + q(p_4+s_2) - \lambda\varepsilon_4^2$, $\pi_{sc} = c_m(fq_0-q) - q_0(c_rf + (f-1)h_2 + U) - (k_4^*)^2\sigma + q(p_4^* + s_2) - \lambda(\varepsilon_4^*)^2$.

Proposition 4. $\pi < \pi_{SC}$. *In all four modes, the total profit of the supply chain under centralized decision-making is always greater than the total profit under decentralized decision-making.*

Proposition 4 demonstrates that the total profit of the supply chain when supply chain enterprises collaborate in decision-making is always higher than when decisions are made independently. Therefore, supply chain enterprises should strengthen cooperation to achieve higher total profit and enhance the overall value of the supply chain.

7. Numerical analysis

7.1. Parameter setting

The comparative sizes of the profits for each member cannot be intuitively compared, so case examples are used for further comparison. To further validate the conclusions, we refer to the parameters assumed in the literature [16], as shown in Table 3.

From Table 4, it is evident that innovation investment by battery manufacturers and the implementation of rewards or penalties for recycling quality can enhance the recycling quality of used batteries and the modularization level of products. Government subsidies significantly increase the profits of both battery manufacturers and automobile manufacturers, thereby enhancing the overall value of the supply chain.In terms of improving the level of product modularization, government R&D subsidies are more effective than government production subsidies. This is because subsidies targeted at the costs of R&D incentivize battery manufacturers to increase their investment in product modularization technology. Additionally, the improvement in the modularization level of power batteries expands the market demand for new energy vehicles, thereby increasing market demand and offsetting the costs of modularization technology for enterprises.

Regarding the increase in profits for battery manufacturers and automobile manufacturers, government production subsidies are more effective than government R&D subsidies. Subsidizing corporate R&D investments does not significantly enhance R&D output, as the output primarily depends on the internal factors of the enterprise, such as its R&D capabilities. Therefore, government subsidy policies should be designed and implemented according to the development stages of the power battery industry.

7.2. Numerical analysis of product modularization design

According to Assumption 3, the market demand for new energy vehicles is a linear function $D = a - bp + vk$. Therefore, the profits of battery manufacturers and the entire supply chain are influenced by the retail price of new energy vehicles and the level of modularization design of power batteries. To more accurately describe the impact on the total profit of the supply chain, a three-dimensional plot illustrating the variation of the total supply chain profit with changes in the retail price of new energy vehicles and the level of modularization design of power batteries is shown in Fig. 2.

As seen in Fig. 2, the total supply chain profit initially increases and then decreases with the rise in the retail price of new energy vehicles and the modularization level of power batteries. This indicates that there is an optimal retail price for new energy vehicles and an optimal level of modularization for power batteries that maximize the supply chain profit, achieving supply chain coordination.

7.3. Numerical analysis of the reward or penalty mechanism for battery manufacturer

Assuming $0 < \gamma < 5$, the profit variations for battery manufacturers and automobile manufacturers are shown in Fig. 3. The profits of automobile manufacturers increase with the intensification of the reward or penalty, while the profits of battery manufacturers decrease. As the costs of implementing the reward or penalty measures increase, the enthusiasm of battery manufacturers for participating in the recycling and remanufacturing of retired power batteries decreases. As seen in Fig. 3, when the reward or penalty intensity $\gamma = 2.58$, the profits of battery manufacturers and automobile manufacturers are equal. Battery manufacturers play a leading role in incentivizing automobile manufacturers to actively recycle. The design of the reward or penalty mechanism needs to be adjusted based on the recycling efforts of automobile manufacturers. The reward or penalty mechanism implemented by battery manufacturers encourages automobile manufacturers to actively recycle retired power batteries. The probability of automobile manufacturers choosing to actively recycle is positively correlated with the intensity of the reward or penalty.

7.4. Impact of government subsidies

Assuming $0 < s_1 < 0.9$ and $0 < s_2 < 0.8$, we obtain the profits of battery manufacturers and automobile manufacturers under government R&D subsidies or production subsidies. As shown in Fig. 4, in the closed-loop supply chain of power batteries, both government R&D subsidies and production subsidies that encourage battery manufacturers to implement technological innovation are beneficial for increasing the profits of both battery manufacturers and automobile manufacturers.

From Fig. 4, it can be seen that when s_1 and s_2 are set at certain values, the effect of government R&D subsidies is greater than that of production subsidies. Under R&D subsidies, the profits of battery manufacturers and automobile manufacturers are higher than under production subsidies. This result indicates that government subsidy measures need to be designed according to the development stages of the power battery industry to effectively play the positive role of government subsidies and incentivize enterprises to create more supply chain value.

As the intensity of government subsidies increases, the rise in profits for the battery manufacturer and the automobile manufacturer

Table 3
Parameters assignment.

a	b	v	m	n	γ	λ	σ	ρ	ζ	θ	e	μ	c_m	s_1	s_2	ε_0	f
3	0.2	0.1	0.1	0.1	2	0.8	0.9	3.5	1	3	4	2	6	0.5	0.5	0.1	0.5

Table 4
Optimal decision parameters and member profits under different scenarios.

	Without innovation	Innovation and recycling quality reward or penalty	Government R&D subsidies	Government production subsidies
p	12.75	12.83	12.91	12.707
ε	0.20	0.54	0.54	0.54
w	10.5	10.55	10.607	10.305
k	–	0.212	0.427	0.219
D	0.45	0.494	0.499	0.519
q_0	0.120	0.154	0.154	0.154
π_M	2.036	1.97	2.012	2.205
π_R	1.035	1.126	1.15	1.244
π_{SC}	3.071	3.096	3.162	3.449

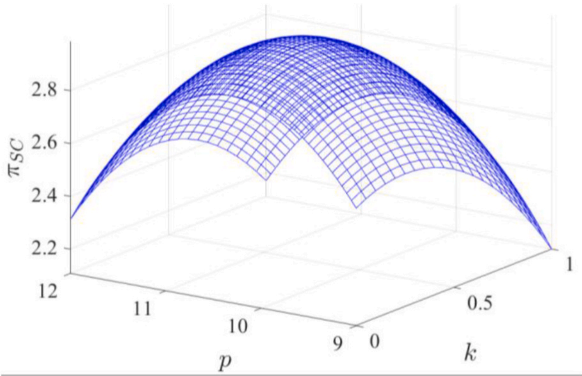

Fig. 2. Variation of total supply chain profit with product modularization level and product price.

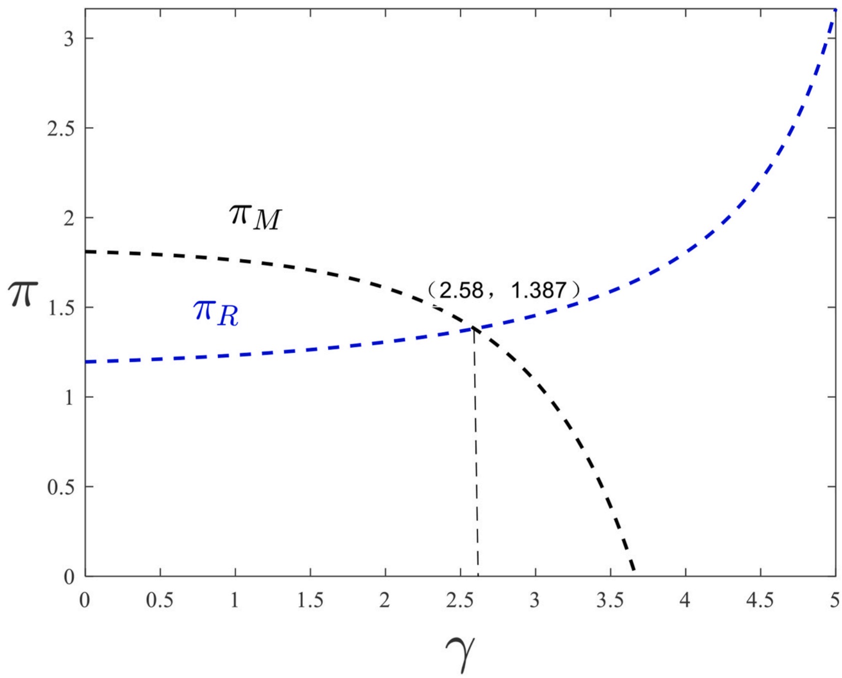

Fig. 3. Trends in profits of battery producers and automobile manufacturers with reward or penalty intensity.

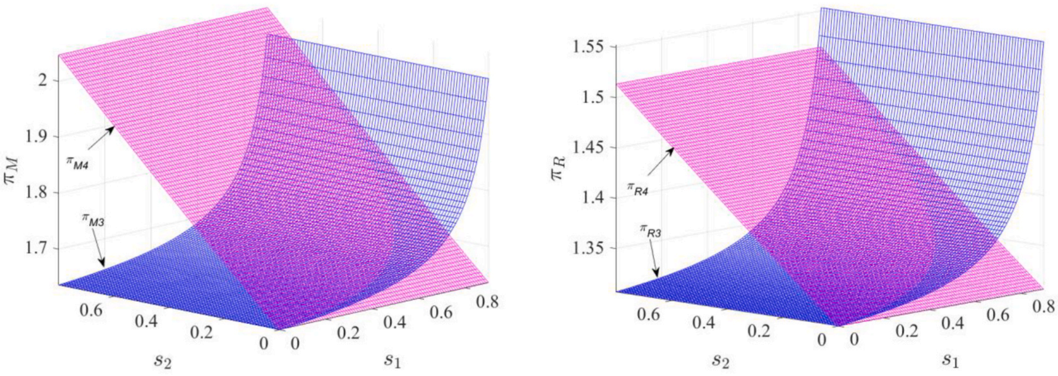

Fig. 4. Profit trends of battery manufacturer and automobile manufacturers under different subsidies.

indicates that government subsidies help enhance supply chain profits. Particularly when supporting technology-innovative industries, the government should aim to maximize subsidy intensity within the budget to incentivize enterprises to invest in innovation and R&D.

7.5. Profits related to K-S coordination

To verify the effectiveness of the coordination mechanism, the K-S solution approach was employed to obtain the profits of each member of the closed-loop supply chain before and after coordination.

As shown in Table 5, regardless of whether members engage in innovation investment or whether the government provides subsidies, the profits of each member in the closed-loop supply chain significantly increase after K-S coordination, achieving coordination in the power battery closed-loop supply chain. Therefore, regardless of the technology investment and subsidy decisions made by supply chain members and the government, choosing a cooperative strategy is always the most beneficial. Supply chain members should actively pursue cooperation to achieve coordination in the closed-loop supply chain.

8. Conclusion

This paper focuses on the investment in modular design and the recycling quality of power batteries. It establishes a closed-loop supply chain model for power batteries under different scenarios of government subsidies and various subsidy methods. The study emphasizes the impact of battery manufacturer's innovation investment, recycling quality reward or penalty measures, and government subsidy methods on the closed-loop supply chain of power batteries.

The research findings indicate that: (1) Compared to decentralized decision-making, centralized decision-making significantly improves the recycling quality of retired batteries and moderately increases the total profit of the closed-loop supply chain. From both economic and environmental perspectives, centralized decision-making through cooperation between enterprises is always superior to decentralized decision-making. (2) Increasing the coefficient of technology R&D investment can effectively enhance the profits of the closed-loop supply chain to a certain extent. This indicates that innovation investment by the battery manufacturer is beneficial for creating product value and supply chain profit, thereby enhancing enterprise competitiveness. (3) Under different government subsidy methods, the modularization level of power batteries, as well as the profits of the battery manufacturer and the automobile manufacturer, increase. However, for improving the modularization level of power batteries, government R&D subsidy strategies are superior to government production subsidy strategies. In terms of profit growth for the battery manufacturer and the automobile manufacturer, government production subsidy strategies are superior to government R&D subsidy strategies. (4) Using the K-S solution approach to coordinate the profits of closed-loop supply chain members, cooperation among supply chain members is always the optimal strategy, regardless of whether the government provides subsidies.

This paper investigates the recycling of power batteries under the leadership of the battery manufacturer, considering innovation investment and government subsidies. It finds that innovation investment by the battery manufacturer can improve the recycling quality, modularization level, recycling volume, and the profits of all members in the supply chain; government subsidies can enhance the profits of supply chain members, especially when the government provides R&D subsidies, which significantly improve the modularization level of the battery manufacturer.

Therefore, in the context of green development, the battery manufacturer should vigorously pursue technological innovation to enhance the recycling quality of retired power batteries, promote the recycling and remanufacturing of power batteries; Battery manufacturers can consider the implementation of reward and punishment measures when recycling, and develop a reasonable reward and punishment strength to ensure the economic benefits and the quality of battery recycling; And in the recycling process, battery manufacturers should strengthen their cooperation with downstream automobile manufacturers to obtain greater profits. The government should formulate relevant subsidy policies according to the different stages of development of the power battery industry, alleviating the financial pressures on related enterprises and thereby enhancing the innovation drive of battery manufacturers, which in turn elevates the environmental awareness and green development level of these enterprises.

Table 5
Profits of each member after closed-loop supply chain coordination in different scenarios.

	No Innovation		Innovation and recycling quality reward or penalty		Government R&D subsidy		Government production subsidy	
	Before coordination	After coordination	Before coordination	After coordination	Before coordination	After coordination	Before coordination	After coordination
π_M	2.036	2.64	1.97	2.599	2.012	2.659	2.205	2.905
π_R	1.035	1.446	1.126	1.581	1.15	1.619	1.244	1.746
π_{sc}	3.071	4.086	3.096	4.18	3.162	4.278	3.449	4.651

This paper has several limitations which suggest interesting directions for future research. It only considers a closed-loop supply chain composed of a single battery manufacturer and a single automobile manufacturer, whereas, in reality, competition often exists among multiple enterprises. Therefore, future research could include additional automobile manufacturers and battery manufacturers to investigate the optimal decisions of each enterprise in a competitive environment. Furthermore, future research should explore the role of public-private partnerships in supporting power battery modular innovation strategies. It is also recommended to examine the impacts of these strategies on social inequality and environmental sustainability. Additionally, in this paper, government subsidies are primarily directed towards the battery manufacturer and do not consider subsidies for the automobile manufacturer. Future studies could incorporate government subsidies for automobile manufacturers to derive more comprehensive research conclusions.

Data availability statement

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

CRediT authorship contribution statement

Juanjuan Liu: Writing – review & editing, Validation, Supervision, Methodology, Conceptualization. **Bin Du:** Writing – review & editing, Supervision, Methodology, Formal analysis. **Jing Xue:** Writing – review & editing, Writing – original draft, Visualization, Software, Investigation, Formal analysis. **Weisi Zhang:** Writing – review & editing, Validation, Supervision, Funding acquisition, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

The authors thank the editor and anonymous reviewers for their numerous constructive comments and encouragement that significantly improved our paper. This research was supported by Humanities and Social Sciences Youth Foundation of Ministry of Education of China (No. 20YJC630215).

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