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Optimal Recovery Mode for New Energy Vehicle Battery Recycling Under Government Policies

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ABSTRACT

The choice of spent new energy vehicle (NEV) battery recovery mode is crucial to improve recovery performance. This paper examines the decision-making rules for the closed-loop supply chain of NEV batteries under the intervention of government policies. It also compares the performance of the supply chain across various recovery modes and the effects of different policies. Results indicate that (1) in terms of total revenue and recovery rate, the battery producer recovery mode, mixed recovery mode involving automobile manufacturer and professional recycler, is more effective. (2) The optimal solution for the decision variable is influenced by government policies, and this influence remains consistent across different recovery modes. (3) The positive impact of the deposit-return system is linked to the relationship between the deposit amount and the reward scale. If the refund constitutes too small a proportion of the deposit, both total revenue and recovery rate will decline. Reducing recycling channel costs and enhancing purchasers' environmental awareness can increase the battery recycling ratio and higher total revenue.

1 | Introduction

The transportation sector accounts for nearly a quarter of total global carbon emissions (Wang et al. 2022). In the context of global climate change, promoting new energy vehicles (NEVs) has become essential in China for decarbonizing not only the entire transportation sector but also the broader economic system. (Ahmad et al. 2017; Valogianni et al. 2020). According to data released by the China Association of Automobile Manufacturers, NEV sales are projected to exceed 10 million units in 2024. In recent years, the vigorous deployment of NEVs has alleviated the shortage of oil resources and reduced pollutant emissions (Karacan and Kayacan 2024; Parker, Tan, and Kazan 2019). However, the future development of NEVs faces significant challenges due to constraints on metal resources (Chen et al. 2019; Saha et al. 2024). The demand for metals required in NEVs is approximately six times greater than that for traditional internal combustion engine vehicles (Vedantam and Iyer 2021). Meanwhile, the critical metal resources essential for NEVs, such as nickel, cobalt, and lithium, are almost 70% dependent on imports from foreign countries (Avci, Girotra, and Netessine 2015). In addition, China faces challenges regarding resource supply security. For nickel, a critical metal for NEV batteries, the imbalance between supply and demand is intensifying. Notably, if nickel-containing end-of-life NEV batteries are fully recycled, they could fulfill nearly one third of the requirements for manufacturing NEV batteries (Lu et al. 2020).

The recycling ratio is currently no more than 25%, underscoring the urgent need for proper disposal of the large volume of used NEV batteries. In contrast to other NEV components, the average lifespan of an NEV battery is 5 to 8 years (Wu, Li, et al. 2024). At the end of their life cycle, NEV batteries typically retain about 80% of their remaining capacity (Wu, Cong, et al. 2023). The remaining capacity can be utilized in various applications to maximize the use of residual energy (Zhang, Wu, and Song 2023). Picatoste, Justel, and Mendoza (2022) stated that the reutilization of NEV batteries can substantially diminish their environmental impact. The primary focus on increasing the recycling rate is how to effectively collect discarded NEV batteries from consumers. In this context, recycling channels play a crucial role as a link between consumers and remanufacturing enterprises, significantly contributing to the enhancement of battery recycling rates. To date, scholars have recognized the importance of recovery modes and have developed models to analyze the impact of different recovery modes on the effectiveness of waste product recycling (Liu et al. 2025; Wang et al. 2023). The differences in the recycling effectiveness of NEV batteries under various recovery modes remain to be explored.

To date, issues such as incomplete channel construction and low environmental awareness among purchasers still need resolution (Li et al. 2022; Liu et al. 2025). The effective resolution of these problems is closely linked to government regulation (Hendrickson et al. 2015; Chen et al. 2024). Notably, some pilot cities have implemented subsidy, deposit-return, and rewards-punishment policies. Government policies play a crucial role in the development of the industry (Wang et al. 2024; Song, Zhang, and Li 2022). Therefore, it is essential to incorporate the impact of government policies into the research framework and analyze their effects. This article examines the selection of recovery modes under government intervention, focusing on the following issues: (1) Which recovery mode is more effective in terms of total revenue and recycling ratio? (2) How do government policies impact closed-loop supply chains, and what strategies can be implemented to optimize them? (3) How do critical factors, such as consumer environmental awareness within the closed-loop supply chain of NEVs, impact overall total revenue?

The remainder of this paper is organized as follows: Section 2 provides an overview of the academic literature. Section 3 defines the problem and presents the relevant notations and assumptions. Section 4 develops the model. Section 5 analyzes the results and summarizes the findings. Finally, Section 6 concludes the study, offering policy recommendations and discussing research limitations.

2 | Literature Review

The recycling and reuse of decommissioned NEV batteries have increasingly attracted global attention. The research areas encompass supply chain decisions, government interventions, and the establishment of recycling channels. Research on recycling channels initially focused on single channels. Hong et al. (2024) compared the economic and environmental benefits of supply chains under single-channel recycling by manufacturers and professional third parties. The results revealed that when consumers have low environmental awareness, manufacturers are more likely to delegate recycling responsibilities to professional third-party recyclers. Wu, Qian, et al. (2023) expanded the research framework by incorporating retailer recycling and analyzed decision-making across three channels: manufacturers, retailers, and professional third parties. They also found that recycling by professional third parties was more effective. The mixed channel is developed from a single channel by integrating multiple recycling pathways, which enhances resource recovery efficiency and overall benefits (Saha et al. 2022). Lin et al. (2023) developed a power battery recycling model based on mixed recycling by manufacturers and retailers. They found that competition in recycling prices negatively affected both the recycling rate and social welfare. Ranjbar et al. (2020) established a three-level supply chain consisting of a manufacturer, retailer, and professional recycler. They conducted a detailed analysis of the optimal decisions under competitive recycling between retailers and professional recyclers, finding that channel competition led to a significant decline in recycling rates and supply chain profitability.

Effective government intervention is essential for ensuring the long-term sustainability and advancement of the NEV battery recycling industry. Several studies have compared these government policies to evaluate their impacts. Saha, Sarmah, and Moon (2016) analyzed the pricing and remanufacturing decisions within closed-loop supply chains for used products under reward policies. Building on this, Saha, Nielsen, and Majumder (2019) further compared the consumer savings, economic benefits, and environmental benefits of closed-loop supply chains, focusing on manufacturers and consumers as the respective reward recipients. Bian and Zhao (2020) compared the roles of rewards and taxes in promoting emission reductions within the supply chain. They found that whereas rewards ensure corporate profits, taxes are more effective in reducing environmental pollution. Due to the economic burden that subsidy policies impose on the government and the limitations of punitive measures, such as taxation, which hinder corporate green investment, deposit-refund policies are increasingly utilized to encourage waste recycling. Wang et al. (2021) assessed the effectiveness of deposit-return policies in the recycling of NEV batteries. The literature comparison is presented in Table 1. In summary, existing studies seldom consider differences in channel structures or evaluate the effects of various policies concurrently.

Therefore, this research paper employs the Stackelberg game framework. The Stackelberg game is a noncooperative game that involves a multilevel strategy selection process among various decision-makers and is widely used to address issues within a leader-follower framework. In the context of NEV battery recycling practices, two recovery modes are identified: single-channel monopoly recycling and hybrid recycling. The key contributions of this paper are as follows: (1) Based on practical NEV battery recycling practices, two recovery modes—single-channel monopoly recycling and mixed recycling—are identified; (2) exploring the strategy selection principles of supply chain enterprises and identifying the optimal recycling mode from the perspective of effective closed-loop supply chain operation; and (3) the effectiveness of the subsidy, tax, and deposit-return mechanism is compared.

TABLE 1 | Literature summary and comparison.

Literature	Recovery mode		Government policies			Stackelberg game	Model comparison
	Single channel	Mixed channel	Reward	Tax	Tax reward		
Hong et al. (2024)	✓	×	×	×	×	✓	✓
Wu, Cong, et al. (2023)	✓	×	×	×	×	✓	✓
Lin et al. (2023)	×	✓	×	×	✓	✓	×
Ranjbar et al. (2020)	✓	✓	×	×	×	✓	✓
Saha, Sarmah, and Moon (2016)	✓	×	✓	×	×	✓	✓
Saha, Nielsen, and Majumder (2019)	✓	×	✓	×	×	✓	×
Bian and Zhao (2020)	×	×	✓	✓	×	×	×
Wang et al. (2021)	✓	×	×	×	✓	✓	×
This paper	✓	✓	✓	✓	✓	✓	✓

3 | Problem Description and Modeling Assumption

3.1 | Problem Description

To enhance the benefits of the reverse supply chain, many firms, both domestically and internationally, including Canon and HP, have adopted closed-loop supply chain management strategies. For instance, Xerox has saved nearly $20 million in costs over 5 years through the recycling of waste electronics. Therefore, this paper constructs a closed-loop supply chain involving a battery producer, an automobile manufacturer, and a professional recycler. In the forward supply chain, the battery producer manufactures and sells NEV batteries to automobile manufacturer, who then use these batteries to produce NEVs for consumers. For reverse recycling, the automobile manufacturer is responsible for collecting used batteries under the extended producer responsibility (EPR) framework. All collected batteries are returned to the battery producer, who evaluates their remaining capacity and charging/discharging efficiency. Qualified batteries are repurposed for secondary use to generate economic benefits, whereas other retired batteries have valuable materials extracted for remanufacturing. As illustrated in Figure 1, we considered four primary recovery modes based on EPR. First, the battery producer establishes its own recycling channels; second, the automobile manufacturer manages the recycling process; third, professional recycler handle recycling; and fourth, the automobile manufacturer and third-party recycling firms compete in the recycling effort.

3.1.1 | NEV Battery Closed-Loop Supply Chain Participants

NEV battery producer is one of the main stakeholders in NEV battery production. These firms hold a crucial place in the entire supply chain, considering that the NEV battery is a core component of NEVs, and its price typically makes up more than 60% of the vehicle's overall cost. In the forward supply chain, the NEV battery producer is usually in a dominant position. The main leading enterprises in the field of domestic NEV battery production include Ningde Times, BYD, and Guoxun High-tech. These manufacturers not only lead in the production of EV batteries but also play an important role in the closed-loop supply chain. Their role encompasses not merely being the foundation for NEV battery production but also being the point of departure for the entire closed-loop supply chain. Alongside their role as the foundation for NEV battery manufacturing, these firms also shoulder the burden of recycling reused materials, embodying the termination of the closed-loop supply chain. As an integral part of the closed-loop supply chain, their obligations encompass not only the provision of raw materials and the fabrication of NEV batteries but also the imperative to proactively participate in the recycling and reuse procedures. This guarantees that spent NEV batteries are thoroughly recycled and repurposed, culminating in the efficient deployment of resources and environmentally sustainable progress.

As the NEV industry experiences a surge in growth, vehicle manufacturer in the traditional automobile industry chain is gradually transforming into NEV producers. Throughout this transformative period, their contributions are indispensable within the downstream supply chain for NEV batteries. First, NEV batteries are manufactured by specialized NEV battery producers and then sold to vehicle manufacturer. The automobile manufacturer assembles NEV batteries with other components into completely NEVs and brings them to market through their sales networks so that purchasers can buy and use them. Therefore, automobile manufacturer is both buyers and users of NEV batteries in the NEV industry, as well as sellers and distributors, playing an important role in connecting NEV battery producers and purchasers. This transformation not only poses new challenges to the vehicle manufacturers' own business model and supply chain management but also introduces fresh possibilities and obligations for the evolution and operation of the NEV battery supply chain. Prominent enterprises in the NEV industry encompass Ideal Automobile, Xiaopeng Automobile, and more.

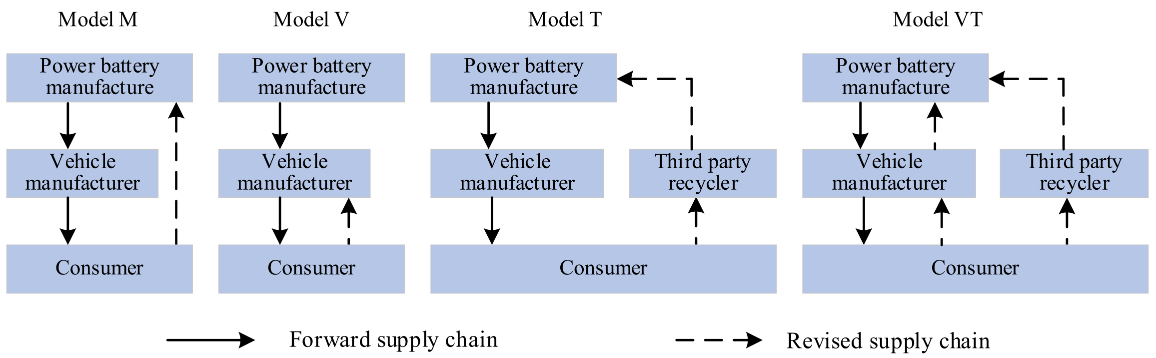

FIGURE 1 | Recovery mode induction.

Professional recycler specializes in recovering decommissioned NEV batteries from purchasers. These firms, such as Grimm and Bump Cycle, are dedicated to collecting waste NEV batteries and recycling or disposing of them. In this study, purchasers mainly refer to individual purchasers, rather than enterprises or government agencies. As the end user of NEV battery, the treatment of waste NEV battery directly affects environmental protection and resource utilization. If the waste NEV battery is discarded at will, it will lead to environmental pollution and waste of resources.

3.2 | Model Assumptions and Parameter Settings

This paper sets up a closed-loop supply chain involving an NEV battery producer, an automobile manufacturer, and a professional recycler. Table 2 provides a comprehensive breakdown of the model's parameters and variables. The analysis proceeds under the following set of assumptions:

1. The individuals comprising the closed-loop supply chain are thoroughly rational and risk-neutral.
2. Referring to the research of Savaskan, Bhattacharya, and Van Wassenhove (2004), the market demand for NEVs is a linear function of market price, $q = a - bp$, where a represents the market requirement when the selling price of the NEV is 0 and b refers to the reaction level of purchasers to the market price, $a, b > 0$.
3. Remanufactured NEV batteries are nearly identical in look and performance to the freshly assembled products available. The selling price of remanufactured NEV batteries is on par with that of newly manufactured ones. Drawing from the research conducted by Wu, Li, et al. (2024) and Wu, Zhang, et al. (2024), the key drivers of customers' willingness to return used batteries are the pricing and the distance with recycling channels. The amount of recovery is affected by the recovery price and channel competition $S = \alpha + \beta r_i - \delta r_z (i, z = m, v, t, \text{and } i \neq z)$. If two or more recycling channels recycle, recycling competition will exist. The recovery volume will be affected by the competition intensity. The cost of the recycling process is denoted as $A_i (i = m, v, t)$. Due to varying distances from the channels to consumers, the automobile manufacturer is closest to the consumer, followed by the professional recycler, whereas

TABLE 2 | Description of parameters and variables.

Symbol	Variable meaning
c_m	The cost of using raw materials to manufacture each NEV battery
c_r	The cost of recycled raw materials to manufacture each NEV battery
c_n	Manual dismantling and safety inspection costs
a	Potential market requirement for NEV batteries
b	The reaction level of purchasers to market price
η	Financial benefit per NEV battery cascaded
$\tilde{V}$	The remaining capacity per unit of decommissioned NEV battery
h	The production cost of new energy vehicles, except for NEV battery cost
A_m	The average channel cost of automobile manufacturer recycling
A_v	The average channel cost of NEV battery producer recycling
A_t	Mean operational cost for professional recycler
R	Disposal funds government charged from NEV battery producer
α	Quantity of batteries willingly given back by purchasers
β	The reaction level of purchasers to collection price
w	The wholesale price of an NEV battery
p	The sales price of new energy vehicles
t	Transfer payment price for used NEV battery recycling
r_m	Collection price of NEV battery producer
r_v	Collection price of used NEV batteries for automobile manufacturer
r_t	Collection price of used NEV batteries for professional recycler

the battery producer is the farthest away. Therefore, the costs are ranked as $A_m > A_t > A_v$.

4. The recycled NEV batteries will cascade utilization at first. Referring to the research of Wu, Li, et al. (2024), Wu, Zhang, et al. (2024), and Wu and Zhang (2024a), the revenue from recycling per unit capacity of waste NEV battery can be described as $\Delta = c_m - c_r + \eta\widetilde{V}$, where c_m and c_r are production costs from raw materials and recycled materials, respectively. η represents net profits for cascade utilization.

4 | Model Construction and Solution

Given the clear sequence of decision-making in this paper, the Stackelberg game framework is employed to model the decision-making process. As producers of products, NEV battery producer, such as Ningde Times, hold a dominant position in the supply chain. Ningde Times, as a leading global producer of EV batteries, offers a wide range of battery types and has formed strategic partnerships with major automobile manufacturers, including Tesla and Mercedes, becoming the preferred supplier for many automotive brands, and firmly establishing its dominance. In the closed-loop supply chain, battery producer is responsible for both the production of NEV batteries and the transfer pricing of retired batteries. Consequently, they serve as the leaders in the Stackelberg game framework. In this framework, the battery producer initiates the decision-making process, whereas the automobile manufacturer, as the follower, makes decisions based on the Nash equilibrium principle. Specifically, the government first charges NEV battery producer an R tax per battery and then provides a proportion recycling reward for recycled waste NEV batteries.

4.1 | NEV Battery Producer Build Recycling Channels (Mode M)

Considering the waste NEV battery recycling scenario under the tax reward, the government first collects NEV battery recycling and disposal funds R from the NEV battery producer and then refunds 50% of the amount when per unit used for battery recycling. The game sequence of model M is as follows: Battery producer first decides the per unit wholesale price w and used battery collection price r_m; automobile manufacturer decides the NEV sales price p. In this model, the maximization profit functions of the battery producer and the automobile manufacturer can be expressed as

$$Max\pi_m^M = (w - c_m - R)(a - bp) + \left(\Delta - r_m - c_n - A_m + \frac{R}{2}\right)(\alpha + \beta r_m), \tag{1}$$

$$s.t.\, \alpha + \beta r_m \le a - bp, \tag{2}$$

$$Max\pi_v^M = (p - w - h)(a - bp), \tag{3}$$

where Equation (2) ensures the recycling number of used batteries does not exceed the sale quantity.

Proposition 1. *In a decentralized strategy selection environment for NEV battery recycling, the optimal decisions that the battery producer and the automobile manufacturer should reach are as follows:*

1. When $\phi_M < 0$,

$$w^* = \frac{a + b(c_m - h + R)}{2b},$$

$$r_m^* = \frac{-\alpha + 2\beta(2\Delta - 2A_m - 2c_n + R)}{2\beta},$$

$$p^* = \frac{3a + b(c_m + h + R)}{4b}.$$

2. When $\phi_M \ge 0$,

$$w^{L*} = \frac{2a(b+\beta) - 2b(\alpha + bh) + b\beta(2A_m + 2c_n + 2c_m - 2h - 2\Delta + R)}{2b(b + 2\beta)},$$

$$r_m^{L*} = \frac{-\alpha b + a\beta - 4\alpha\beta + b\beta(\Delta - A_m - c_n + h)}{4\beta(b + 2\beta)},$$

$$p^{L*} = \frac{4ab + 6a\beta - 2\alpha b + b\beta(R - 2\Delta + 2A_m + 2c_m + 2c_n + 2h)}{4b(b + 2\beta)},$$

$$\phi_M = \frac{-2\alpha + a - 2\Delta\beta + 2\beta(c_n + A_m) - b(c_m + h + R)}{b + 2\beta}.$$

Considering that there are constraints in formula (1), two distinct strategy selection approaches are available to the NEV battery manufacturer, determined by the threshold level ϕ_M. One is that the NEV battery recycling volume is not bound by the sale quantity of NEVs $\phi_M < 0$, and the other NEV battery recycling volume is secured by NEV sale quantity $\phi_M \ge 0$. First, the amount of NEV battery recycling is not limited by the sales quantity. Adopting backward induction, the automobile manufacturer reacts first. As $\frac{\partial^2 \pi_v^M}{\partial p^2} = -2b < 0$, π_v^M is a concave function about p. Therefore, a maximum value of p exists. Let $\frac{\partial \pi_v^M}{\partial p} = 0$; the reaction function of the automobile manufacturer can be obtained: $p = \frac{a + b(w+h)}{2b}$. Taking the reaction function of the automobile manufacturer into the profit function of the battery producer and calculating the second-order partial derivative of the profit function of the NEV battery producer concerning the wholesale price w and the collection price r_m, build the Hessian matrix $|H_1| = \begin{vmatrix} \frac{\partial^2 \pi_m^M}{\partial w^2} & \frac{\partial^2 \pi_m^M}{\partial w \partial r_m} \\ \frac{\partial^2 \pi_m^M}{\partial w \partial r_m} & \frac{\partial^2 \pi_m^M}{\partial r_m^2} \end{vmatrix} = \begin{vmatrix} -b & 0 \\ 0 & -\beta \end{vmatrix}$. Because $|H_1|_1 = -b < 0$, $|H_1|_1 = b\beta > 0$, π_m^M is a concave function about w, r_m. By calculating $\frac{\partial \pi_v^M}{\partial w} = 0$, $\frac{\partial \pi_v^M}{\partial r_m} = 0$, the maximum value of w, r_m can be calculated, $w^* = \frac{a + b(c_m - h + R)}{2b}$, $r_m^* = \frac{-\alpha + 2\beta(2\Delta - 2A_m - 2c_n + R)}{2\beta}$. Taking w^* and r_m^* into the reaction function of the NEV battery producer, $p^* = \frac{3a + b(c_m + h + R)}{4b}$ can be gotten.

Then, we consider NEV battery recycling volume bound by NEV sale quantity. The optimization problem in the profit function of NEV battery producer can be expressed as $L_M = (w - c_m - R)(a - bp) + \left(\Delta - r_m - c_n - A_m + \frac{R}{2}\right)(\alpha + \beta r_m) + \lambda\left[(\alpha + \beta r_m) - (a - bp)\right]$, where $\lambda > 0$ is the Lagrangian multiplier. Similarly, make the first-order condition equal to zero. The final solution can be obtained.

Proposition 1 suggests that the costs associated with manufacturing EV batteries from raw materials, as well as the costs of vehicle production, determine the trade and market prices of NEVs, provided that the retail volume of NEVs does not limit the recycling volume of EV batteries. The collection price is linked to the revenue generated from recycling per unit capacity of used batteries, along with channel costs and labor costs. Conversely, when the sale quantity of NEVs constrains the recycling volume of NEV batteries, the wholesale price, sale price, and recovery price are all interconnected with the revenue from recycling per unit capacity of used batteries, channel costs, and labor costs. In comparison to a scenario without a tax-reward policy, in Mode M, the wholesale price of batteries, the sale price of NEVs, the transfer payment price, and the recycling volume are all influenced by the government policy.

4.2 | Automobile Manufacturer Recovery Mode (Mode V)

The gameplay in Mode V follows this order: The battery supplier first establishes the per-unit wholesale price w and the transfer payment price t. the automobile manufacturer formulates the sales price p of NEVs and NEV battery recovery price r_v. Under Model V, the profit-optimization objectives of the battery producer and the automobile manufacturer can be written as

$$Max\pi_m^V = (w - c_m - R)(a - bp) + \left(\Delta - t - c_n + \frac{R}{2}\right)(\alpha + \beta r_v), \tag{4}$$

$$Max\pi_v^V = (p - w - h)(a - bp) + (t - r_v - A_v)(\alpha + \beta r_v), \tag{5}$$

$$s.t.\ \alpha + \beta r_v \leq a - bp. \tag{6}$$

The first component of Equation (4) corresponds to the profit of the NEV battery producer, and the second component corresponds to the profit from recycling NEV batteries. In Equation (5), the primary part indicates the profit from NEV sales, and the second part indicates the profit from recycling retired EV batteries. Equation (6) ensures that the amount of recycled waste EV batteries does not exceed the sales number of EV batteries.

Proposition 2. *In recovery Mode V, the optimal strategies for the battery producer and the automobile manufacturer are as follows:*

1. When $\phi_V < 0$,

$$w^* = \frac{a + b(c_m - h + R)}{2b}, \tag{7}$$

$$t^* = \frac{-2\alpha + \beta(2\Delta - 2c_n + R) + 2\beta A_v}{4\beta}, \tag{8}$$

$$p^* = \frac{3a + b(c_m + h + R)}{4b}, \tag{9}$$

$$r_v^* = \frac{-6\alpha + \beta(2\Delta - 2A_v - 2c_n + R)}{8\beta}. \tag{10}$$

2. When $\phi_V \geq 0$,

$$w^{L*} = \frac{2ab + a\beta - \alpha b - 2b^2 h + b\beta(X - M + A_v - h)}{2b(b + \beta)}, \tag{11}$$

$$t^{L*} = \frac{a\beta - \alpha b - 2\alpha\beta + 2b^2 A_v + b\beta(M - X + A_v - h)}{2\beta(b + \beta)}, \tag{12}$$

$$p^{L*} = \frac{4ab + 3a\beta - \alpha\beta + b\beta(X - M + A_v + h)}{4b(b + \beta)}, \tag{13}$$

$$r_v^{L*} = \frac{-3\alpha b + a\beta - 4\alpha\beta - b\beta(X - M + A_v + h)}{4\beta(b + \beta)}, \tag{14}$$

where $M = \frac{2(\Delta - c_n) - R}{2}$, $\phi_V = \frac{-\alpha + a - \beta(M - A_V) - b(X + h)}{b + \beta}$.

Paralleling the earlier discussion, the strategic choices of the NEV battery producer can be segregated into two categories reliant on the threshold value ϕ_V. One is that the NEV battery recycling volume is not bound by the sale quantity of NEVs $\phi_V < 0$, and the other NEV battery recycling volume is secured by NEV sale quantity $\phi_V \geq 0$. First, the amount of NEV battery recycling is not limited by the sale quantity of NEVs. Adopting backward induction, the automobile manufacturer reacts first. As $\frac{\partial^2 \pi_v^V}{\partial p^2} = -2b < 0$, $\frac{\partial^2 \pi_v^V}{\partial r_v} = -2\beta < 0$, and π_v^V is a concave function toward p and r_v, there exists a maximum value. By $\frac{\partial \pi_v^V}{\partial p} = 0$ and $\frac{\partial \pi_v^V}{\partial r_v} = 0$, the reaction function of the automobile manufacturer can be obtained: $p = \frac{a + b(w + h)}{2b}$, and $r_v = \frac{\alpha + \beta(A_V - t)}{2\beta}$. Taking the reaction function into the profit function of the NEV battery producer, the Hessian matrix of the profit function of the NEV battery producer with respect to wholesale price w and transfer price t is calculated: $|H_2| = \begin{vmatrix} \frac{\partial^2 \pi_m^V}{\partial w^2} & \frac{\partial^2 \pi_m^V}{\partial wt} \\ \frac{\partial^2 \pi_m^V}{\partial wr_v} & \frac{\partial^2 \pi_m^V}{\partial t^2} \end{vmatrix} = \begin{vmatrix} -b & 0 \\ 0 & -\beta \end{vmatrix}$. Because $|H_2|_1 = -b < 0$ and $|H_2|_2 = b\beta > 0$, π_m^V is a concave function about w, t. By calculating $\frac{\partial \pi_m^V}{\partial w} = 0$ and $\frac{\partial \pi_m^V}{\partial t} = 0$, the maximum value of w and t can be calculated, $w^* = \frac{a + b(c_m - h + R)}{2b}$, $t^* = \frac{-2\alpha + \beta(2\Delta - 2c_n + R) + 2\beta A_v}{4\beta}$. Taking w^* and t^* into the reaction function of the NEV battery producer, $p^* = \frac{3a + b(c_m + h + R)}{4b}$ and $r_v^* = \frac{-6\alpha + \beta(2\Delta - 2A_v - 2c_n + R)}{8\beta}$ can be gotten.

Then, we consider NEV battery recycling volume bound by NEV sale quantity. The optimization problem in the profit function of

NEV battery producer can be expressed as $L_V = (w - c_m - R)(a - bp) + \left(\Delta - t - c_n + \frac{R}{2}\right)(\alpha + \beta r_v) + \lambda\left[(\alpha + \beta r_v) - (a - bp)\right]$, where $\lambda > 0$ is the Lagrangian multiplier. Similarly, make the first-order condition equal to zero. The final solution can be obtained.

Several conclusions can be drawn from Proposition 2. First, when the amount of recycled waste NEV batteries is not constrained by the sales of NEVs, the optimal sale price for these vehicles is influenced by potential market demand, consumer sensitivity to sale prices, the cost of raw materials for producing EV batteries, and the production costs of NEVs. The collection price is associated with consumer environmental awareness, sensitivity to collection prices, recycling revenue per battery, channel costs, and manual processing costs. The factors influencing the transfer payment price align with those affecting the collection price; specifically, although NEV production costs have a positive relationship with transfer payments, they negatively impact collection prices. Similarly, the factors affecting the wholesale price of NEV batteries produced by NEV battery manufacturers mirror those influencing the sale price of NEVs. However, the production cost of NEVs is negatively correlated with the wholesale price of NEV batteries but positively correlated with the sale price of NEVs. Compared to Proposition 1, in Model M, the NEV battery producer will lower the collection price due to increased costs associated with self-built recycling channels. In contrast, in Model V, an increase in the channel costs for automobile manufacturers will raise the transfer payment price. Furthermore, the wholesale price of batteries, the sale price of NEVs, the transfer payment price, and the recycling volume are all interconnected with the government policy in Model V.

4.3 | Professional Recycler Recovery Mode (Mode T)

The game sequence of Mode T is as follows: The battery producer first determines wholesale price per unit NEV battery w and transfer payment price t; the automobile manufacturer determines the NEVs price p according to the decision of the battery producer; and the professional recycler determines collection price r_t. In Model T, the maximization profit functions of battery producers, automobile manufacturers, and professional recycler can be expressed as

$$Max\pi_m^T = (w - c_m - R)(a - bp) + \left(\Delta - t - c_n + \frac{R}{2}\right)(\alpha + \beta r_t), \tag{15}$$

$$Max\pi_v^T = (p - w - h)(a - bp), \tag{16}$$

$$Max\pi_t^T = (t - r_t - A_t)(\alpha + \beta r_t), \tag{17}$$

$$s.t. \alpha + \beta r_t \le a - bp. \tag{18}$$

Proposition 3. *Under recovery Mode T, the optimal decisions of the battery producer and the automobile manufacturer are as follows:*

1. When $\phi_T < 0$,

$$w^* = \frac{a + b(c_m - h + R)}{2b}, \tag{19}$$

$$t^* = \frac{M\beta - \alpha + \beta A_t}{2\beta}, \tag{20}$$

$$p^* = \frac{3a + b(c_m + h + R)}{4b}, \tag{21}$$

$$r_t^* = \frac{-3\alpha + M\beta + \beta}{4\beta}. \tag{22}$$

2. When $\phi_T \ge 0$,

$$w^{L*} = \frac{2ab + a\beta - \alpha b - 2b^2h + b\beta(c_m + R - M + A_t - h)}{2b(b + \beta)}, \tag{23}$$

$$t^{L*} = \frac{a\beta - \alpha b - 2\alpha\beta + 2\beta^2 A_t + b\beta(M - c_m - R - c_n + A_t - h)}{2\beta(b + \beta)}, \tag{24}$$

$$p^{L*} = \frac{4ab + 3a\beta - \alpha b + b\beta(c_m + R - M + A_t + h)}{4\beta(b + \beta)}, \tag{25}$$

$$r_t^{L*} = -\frac{3\alpha b - a\beta + 4\alpha\beta + b\beta(c_m + R - M + A_t + h)}{4\beta(b + \beta)}, \tag{26}$$

where $M = \frac{2(\Delta - c_n) + R}{2}$, $\phi_T = -\frac{\alpha - a + \beta(M - A_t) + b(c_m + R + h)}{b + \beta}$.

The strategy selection of NEV battery producer can be divided into two categories based on the value of threshold ϕ_T. One is that the NEV battery recycling volume is not bound by the sale quantity of NEVs $\phi_T < 0$, and the other NEV battery recycling volume is secured by NEV sale quantity $\phi_T \ge 0$. First, the amount of NEV battery recycling is not limited by the sale quantity of NEVs. Adopting backward induction, the automobile manufacturer reacts first. As $\frac{\partial^2 \pi_v^T}{\partial p^2} = -2b < 0$ and $\frac{\partial^2 \pi_v^V}{\partial r_t} = -2\beta < 0$, π_v^T is a concave function about p and r_t. Therefore, a maximum value of p and r_t exists.

Let $\frac{\partial \pi_v^T}{\partial p} = 0$ and $\frac{\partial \pi_t^V}{\partial r_t} = 0$; the reaction function of the automobile manufacturer can be obtained: $p = \frac{a + b(w + h)}{2b}$, and $r_t = \frac{\alpha + \beta(A_T - t)}{2\beta}$. Taking the reaction function into the profit function of the NEV battery producer, the Hessian matrix of the profit function of the NEV battery producer with respect to wholesale price w and transfer price t is calculated: $|H_3| = \begin{vmatrix} \frac{\partial^2 \pi_m^T}{\partial w^2} & \frac{\partial^2 \pi_m^T}{\partial w \partial t} \\ \frac{\partial^2 \pi_m^T}{\partial w \partial t} & \frac{\partial^2 \pi_m^T}{\partial t^2} \end{vmatrix} = \begin{vmatrix} -b & 0 \\ 0 & -\beta \end{vmatrix}$. Because $|H_3|_1 = -b < 0$ and $|H_3|_2 = b\beta > 0$, π_m^M is a concave function about w, t. By calculating $\frac{\partial \pi_m^T}{\partial w} = 0$ and $\frac{\partial \pi_m^T}{\partial t} = 0$, the maximum value of w and t can be calculated, $w^* = \frac{a + b(c_m - h + R)}{2b}$, $t^* = \frac{M\beta - \alpha + \beta A_t}{2\beta}$. Taking w^* and t^* into the reaction function of the NEV battery producer, $p^* = \frac{3a + b(c_m + h + R)}{4b}$ and $r_t^* = \frac{-3\alpha + M\beta + \beta}{4\beta}$ can be gotten.

Then, we consider NEV battery recycling volume bound by NEV sale quantity. The optimization problem in the profit function of NEV battery producer can be expressed as $L_T = (w - c_m - R)(a - bp) + \left(\Delta - t - c_n + \frac{R}{2}\right)(\alpha + \beta r_t) + \lambda\left[(\alpha + \beta r_t) - (a - bp)\right]$, where $\lambda > 0$ is the Lagrangian multiplier. Similarly, make the first-order condition equal to zero. The final solution can be obtained.

Proposition 3 indicates that the wholesale price of NEV batteries and the sale price of NEVs are influenced by the production costs of these vehicles, excluding the costs associated with batteries, when the sales volume does not limit the recycling volume. The transfer payment price and the recycling quantity are linked to the net profit from recycling each battery, as well as manual processing costs and channel costs. However, the optimal solutions for the wholesale price of NEV batteries, the sale price of NEVs, the transfer payment price, and the recycling quantity are interconnected with the production costs of NEVs, excluding battery costs, manual processing costs, and channel costs. The conclusions of Proposition 3 are similar to those of Proposition 2, but they differ in terms of recovery channel costs. Specifically, Proposition 3 shows that the sale price of NEVs is unaffected by the tax-reward policy when the battery recycling volume is not constrained by vehicle sales. However, the government policy does influence the wholesale price of batteries, the transfer payment price, and the amount of battery recovery.

4.4 | Automobile Manufacturer and Professional Recycler Competitive Recovery (Mode VT)

Yiwei Lithium Energy is the NEV battery supplier of Xiaopeng Automobile. In terms of recycling, Yiwei Lithium Energy and Xiaopeng Automobile have arranged recycling work. The game sequence of mode VT is as follows: The battery producer first determines wholesale price per unit NEV battery w and transfer payment price t; the automobile manufacturer determines the NEV price p according to the decision of the battery producer; and the automobile manufacturer and professional recycler determine collection price r_t and r_t, respectively. In Model T, the maximization profit functions of battery producer, automobile manufacturer, and professional recycler can be expressed as

$$Max\pi_m^{VT} = (w - c_m - R)(a - bp) + \left(\Delta - t - c_n + \frac{R}{2}\right)\left[u + v + (k_1 - k_2)(r_v + r_t)\right], \tag{27}$$

$$Max\pi_v^{VT} = (p - w - h)(a - bp) + \left(t - r_v - A_m\right)\left(u + k_1 r_v - k_2 r_t\right), \tag{28}$$

$$Max\pi_t^{VT} = \left(t - r_t - A_t\right)\left(v + k_1 r_t - k_2 r_v\right), \tag{29}$$

$$s.t. \, v + u + \left(k_1 - k_2\right)\left(r_v + r_t\right) \le a - bp. \tag{30}$$

Proposition 4. *In recovery Mode VT, the optimal strategies for the battery producer, the automobile manufacturer, and the professional recycler are as follows:*

1. When $\phi_{VT} < 0$,

$$w^* = \frac{a + b(c_m - h + R)}{2b}, \tag{31}$$

$$t^* = \frac{4L_3k_1\left(L_1 - H_1 + H_2H_4\right) + L_2 + L_4 + L_3A_mk_2 - 2L/K + K\left(X + \frac{R}{2}\right)\left[\left(k_2^3 + L_3k_2\right) - 2H_2\left(H_3 - 1\right) + 1\right]}{2\left[k_2^3 + L_3k_2 - 4L_3k_1H_2\left(H_3 - 1\right) + 2L_3k_1\right]}, \tag{32}$$

$$p^* = \frac{3a + b(c_m + h + R)}{4b}, \tag{33}$$

$$r_v^* = H_1 - \frac{2H_2\left(2K\Gamma_1H_4 - \Gamma_1 + H_3\Gamma_1\right) - \Gamma_1}{4KT_2}, \tag{34}$$

$$r_t^* = T_1 - L_1 - \frac{L_2 + L_4 + L_3k_2\left(A_V - T_1\right) - \frac{k_2^3}{2KT_2}\frac{K(L_1 - H_1 + H_2H_4 + \left(L_2 + L_4 + L_3A_vk_2\right) - 4L_3k_1\left[L - 2K(2X + R)T_2\right]}{4L_3k_1}}{4L_3k_1}. \tag{35}$$

2. When $\phi_{VT} \ge 0$,

$$w^{L*} = \Omega_5 - \frac{2L - 2a + b\left(\Omega_5 + 2\Omega_7\right) - b\left(\Omega_5 - c_n\right) + 2K\left(\Omega_4 - \Omega_1 + \Omega_6 + \Omega_2\Omega_6 + \Omega_3\Omega_6\right) + K\left(R - 2\Omega_6 + 2X\right)\left(\Omega_2 + \Omega_3 + 1\right)}{b + 2K\left(\Omega_2 + \Omega_3 + 1\right)}, \tag{36}$$

$$t^* = \Omega_6 - \frac{2L - 2a + b\left(\Omega_5 + 2\Omega_7\right) - b\left(\Omega_5 - c_n\right) + 2K\left(\Omega_4 - \Omega_1 + \Omega_6 + \Omega_2\Omega_6 + \Omega_3\Omega_6\right) + K\left(R - 2\Omega_6 + 2X\right)\left(\Omega_2 + \Omega_3 + 1\right)}{b + 2K\left(\Omega_2 + \Omega_3 + 1\right)}, \tag{37}$$

$$p^* = \frac{\Omega_5}{2} + \Omega_7 - \frac{2L - 2a + b\left(2\Omega_7 + R + c_n\right) + 4K(2\Omega_4 - 2\Omega_1 + 2\Omega_6 + 2\Omega_2\Omega_6 + 2\Omega_3\Omega_6 + 2\Omega_2 + 2\Omega_3 + 2 + R - 2\Omega_6 + 2X)}{4\left(2K + b + 2K\Omega_2 + 2K\Omega_3\right)}, \tag{38}$$

$$r_t^* = \Omega_6\left(1 + \Omega_2\right) - \Omega_1 - \frac{\left(1 + \Omega_2\right)\left[2L - 2a + 2K\left(\Omega_4 - \Omega_1 + \Omega_6 + \Omega_2\Omega_6 + \Omega_3\Omega_6\right) + b\left(R + 2\Omega_7 + c_n\right) + K\left(K - 2\Omega_6 + 2X\right)\left(\Omega_2 + \Omega_3 + 1\right)\right]}{2\left(K + b + 2K\Omega_2 + 2K\Omega_3\right)}, \tag{39}$$

$$r_v^* = \Omega_4 + \Omega_3\Omega_6 - \frac{2L - 2a + 2b\Omega_5 + \Omega_7 - b\left(\Omega_5 - c_n\right) + 2K\left(\Omega_4 - \Omega_1 + \Omega_6 + \Omega_2\Omega_6 + \Omega_3\Omega_6\right) + 4K\Pi_1\left(\mathrm{R}/2 - \Omega_6 + X\right)}{b + 2K\Pi_1}, \tag{40}$$

where $\Gamma_1 = \frac{K(L_1 - H_1 + H_2H_4 + \frac{L_2 + L_4 + L_3c^lk_2}{4L_3k_1} - L + K\left(X + \frac{R}{2}\right)T_2}{2KT_2}$, $\Omega_1 = L_1 + \frac{L_3c^lk_2 + L_2 + L_4}{4L_3k_1}$, $\Omega_2 = \frac{k_2L_3 + k_2^3}{4L_3k_1}$, $\Omega_3 = H_2\left(1 - H_3\right) - \frac{1}{2}$, $\Omega_4 = H_1 - H_2H_4$, $\Omega_5 = \frac{a + bc_n - bh}{2b}$, $\Omega_6 = \frac{K\left(\Omega_1 - \Omega_4\right) - L + KX\left(\Omega_2 + \Omega_3 + 1\right)}{2K\left(1 + \Omega_2 + \Omega_3\right)}$, $\Omega_7 = \frac{a + bh}{2b}$, $\Pi_1 = \frac{\Omega_2 + \Omega_3 + 1}{2}$, and $\phi_{VT} = -\frac{2L - 2a + 2b\Omega_5 + \Omega_7 - b(\Omega_5 - c_n) + 2K(\Omega_4 - \Omega_1 + \Omega_6 + \Omega_2\Omega_6 + \Omega_3\Omega_6) + 4K\Pi_1(\mathrm{R}/2 - \Omega_6 + X)}{b + 2K\Pi_1}$.

The NEV battery producer's strategy selection can be categorized into two groups based on the value of the threshold ϕ_{VT}. One is that the NEV battery recycling volume is not bound by the sale quantity of NEVs $\phi_{VT} < 0$, and the other NEV battery recycling volume is secured by NEV sale quantity $\phi_{VT} \geq 0$. First, the sale quantity of NEVs is not bound to NEV battery recycling volume. As $\frac{\partial^2 \pi_v^{VT}}{\partial p^2} = -2b < 0$, $\frac{\partial^2 \pi_t^{VT}}{\partial r_t^2} = -2k_1 < 0$, and $\frac{\partial^2 \pi_v^{VT}}{\partial r_v^2} = \frac{k_2^2}{k_1} - 2k_1 < 0$, maximum values of p, r_v, and r_t exist. Let $\frac{\partial \pi_v^{VT}}{\partial p} = 0$, $\frac{\partial \pi_v^{VT}}{\partial r_v} = 0$, and $\frac{\partial \pi_t^{VT}}{\partial r_t} = 0$; the reaction function of p, r_v, and r_t can be obtained: $p = \frac{a + b(w + h)}{2b}$, $r_v = \frac{u + (A_V - t)\left(-\frac{k_2^2}{2k_1} + k_1\right) + \frac{k_2[v + k_1(A_t - t)]}{2k_1}}{-\frac{k_2^2}{k_1} + 2k_1}$, and $r_t = -\frac{v + k_1(A_t - t) + \frac{k_1k_2\left[u + \frac{(A_t - t)\left(2k_1^2 - k_2^2\right) + k_2(v + A_tk_1 - k_1t)}{2k_1}\right]}{2k_1^2 - k_2^2}}{2k_1}$. Taking the reaction function into the profit function of the NEV battery producer, the Hessian matrix of the profit function of the NEV battery producer with respect to wholesale price w and transfer price t is calculated: $\left|H_4\right| = \begin{vmatrix} \frac{\partial^2 \pi_m^{VT}}{\partial w^2} & \frac{\partial^2 \pi_m^{VT}}{\partial w \partial t} \\ \frac{\partial^2 \pi_m^{VT}}{\partial w \partial t} & \frac{\partial^2 \pi_m^{VT}}{\partial t^2} \end{vmatrix} = \begin{vmatrix} -b & 0 \\ 0 & -\frac{(k_1 - k_2)(-8k_1^2 - 4k_1^2k_2 + 3k_1k_2^2 + k_2^3)}{-4k_1^3 + 2k_1k_2^2} \end{vmatrix}$. Because $\left|H_4\right|_1 = -b < 0$ and $\left|H_4\right|_2 = \frac{b\left(k_1 - k_2\right)\left(-8k_1^2 - 4k_1^2k_2 + 3k_1k_2^2 + k_2^3\right)}{-4k_1^3 + 2k_1k_2^2} > 0$, π_m^{VT} is a concave function about w and t. By calculating $\frac{\partial \pi_m^{VT}}{\partial w} = 0$ and $\frac{\partial \pi_m^{VT}}{\partial t} = 0$, the maximum value of w and t can be calculated, $w^* = \frac{a + b\left(c_m - h + R\right)}{2b}$,

$$t^* = \frac{4L_3k_1\left(L_1 - H_1 + H_2H_4\right) + L_2 + L_4 + L_3A_mk_2 - 2L/K + K\left(X + \frac{R}{2}\right)\left[\left(k_2^3 + L_3k_2\right) - 2H_2\left(H_3 - 1\right) + 1\right]}{2\left[k_2^3 + L_3k_2 - 4L_3k_1H_2\left(H_3 - 1\right) + 2L_3k_1\right]}.$$

Taking w^* and t^* into the reaction function of the NEV battery producer, $p^* = \frac{3a + b\left(c_m + h + R\right)}{4b}$, $r_v^* = H_1 - \frac{2H_2\left(2K\Gamma_1H_4 - \Gamma_1 + H_3\Gamma_1\right) - \Gamma_1}{4KT_2}$, and

$$r_t^* = T_1 - L_1 - \frac{L_2 + L_4 + L_3k_2\left(A_V - T_1\right) - \frac{k_2^3}{2KT_2}\,\frac{K(L_1 - H_1 + H_2H_4 + \left(L_2 + L_4 + L_3A_vk_2\right) - 4L_3k_1\left[L - 2K(2X + R)T_2\right]}{4L_3k_1}}{4L_3k_1}$$

can be gotten.

Then, we consider NEV battery recycling volume bound by NEV sale quantity. The optimization problem in the profit function of NEV battery producer can be expressed as $L_{VT} = \left(w - c_m - R\right)(a - bp) + \left(\Delta - t - c_n + \frac{R}{2}\right)\left[u + v + \left(k_1 - k_2\right)\left(r_v + r_t\right)\right] + \lambda\left[v + u + \left(k_1 - k_2\right)\left(r_v + r_t\right)\right]$, where $\lambda > 0$ is the Lagrangian multiplier. Similarly, make the first-order condition equal to zero. The final solution can be obtained.

Proposition 4 indicates that in scenarios where the recycling volume of NEV batteries is not restricted by the sales quantity of NEVs, several key factors influence both the wholesale price of NEV batteries and the sale price of NEVs. These factors include the production costs of raw materials for batteries and NEVs, excluding the production cost of batteries themselves. Additionally, the transfer payment price and the battery recycling volume for both automobile manufacturers and professional recyclers are affected by elements such as net profits per used battery, manual processing costs, and channel expenses. In similar situations where the recycling volume of NEV batteries is unconstrained by the sales quantity of NEVs, the wholesale price of NEV batteries, the sale price of NEVs, the transfer payment price, and the battery recycling volume for both automobile manufacturers and professional recyclers are determined by these factors. Compared to other models, the dual-channel competitive recovery mode incorporates a wider range of influencing factors, making it more complex. Under the tax-reward policy, the wholesale price, recovery transfer payment price, recovery volume, and recovery price of EV batteries are all related to the tax-reward mechanism.

5 | Results and Discussion

5.1 | Equilibrium Analysis of Decision Variables in Forward Supply Chain

Table 3 presents the optimal solutions for the decision variables in the forward supply chain. The optimal wholesale and sale prices for each recovery mode in the forward supply chain are identical. This similarity occurs because the optimal trade and sale prices are influenced solely by the costs of raw materials, vehicle production costs, and the tax amount, which remain constant across all recovery modes. When the refund amount is set at 50% of the tax, the tax-reward leads to an increase in the wholesale price of batteries, a decrease in the transfer payment price for recycling, an increase in the sale price of NEVs, and a reduction in the volume of battery recycling. This pattern holds regardless of whether the recycling volume is constrained by sales quantity.

5.2 | Analysis of Optimal Decision Variables in Reverse Supply Chain

As shown in Table 4, the collection price under each recovery mode meets the following requirements: $r_m^{M*} > r_v^{V*} > r_v^{VT*} > r_t^{VT*} > r_t^{T*}$. The transfer payment price of each recovery mode meets $t^{T*} > t^{V*} > t^{VT*}$. In Mode M, the NEV battery producer recycles directly to the purchaser, so its

TABLE 3 | Optimal solution of forward supply chain decision variable.

Models	w^*	p^*
Model M	$\frac{a + b\left(c_m - h + R\right)}{2b}$	$\frac{3a + b\left(c_m + h + R\right)}{4b}$
Model V	$\frac{a + b\left(c_m - h + R\right)}{2b}$	$\frac{3a + b\left(c_m + h + R\right)}{4b}$
Model T	$\frac{a + b\left(c_m - h + R\right)}{2b}$	$\frac{3a + b\left(c_m + h + R\right)}{4b}$
Model VT	$\frac{a + b\left(c_m - h + R\right)}{2b}$	$\frac{3a + b\left(c_m + h + R\right)}{4b}$

TABLE 4 | Optimal solution of reverse supply chain decision variable.

Models	r^*	t^*
Model M	$r_m^* = \frac{-\alpha + 2\beta(2\Delta - 2A_m - 2c_n + R)}{2\beta}$	
Model V	$r_v^* = \frac{-6\alpha + \beta(2\Delta - 2A_v - 2c_n + R)}{8\beta}$	$\frac{-2\alpha + \beta(2\Delta - 2c_n + R) + 2\beta A_v}{4\beta}$
Model T	$r_t^* = \frac{-6\alpha + \beta(2\Delta - 2A_t - 2c_n + R)}{8\beta}$	$\frac{4L_3k_1(L_1 - H_1 + H_2H_4) + L_2 + L_4 + L_3A_mk_2 - 2L/K + K\left(X + \frac{R}{2}\right)\left[\left(k_2^3 + L_3k_2\right) - 2H_2(H_3 - 1) + 1\right]}{2\left[k_2^3 + L_3k_2 - 4L_3k_1H_2(H_3 - 1) + 2L_3k_1\right]}$
Model VT	$r_v^* = H_1 - \frac{2H_2(2K\Gamma_1H_4 - \Gamma_1 + H_3\Gamma_1) - \Gamma_1}{4KT_2}$ $r_t^* = T_1 - L_1 - \frac{-\frac{k_2^3}{2KT_2}\frac{L_2 + L_4 + L_3k_2(A_V - T_1)\, K(L_1 - H_1 + H_2H_4 + (L_2 + L_4 + L_3A_vk_2)4L_3k_1\left[L - 2K(2X + R)T_2\right]}{4L_3k_1}}{4L_3k_1}$	$\frac{4L_3k_1(L_1 - H_1 + H_2H_4) + L_2 + L_4 + L_3A_mk_2 - 2L/K + K\left(X + \frac{R}{2}\right)\left[\left(k_2^3 + L_3k_2\right) - 2H_2(H_3 - 1) + 1\right]}{2\left[k_2^3 + L_3k_2 - 4L_3k_1H_2(H_3 - 1) + 2L_3k_1\right]}$

collection price is higher. For automobile manufacturer and professional recycler, the collection price depends on the recycling cost, and the recycling cost of automobile manufacturer is lower, so its collection price is higher than that of professional recycler. In the competitive recovery mode, the market is jointly participated by automobile manufacturer and professional recycler, and the average recycling cost is between the automobile manufacturer and professional recycler. The transfer payment price is set at a higher level in the professional recycler recovery mode because the recycling costs borne by the professional recycler are usually greater than those of the automobile manufacturer. This difference in recycling costs is ultimately covered by the price transfer to the NEV battery producer.

5.3 | Numerical Example Analysis

The focus of this section is to analyze the impact of tax, reward and tax-reward policies on the profit, and recovery rate within the closed-loop supply chain system. It also delves deeper into exploring the effect of changes to critical parameters under each recycling mode. The parameter value and setting basis are as follows: When the amount of NEV battery recycling is not constrained by the sale quantity of NEVs, it needs to meet $\phi_M < 0$, $\phi_V < 0$, $\phi_T < 0$, and $\phi_{VT} < 0$. Similarly, when the amount of waste battery recycling is constrained by the sale quantity of NEVs, $\phi_M \geq 0$, $\phi_V \geq 0$, $\phi_T \geq 0$, and $\phi_{VT} \geq 0$ need to be satisfied. Based on 2023 Tesla Model Y retail sales data, $a = 300{,}000$. Referring to the research of Wu, Li, et al. (2024), Wu and Zhang (2024b), and Wu, Zhang, et al. (2024), the price reaction level of purchasers to NEVs is $b = 1.1$. Taking the highest selling Tesla Model Y as an example, the battery capacity is 77 KWh, and the cost is about 1340/KWh, so the cost of a set of NEV batteries is about 103,218 RMB. The Tesla car battery weighs 900 kg, and the recycling of lithium-ion batteries can generate a profit of 36,337 RMB/ton; $c_r = 32{,}703$ can be obtained. According to the estimates of Ding, Zhang, and Pu (2024), the cascade utilization of EV batteries can generate a profit of 527 RMB/kWh. According to the existing data (Wu, Cong, et al. 2023), when the capacity of the NEV battery decays below 80%, it needs to be replaced and used in cascades, and the income of the cascade utilization of the waste NEV battery per unit can be obtained: $\eta = 35{,}166$ RMB. According to the Cinda Securities R&D Center calculation data, the labor cost, equipment depreciation cost, and house occupation cost nearly 100 per battery unit. Thus, the cost of $c_n = 100$ RMB for each set of NEV batteries can be calculated. To generate funds for the recycling and disposal of EV batteries, 20 RMB per kilowatt-hour charge will be added to sale prices. Finally, 50% will refund when the battery is recycled. Thus, we can calculate $R = 1540$ RMB.

5.3.1 | Total Revenue and Recovery Rate

The data in Table 5 indicate that the overall profit of the supply chain and recovery rate for modes M and VT is the highest, regardless of whether the recycling volume of NEV batteries is constrained by the sale quantity. Conversely, when the refund is set at 50% of the tax-reward amount, the overall profit and recovery rate of the supply chain will see a decrease, regardless of whether the NEV battery recycling volume is limited by the sale quantity.

This paper has explored the case where the refund (tax) amount is 50% of the deposit (reward) amount. In this section, we will delve deeper into the implications of varying the refund amount as a proportion of the deposit. Specifically, we will analyze total revenue under different refund ratios, illustrating how these variations impact the overall financial dynamics of the supply chain. Figure 2a–d represents the total revenue across four distinct recovery modes. The X and Y axes represent the deposit and return amount, respectively, and the Z axis represents the profit level of each recovery mode. Notably, when the refund ratio is set to 0, we observe that total revenue is inversely proportional to the

TABLE 5 | Comparison of the optimal profit and recovery rate (profit 10^7).

	π_m^*	π_r^*	π_t^*	S(π)	Recovery rate
The amount of NEV battery recycling is not bound by the sale quantity of new energy vehicles					
Model M	30.059	10.021		40.08	0.0350
Model V	27.901	13.512		41.413	0.0292
Model T	27.639	6.9097	6.9095	41.4582	0.0291
Model VT	37.196	15.257	2.9143	55.3673	0.0383
The amount of NEV battery recycling is bound by the sale quantity of new energy vehicles					
Model M	103.11	26.032		129.142	0.0627
Model V	88.037	35.682		123.719	0.0506
Model T	87.620	15.373	20.860	123.853	0.0505
Model VT	115.79	38.395	8.6082	162.7932	0.0654

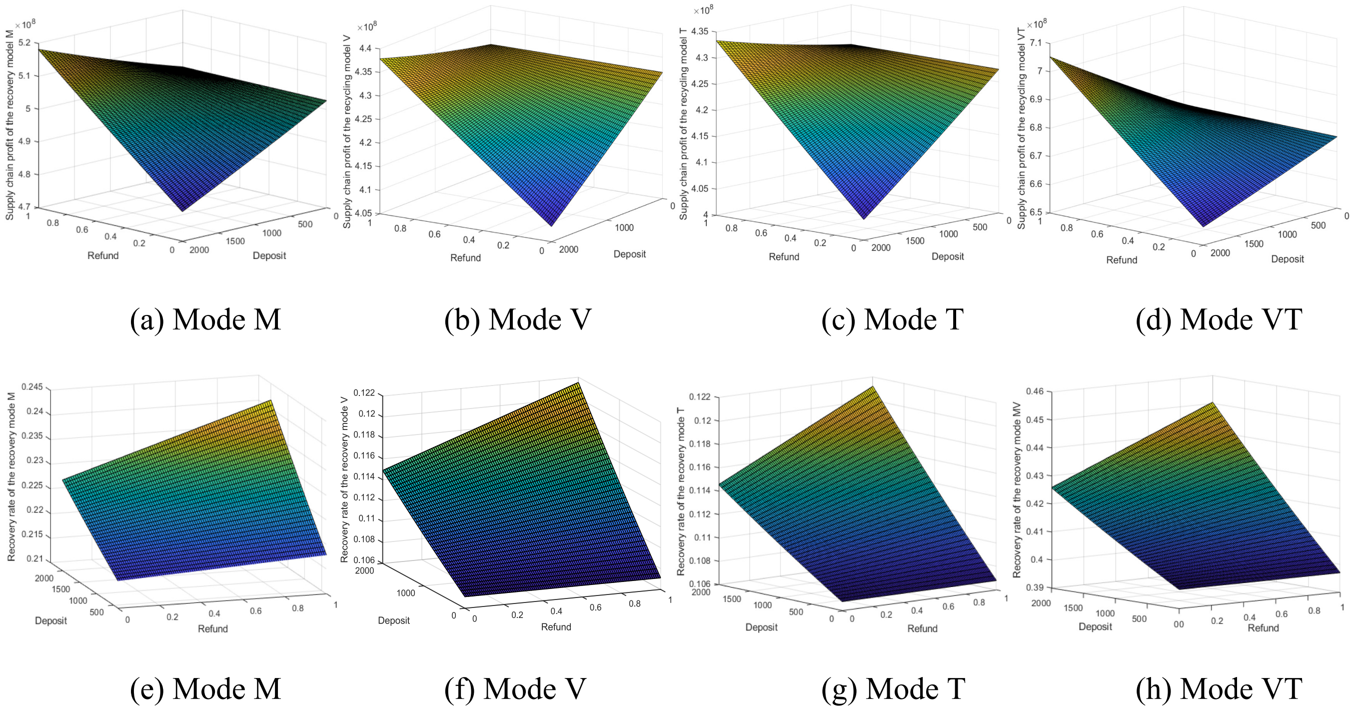

FIGURE 2 | The influence of the proportion between deposit and refund on total revenue and collection rate under each recovery mode. (a) Mode M, (b) Mode V, (c) Mode T, (d) Mode VT, (e) Mode M, (f) Mode V, (g) Mode T, and (h) Mode VT.

increase in deposit amount. This suggests that, in the absence of refund incentives, participants may feel discouraged by higher deposits, potentially diminishing their engagement and overall efficiency in the supply chain. Conversely, under a certain threshold of deposit, the profit of the supply chain begins to increase as the proportion of subsidies rises. This trend continues until the refund proportion reaches 1, at which point supply chain profits peak. This indicates that appropriate subsidies can motivate participants and enhance overall revenue. This finding indicates a critical relationship between deposit amounts and refund ratios, where the right balance can significantly enhance profitability.

Figure 2e–h illustrates the variations in the recovery rate across different recovery modes as a function of deposit-return ratios. When the return amount is set to 0, the recovery rate exhibits a clear upward trend with increasing deposit amounts. Conversely, when the deposit amount is 0, an increase in the return amount does not lead to significant changes in the recovery rate. This indicates that taxes can play a substantial role in enhancing recycling rates. Overall, in terms of comprehensive supply chain profitability and recovery rates, the deposit-return policy outperforms both tax and reward systems.

5.3.2 | Effect of Recycling Channel Cost on Total Revenue and Recovery Rate

This section investigates the influence of recycling channel expenses on total revenue. Figure 3a–d illustrates the profit trends for battery producer, automobile manufacturers, professional recycler, and the overall supply chain in relation to variations in channel costs. It is evident that profits across all channels, as well as the total profit, exhibit a downward trend. Notably, the mixed recycling channel supply chain demonstrates the highest profit levels among the various channels analyzed. Notably, professional recycler experiences the most significant shift in profit. In line with profitability trends, the level of change in recycling rates also exhibits a downward trajectory. This decline occurs because rising recycling costs can lead companies and consumers to perceive a reduction in the economic benefits associated with recycling. Consequently, businesses may become reluctant to allocate additional resources to recycling initiatives.

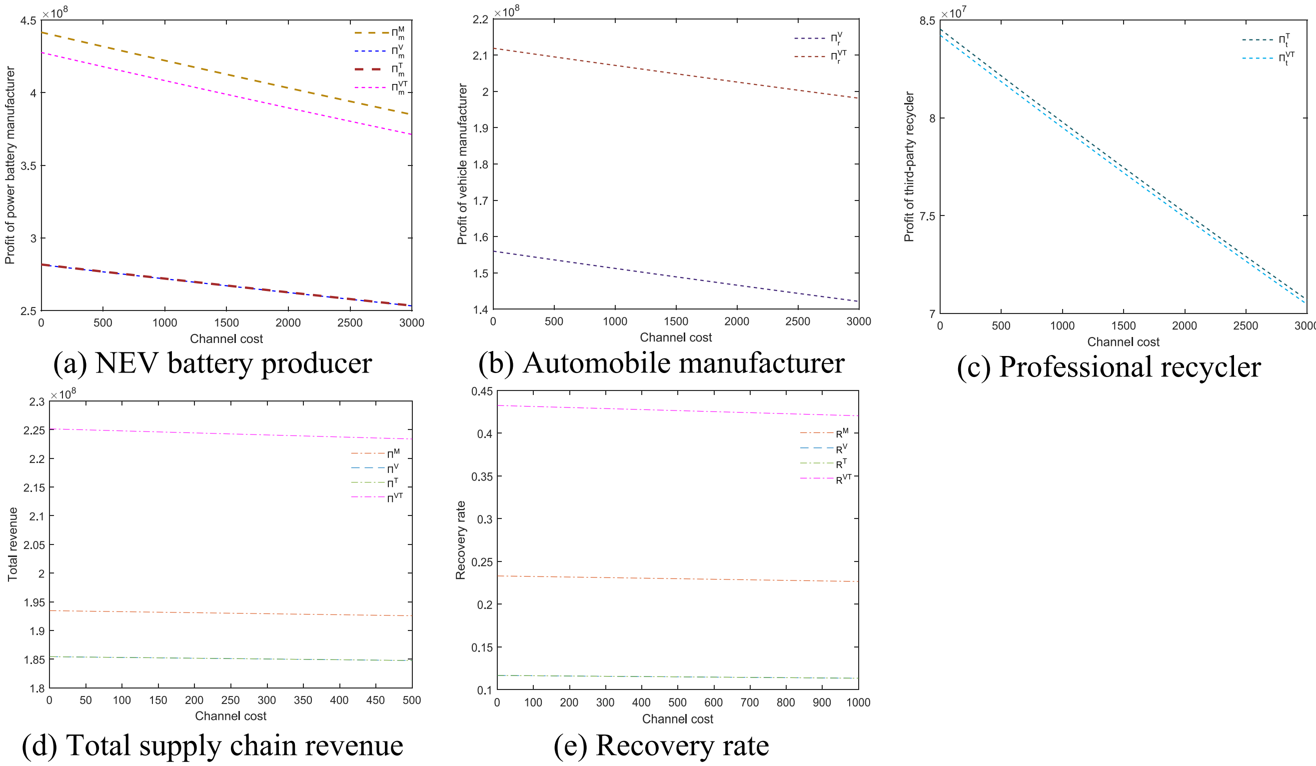

FIGURE 3 | The influence of the channel cost on the profit and recovery rate. (a) NEV battery producer, (b) automobile manufacturer, (c) professional recycler, (d) total supply chain revenue, and (e) recovery rate.

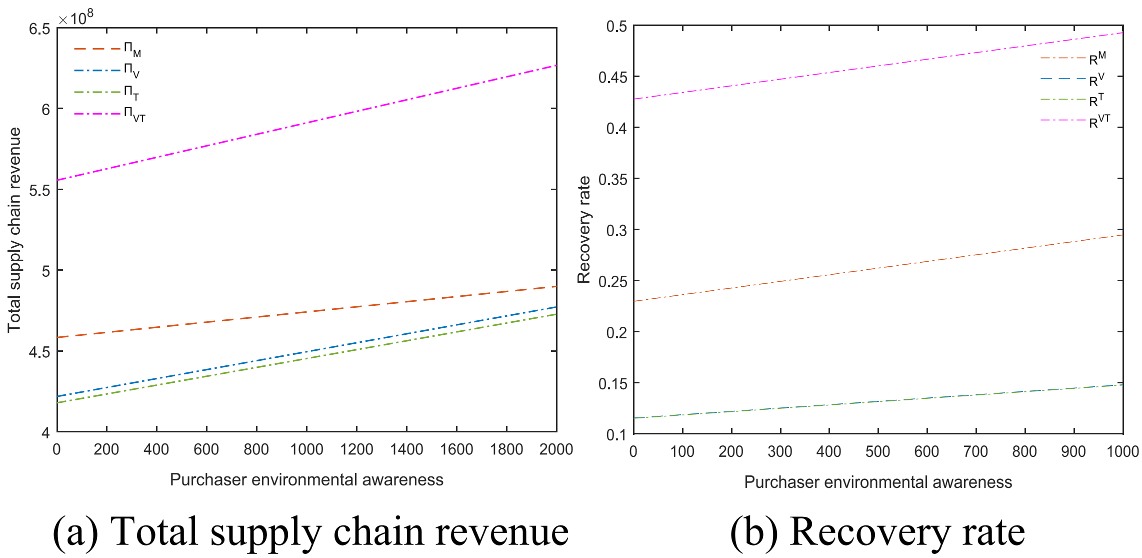

FIGURE 4 | The influence of purchaser environmental awareness on total revenue and recovery rate. (a) Total supply chain revenue and (b) recovery rate.

5.3.3 | Sensitivity Analysis of Purchaser Environmental Awareness

This section examines the impact of changes in purchaser environmental awareness on total revenue and recovery rate. As shown in Figure 4a, an increase in purchasers' environmental awareness positively influences supply chain earnings. Among the four recycling methods analyzed, the mixed recycling approach demonstrates the most significant improvement in total revenue. This indicates that mixed recycling not only enhances environmental conservation but also optimizes economic benefits for the supply chain, creating a win-win scenario for both environmental and economic objectives. Figure 4b further illustrates that the recycling rate rises with improvements in purchaser environmental awareness. This relationship is straightforward: As purchasers become more environmentally conscious, their participation in recycling activities increases. If sales volume remains constant, this increased awareness directly contributes to a higher recycling rate.

6 | Conclusions and Implications

This paper explores four recycling approaches for waste EV batteries from NEVs, situated within the EPR system. During the evaluation, we incorporate the sequential utilization process of discarded batteries. Using the Stackelberg model, we delve into the implications of the deposit refund policy. Concurrently, we investigate the impacts of channel cost revisions and variations in purchaser environmental sensibility on supply chain turnover. The key findings and policy implications are outlined as follows: When evaluating the recycling model, it is evident that, regardless of whether the recycling volume of NEV batteries is constrained by the sales volume of NEVs, both M and VT types consistently achieve the highest profits and recycling ratios. Similarly, under government policy constraints, both M and VT types demonstrate superior performance. Government policies play a crucial role in regulating the recycling rate of used NEV batteries across the entire supply chain. Their impact is multifaceted, influencing various factors such as the market price of NEVs, collection prices, transfer payment prices, and ultimately, recycling volumes. When comparing different policies, tax policies can enhance the recycling rate, whereas reward policies can improve the profitability of the supply chain. However, the deposit-return policy proves to be the most effective overall. Experimental data indicate that the ratio of deposits to refunds significantly affects the profitability of the supply chain; an inappropriate ratio can lead to a decline in overall profits. Therefore, establishing a reasonable ratio of deposits to refunds is essential for ensuring the viability and success of the supply chain. Additionally, reducing recycling costs and enhancing purchaser environmental awareness contribute positively to the efficiency of supply chain operations. Based on the above conclusions, the main policy recommendations drawn in this paper include:

1. Support the adoption of mixed recycling methods, as they have shown to yield higher profits and better recycling ratios. Provide recycling technology training and guidance to companies to help them optimize their recycling processes.
2. Tailor government policies to balance between tax incentives, collection pricing, and transfer payments to maximize recycling volumes and supply chain profitability. Develop and implement reasonable deposit-return ratios to enhance supply chain profitability and encourage higher recycling rates.
3. Encourage investment in technologies and practices that lower recycling costs, thereby making recycling operations more efficient and economically viable. Implement educational campaigns to raise purchaser environmental awareness, fostering greater participation in recycling initiatives.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

References

Ahmad, N., L. S. Du, J. Y. Lu, et al. 2017. "Modelling the CO2 Emissions and Economic Growth in Croatia: Is There any Environmental Kuznets Curve?" *Energy* 123: 164–172.

Avci, B., K. Girotra, and S. Netessine. 2015. "Electric Vehicles With a Battery Switching Station: Adoption and Environmental Impact." *Management Science* 61, no. 4: 772–794.

Bian, J., and X. Zhao. 2020. "Tax or Subsidy? An Analysis of Environmental Policies in Supply Chains With Retail Competition." *European Journal of Operational Research* 283: 901–914.

Chen, J., Z. Han, X. Sun, and J. Liu. 2024. "Technology Innovation Decision-Making and Optimal Government Subsidy Strategy With Endogenous Bargaining Power in a Vertical Supply Chain." *Managerial and Decision Economics* 46: 21–51. https://doi.org/10.1002/mde.4351.

Chen, M. Y., X. T. Ma, B. Chen, et al. 2019. "Recycling End-Of-Life Electric Vehicle Lithium-Ion Batteries." *Joule* 3, no. 11: 2622–2646.

Ding, J., W. Zhang, and X. Pu. 2024. "Optimal Reverse Channel for End-Of-Life Vehicle Closed-Loop Supply Chains." *Managerial and Decision Economics* 46: 529–544. https://doi.org/10.1002/mde.4389.

Hendrickson, T. P., O. Kavvada, N. Shah, R. Sathre, and C. D. Scown. 2015. "Life-Cycle Implications and Supply Chain Logistics of Electric Vehicle Battery Recycling in California." *Environmental Research Letters* 10, no. 1: 014011.

Hong, Z., J. Chu, L. L. Zhang, and N. Wang. 2024. "Recycling Channel Selection for a Manufacturer Involving Consumers' Green-Return Behavior." *IEEE Transactions on Engineering Management* 71: 8761–8776.

Karacan, R., and E. Y. Kayacan. 2024. "How Environmentally Friendly Are Electric Cars? The Relationship Between Lithium Usage and Water Resources, Chile Example." *Managerial and Decision Economics* 45, no. 8: 5346–5358. https://doi.org/10.1002/mde.4324.

Li, F. Q., P. Wang, W. Chen, W. Q. Chen, B. J. Wen, and T. Dai. 2022. "Exploring Recycling Potential of Rare, Scarce, and Scattered Metals:

Present Status and Future Directions." *Sustainable Production and Consumption* 30: 988–1000.

Lin, Y., Z. Yu, Y. Wang, and M. Goh. 2023. "Performance Evaluation of Regulatory Schemes for Retired Electric Vehicle Battery Recycling Within Dual-Recycle Channels." *Journal of Environmental Management* 332: 117354.

Liu, S., C. Duan, J. Qiao, and Y. Sun. 2025. "Manufacturer's Cooperative Recycling Strategies Considering the Negative Externality of Unrecycled Products: Non-cooperative, Fund-Cooperative, or Labour-Cooperative." *Managerial and Decision Economics* 46: 201–221.

Lu, C., J. Tao, Q. X. An, and X. D. Lai. 2020. "A Second-Order Cone Programming-Based Robust Data Envelopment Analysis Model for the New-Energy Vehicle Industry." *Annals of Operations Research* 292, no. 1: 321–339.

Parker, G. G., B. Tan, and O. Kazan. 2019. "Electric Power Industry: Operational and Public Policy Challenges and Opportunities." *Production and Operations Management* 28, no. 11: 2738–2777.

Picatoste, A., D. Justel, and J. M. F. Mendoza. 2022. "Mendoza, Circularity and Life Cycle Environmental Impact Assessment of Batteries for Electric Vehicles: Industrial Challenges, Best Practices and Research Guidelines." *Renewable and Sustainable Energy Reviews* 169: 112941.

Ranjbar, Y., H. Sahebi, J. Ashayeri, and A. Teymouri. 2020. "A Competitive Dual Recycling Channel in a Three-Level Closed Loop Supply Chain Under Different Power Structures: Pricing and Collecting Decisions." *Journal of Cleaner Production* 272: 122623.

Saha, S., Z. Banaszak, G. Bocewicz, and I. E. Nielsen. 2022. "Pricing and Quality Competition for Substitutable Green Products With a Common Retailer." *Operations Research* 22: 3713–3746.

Saha, S., B. Mantin, S. Majumder, and I. Nielsen. 2024. "On the Interdependence of Strategic Inventories and New Product Generation Introduction." *International Journal of Production Economics* 271: 109195.

Saha, S., I. E. Nielsen, and S. Majumder. 2019. "Dilemma in Two Game Structures for a Closed-Loop Supply Chain Under the Influence of Government Incentives." *Journal of Industrial Engineering International* 15: 291–308.

Saha, S., S. P. Sarmah, and I. Moon. 2016. "Dual Channel Closed-Loop Supply Chain Coordination With a Reward-Driven Remanufacturing Policy." *International Journal of Production Research* 54: 1503–1517.

Savaskan, R. C., S. Bhattacharya, and L. N. van Wassenhove. 2004. "Closed-Loop Supply Chain Models With Product Remanufacturing." *Management Science* 50, no. 2: 239–252.

Song, H., J. Zhang, and J. Li. 2022. "The Impacts of Subsidy Strategies and Recycling Modes on the Closed-Loop Supply Chain." *Managerial and Decision Economics* 43: 4106–4123.

Valogianni, K., W. Ketter, J. Collins, and D. Zhdanov. 2020. "Sustainable Electric Vehicle Charging Using Adaptive Pricing." *Production and Operations Management* 29, no. 6: 1550–1572.

Vedantam, A., and A. Iyer. 2021. "Capacity Investment Under Bayesian Information Updates at Reporting Periods: Model and Application." *Production and Operations Management* 30, no. 8: 2707–2725.

Wang, J., W. Li, M. Nozomu, and T. Adachi. 2021. "Closed-Loop Supply Chain Under Different Channel Leaderships: Considering Different Deposit–Refund Systems Practically Applied in China." *Journal of Material Cycles and Waste Management* 23: 1765–1776.

Wang, T., Z. Wu, P. Cheng, and Y. Wang. 2024. "The Effect of Carbon Quota Allocation Methods on Maritime Supply Chain Emission Reduction." *Transport Policy* 157: 155–166.

Wang, Y., Q. Jiang, X. Guan, and X. Guan. 2023. "Recycling Channel Design and Coordination in a Reverse Supply Chain With Customer Green Preference." *Transportation Research Part E: Logistics and Transportation Review* 179: 103329.

Wang, Y. X., B. J. Tang, M. Shen, et al. 2022. "Environmental Impact Assessment of Second Life and Recycling for LiFePO4 EV Batteries in China." *Journal of Environmental Management* 314: 115083.

Wu, W., N. Cong, X. Zhang, Q. Yue, and M. Zhang. 2023. "Life Cycle Assessment and Carbon Reduction Potential Prediction of Electric Vehicles Batteries." *Science of the Total Environment* 903: 166620.

Wu, W., M. Li, M. Zhang, Y. Wang, L. Wang, and Y. You. 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 Environment Protection* 192: 1467–1482.

Wu, W., M. Zhang, D. Jin, P. Ma, W. Wu, and X. Zhang. 2024. "Decision-Making Analysis of Electric Vehicle Battery Recycling Under Different Recycling Models and Deposit-Refund Scheme." *Computers and Industrial Engineering* 191: 110109.

Wu, W. Q., and M. Zhang. 2024a. "Decision-Making Analysis of Power Battery Recycling Under Carbon Cap-and-Trade Mechanism and Subsidy Policy." *Chinese Journal of Management Science*. https://doi.org/10.16381/j.cnki.issn1003-207x.2023.1828.

Wu, W. Q., and M. Zhang. 2024b. "Pricing and Coordination Strategy of Power Battery Closed-Loop Supply Chain Under Policy." *Industrial Engineering and Management* 29: 147–158.

Wu, Z., X. Qian, M. Huang, W. K. Ching, X. Wang, and J. Gu. 2023. "Recycling Channel Choice in Closed-Loop Supply Chains Considering Retailer Competitive Preference." *Enterprise Information Systems* 17, no. 2: 1923065. https://doi.org/10.1080/17517575.2021.1923065.

Zhang, M., W. Wu, and Y. Song. 2023. "Study on the Impact of Government Policies on Power Battery Recycling Under Different Recycling Models." *Journal of Cleaner Production* 413: 137492.