

Incentive mechanism design for electric vehicle battery supply chain under information asymmetry and government intervention

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Abstract

Purpose - To settle the recycling ability and effort information asymmetry between manufacturer and recycler in electric vehicle battery supply chain, this paper constructs an information screening mechanism based on the principal-agent theory to and evaluates its effectiveness. Two types of recyclers, automobile manufacturers and third-party recycling companies, are discussed separately.

Design/methodology/approach - The essence of the information screening mechanism is to design differentiated benefits distributed mechanism according to the recycling ability of the recyclers and inspire them to make their best effort to recycle. And the effectiveness of the mechanism is examined and discussed. In addition, the interaction between the government subsidy and information screening mechanism is further

analyzed.

Findings - Recyclers are incentivized to truthfully report their recycling capabilities under an optimal benefits distribution mechanism, as this obtains greater rewards than misreporting. Government subsidies can enhance information screening by increasing rewards for recyclers who invest more effort. As rewards per unit of EV battery recycled rise, recyclers' efforts also increase. A higher proportion of capable recyclers reduces the profitability of false reporting while boosting manufacturers' profits.

Originality/value – This paper proposes an information screening mechanism to enhance transparency and efficiency in the EV battery recycling supply chain, addressing information asymmetry. It examines the impact of government subsidy policies on the screening process and analyzes how changes in recycler capabilities influence supply chain dynamics, aiming to develop adaptive coordination mechanisms that support sustainable transportation through improved EV battery recycling.

Keywords Electric vehicle battery supply chain; Information asymmetry; Government subsidy; Incentive mechanism

Paper type Research paper

1. Introduction

Countries worldwide are developing electric vehicles as part of sustainable transportation efforts to reduce greenhouse gas emissions. As a key component of green mobility, electric vehicles help decrease dependence on oil, while promoting the diversification and stability of energy supply, thus advancing the development of a low-carbon economy (Xu et al., 2023a; Kong et al., 2024). The comparison between traditional internal combustion engine vehicles and electric vehicles highlights the significant environmental benefits of electric vehicles, especially their zero-emissions feature, which is crucial in promoting low-carbon, sustainable transportation by reducing air pollution and enhancing urban air quality. It's noteworthy that China has emerged as a pivotal player in the electric vehicle market, boasting the largest market share globally. This is evidenced by the substantial sales volume and user base for electric vehicles in the country, as highlighted by He and Sun (2022). Additionally, the growth trajectory of new energy vehicle production and demand has led to a corresponding expansion in the installed capacity of electric vehicle batteries. As Zhang et al. (2023) point out, China has taken the lead in both the installation and application of EV batteries globally. This underscores China's commitment to advancing electric vehicle technology and its position as a key contributor to the global transition towards sustainable transportation.

Data from the China Automobile Manufacturers Association indicates that the global installed capacity of electric vehicle (EV) batteries reached 705.5 GWh in 2023, with China contributing significantly with an installed capacity of 387.7 GWh, constituting 54.95% of the global total (Li et al., 2022). However, the looming challenge of recycling retired EV batteries post-service poses significant hurdles (Chen et al., 2022). As EV batteries reach the end of their operational life, recycling becomes imperative. When the remaining capacity of an EV battery declines to 80% of its initial capacity, it can no longer support the normal functions of the vehicle and must be retired (Gu et al., 2021). Projections suggest that by 2030, the cumulative volume of retired EV batteries could exceed 200 GWh. Failure to effectively recycle these retired batteries poses serious threats, both environmentally and economically (Hua et al., 2021). It could result in severe environmental pollution and substantial economic losses if left unaddressed. Therefore, devising efficient recycling strategies for retired EV batteries is crucial to mitigate these risks and ensure a sustainable transition towards electric mobility (Kong et al., 2023a).

Retired electric vehicle (EV) batteries pose a significant environmental and health risk due to the presence of electrolytes, heavy metals, and other harmful substances (Wu et al., 2023a). However, it's worth noting that despite reaching the end of their primary use, retired EV batteries still retain a considerable portion of their capacity, typically ranging from 70-80%. Harnessing this remaining capacity presents an opportunity for secondary use in various sectors such as power grid enterprises, communication base stations, and low-speed electric vehicles, among others. Such repurposing not only yields economic benefits but also promotes energy conservation (Ma et al., 2023). Furthermore, the escalating demand for essential metals like lithium, cobalt, and nickel, crucial components in EV batteries, has outpaced the availability of these resources (Yao et al., 2021). This surge in demand has been accompanied by a sharp rise in resource prices, underscoring the need for sustainable solutions. Recycling retired EV batteries offers a promising avenue to address both environmental concerns and resource scarcity. Studies suggest that recycling these materials could potentially fulfill nearly one-third of the demand for essential metals (Wei et al., 2023).

The EV battery recycling work, currently in the initial stage, has yet to form a complete system. At present, the most urgent problem is the high recycling cost. To cope with high recycling costs, the government issues subsidy policies to incentivize EV battery recyclers (Hoarau and Lorang, 2022; Zhou et al., 2024). Under the guidance of recycling policies, a series of enterprises have successfully launched EV battery recycling service network layout work. Competition among recycling channels can lead to

inefficiencies in closed-loop supply chains, and the government advocates for companies to build and share recycling channels jointly (Wang et al., 2023a; Kong et al., 2023b). For companies that pursue profit maximization, profit distribution is a crucial factor affecting cooperation between companies and the efficiency of the supply chain. Although existing literature has attempted to promote cooperation between companies and overcome inefficiencies in the supply chain through contract agreements, the common assumption of these studies is that all supply chain members have the same amount of information, which is rarely the case (Heydari et al., 2017; Raj et al., 2021). In practice, enterprises in EV battery closed-loop supply chains have different preferences and benefits goals (Liu et al., 2023). They make their own decisions and strive to achieve their own goals. Some private information may be retained for their interest considerations. Under this background, information asymmetry between supply chain enterprises decreases work efficiency (Cheng et al., 2024; Wan and Fan, 2024).

Due to the complex market information for battery recycling, there is information asymmetry between the reverse supply chain recyclers and manufacturers in the transaction process (Wang et al., 2017; Mobini et al., 2019). As the manufacturer is responsible for the recycling work, they need to entrust the recycler to finish the work. Manufacturers need to consider their recycling ability when choosing a consigned recycler. Recyclers in the market have different recycling abilities, and their recycling ability is difficult to observe (Pakseresht et al., 2023). Game theory stands out as the predominant method for investigating the strategic decision-making processes of supply chain members (Wu et al., 2024a; Chen et al., 2024). Furthermore, when decision-making order is evident, the Stackelberg model emerges as the most frequently employed approach (Liu and Szeto, 2020). Building upon Stackelberg game theory, this study introduces a coordination mechanism aimed at addressing the information asymmetry between EV battery remanufacturers and recyclers. The contributions of this research are threefold: (1) Designing an information screening mechanism and assessing its effect within the EV battery recycling supply chain under conditions of information asymmetry. This mechanism aims to mitigate the adverse effects of information asymmetry by enhancing transparency and facilitating more informed decision-making among supply chain actors. (2) Investigating the interactive effects between government subsidy policies and the information screening mechanism. By analyzing how these two factors interact, the study aims to elucidate the potential synergies or conflicts between policy interventions and market-driven mechanisms in promoting sustainable EV battery recycling practices. (3) Clarifying the impact of dynamic changes in the

recycler's recycling capability on the overall supply chain dynamics. Understanding how variations in the recycler's capacity and capabilities affect the functioning of the supply chain is crucial for devising robust and adaptive coordination mechanisms that can effectively respond to changing market conditions and technological advancements in EV battery recycling.

The subsequent sections of this paper are structured as follows: Section 2 provides an overview of the existing literature, emphasizing the unique contributions of this study to the field. In Section 3, we delve into the conceptual framework and development of the model, elucidating the key factors and methodologies employed in our analysis. Section 4 is dedicated to the formulation of supply chain models within the framework of incentive mechanisms, outlining the strategic approaches adopted to enhance sustainability and efficiency. Following this, Section 5 offers a comprehensive validation of our findings through numerical analysis, providing empirical support for the conclusions drawn from our model. Lastly, Section 6 encapsulates the key insights and findings of our study, offering a succinct summary of the paper's contributions and implications for future research and practical applications.

2. Literature review

The field of electric vehicle (EV) battery recycling has witnessed significant growth, as evidenced by a burgeoning body of literature (Zhu et al., 2024; Zhang et al., 2022). This research landscape encompasses various dimensions, with a predominant focus on assessing the environmental impact of power battery (Zhang et al., 2023a), evaluating different recycling models (Liu et al., 2022; Yang et al., 2020), and exploring strategies for supply chain coordination (Heydari et al., 2017). For example, Wang et al. (2022) assessed the environmental effects of lithium iron phosphate batteries from cradle to grave. They found that cascade utilization can significantly reduce the environmental impact of power batteries. Furthermore, battery recycling can save more than 30% of metal resources. Lai et al. (2022) pointed out that power battery recycling can mitigate the environmental and resource impact of battery production and have considerable environmental and economic value. As for recycling model selection, Zhang et al. (2023b) conducted a comparative analysis using Stackelberg game theory to assess six different recycling modes. Their findings highlight the superiority of a cooperative recycling approach involving collaboration between battery and automobile manufacturers, demonstrating higher recovery rates, and enhanced social welfare.

To enhance the government's decision-making on regulatory policies for power battery recycling, numerous studies have undertaken comprehensive comparisons of government policies from diverse angles.

Joshi et al. (2021) utilized the system dynamics approach to simulate the efficacy of tax incentives and subsidies in shaping the landscape of used battery recycling within both formal and informal sectors. Their findings underscored the transformative potential of both tax reductions and subsidies, indicating that they facilitate the transition of recyclers from informal to formal sectors, with subsidies particularly enhancing the recovery rates of formal recyclers. Wu et al. (2024a) emphasized the pivotal role of recycling regulations and subsidies in driving manufacturers toward the collection and proper disposal of end-of-life products. Heydari et al. (2017) delved into the impact of government tax exemptions and subsidy policies on enhancing supply chain coordination. Their analysis revealed that these incentive mechanisms bolstered the total profit of the supply chain, with incentives directed towards manufacturers yielding superior results compared to those targeting retailers. In a recent study by Wu et al. (2024ab), an exhaustive examination was conducted on the ramifications of various government subsidy strategies on the decision-making behaviors of all stakeholders within the power battery supply chain. Their analysis elucidated how two distinct subsidy schemes influenced the recovery rates of power batteries for both battery and automobile manufacturers. Remarkably, the study demonstrated that subsidized battery manufacturers achieved higher recovery rates, while subsidized automobile manufacturers contributed to elevated supply chain profits.

Most studies concentrating on supply chain coordination endeavor to mitigate inefficiencies through contractual mechanisms. For instance, Zhang et al. (2023ab) examined contract coordination strategies within supply chains operating under various recycling modes led by battery manufacturers. Their investigation underscored the efficacy of joint-sharing contracts in fostering supply chain coordination, particularly when battery manufacturers participate in revenue sharing for both sales and recycling activities. Liu et al. (2019) delved into the impact of information asymmetry on decision-making among supply chain members and put forward a contract aimed at incentivizing manufacturers to provide accurate information. By aligning incentives with information disclosure, their proposed contract sought to alleviate the negative repercussions of asymmetric information on supply chain operations. Similarly, Liao et al. (2022) devised tailored contractual arrangements to promote collaboration among different types of companies within the supply chain. Their study illustrated that the implementation of bespoke contracts could augment manufacturers' profits, especially in scenarios marked by asymmetric carbon reduction information. Xu et al. (2023b) developed a nonlinear contract to address the issue of information asymmetry regarding product

greenness between the government and enterprises, effectively enhancing the environmental quality of the products. Zhang et al. (2021) designed a dynamic contract to address the information asymmetry in demand between retailers and manufacturers. They found that the quick response, due to its flexibility, consistently benefits manufacturers.

The existing methods to solve information asymmetry mainly rely on designing contracts based on the principal-agent theory to identify information. Among them, price transfer and profit-sharing mechanisms are the two main types of contracts. Price transfer can play a role in incentive and information screening. However, this method is challenging to motivate the agent to make more effort, and the transfer price is generally determined in advance, making it difficult to respond to market uncertainty. Therefore, profit-sharing mechanisms are more commonly used. Profit-sharing mechanisms can be divided into linear and non-linear categories. The linear profit-sharing mechanism is easier to operate and analyze than non-linear ones, so they have been widely used (Liao et al., 2022). Therefore, the linear profit-sharing mechanism is used in this paper to settle the recycling ability information asymmetry between battery manufacturer and recycler. The research conclusions of this paper show that under the coordination of a linear profit-sharing mechanism, recyclers always make more profits by reporting true recycling capabilities than by reporting false information.

In summary, power battery recycling has attracted great attention from scholars, but most studies focus on the technical feasibility, economic and environmental impact of power battery recycling, consumer behavior, and cascade utilization, while only a few studies focus on the asymmetric information of power battery supply chain, and none of them well reflect the characteristics of electric vehicle power batteries. Few studies have considered the impact of government intervention on power battery supply chain decisions, and only a few studies have addressed power battery recycling subsidy policies. In the context of the continuous adjustment of the existing power battery recycling subsidy policy, the impact of this factor on the power battery recycling decision-making should be considered.

3. Problem description and model building

Drawing upon practical insights and existing literature (Hoarau and Lorang, 2022; Jiang et al., 2021), the closed-loop recycling system of EV batteries depicted in Figure 1 is established. The supply chain is mainly composed of battery manufacturer, automobile manufacturer, third-party collection enterprise, and consumer, whose roles in the supply chain operation are as follows:

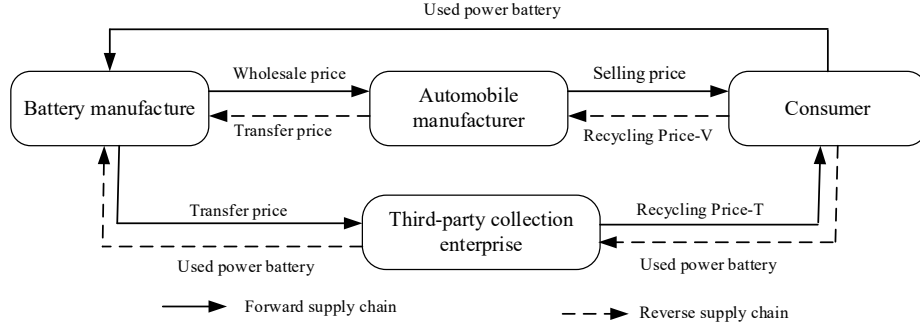
(1) Power battery manufacturer. In the forward supply chain, power battery manufacturer is usually in a dominant position. The major leading companies in the domestic power battery production field include CATL, BYD, and Guoxuan High-tech (Wu et al., 2024ab). They are not only the source of power battery production, but also bear the responsibility of using recycled materials for power battery remanufacturing, and are therefore also the end point of the closed-loop supply chain. They are involved in the entire process from the production of raw materials to the manufacturing, recycling, and reuse of power batteries, ensuring that waste power batteries are fully recycled and reused, thereby achieving effective use of resources and sustainable development of the environment.

(2) Automobile manufacturer. Automobile manufacturers assemble power batteries and other components into complete electric vehicle and ultimately push them to the market through their sales networks so that consumers can purchase and use them. Therefore, automobile manufacturers are not only buyers and users of power batteries in the electric vehicle industry, but also sellers and distributors, and they play an important role in connecting power battery manufacturers and consumers. In the electric vehicle industry, some representative companies include Ideal Auto, Xiaopeng Motors, and NIO.

(3) Third-party collection enterprise. Third-party collection enterprise specializes in recycling retired power batteries from consumers. These companies, such as GEM and Brunp Recycling, are dedicated to collecting waste power batteries and recycling or processing them.

(4) Consumer. As the final user of power batteries, the way consumers deal with used power batteries directly affects environmental protection and resource utilization. If used power batteries are discarded at will, it will lead to environmental pollution and waste of resources.

In all supply chain configurations incorporating remanufacturing, the battery manufacturer possesses significant channel power over both the automobile manufacturer and the third-party collection enterprise, enabling it to assume the role of a Stackelberg leader. As followers, the automobile manufacturer and third-party collection enterprise observe the decisions of the battery manufacturer and respond accordingly.



Source(s): Authors' own creation

Figure 1 EV battery recycling system

The following modeling assumptions are satisfied in this paper.

Assumption 1: Each member in the closed-loop supply chain is completely rational and risk-neutral and makes the optimal decision to maximize their expected profitability.

Assumption 2: The battery manufacturer has incorporated the disassembly and cascade utilization process for end-of-life EV batteries into their original production line to manufacture a new EV battery from raw materials or remanufacture part or whole of a returned unit into a new product (Zhu et al., 2024).

Assumption 3: The remanufactured EVs and new batteries have no difference in appearance. They can be sold at the same price (Zhang et al., 2023b; Wang et al., 2019). Considering the difference in battery size and specification, the EV battery here is assumed to be the same type.

Assumption 4: The profitability per set of EV batteries consists of two parts: $(c_m - c_r) + \eta\tilde{V}$. The first part represents the profit from remanufacturing. The second part is the profit from cascade utilization. η indicates the net cascade utilization profitability per unit EV battery. \tilde{V} is the remaining capacity per unit retired EV battery and complies with normal distribution with mean μ_V and variance σ_V^2 . To guarantee profitability in the remanufacturing process, $\Delta > 0$ needs to be satisfied.

Assumption 5: Referring to Savaskan et al. (2004), the market demand for EV batteries is $D(p) = \phi - \theta p$. ϕ is the primary market demand for EV batteries, θ represents the consumer's sensitivity to EV's selling price.

Assumption 6: The recycling capability C_i is private information of the recycler and there are only two types of recyclers with different capabilities: high-capability recyclers C_H and low-capability recyclers C_L . Before signing a contract, the battery manufacturer observes the recycling activities of the recyclers and concludes that the probabilities of having high-capability recycler C_H and low-capability recycler C_L are

P and 1-P, respectively. Under asymmetric information, C_{ij} denotes the recycler's recycling ability as i and reports as j , where $i, j \sim (H, L)$.

Assumption 7: On the one hand, the recycler needs to pay fixed costs for recycling, including labor costs, warehouse leasing, and transportation costs AS . On the other hand, the recycler needs to pay specific incentives or advertising costs, represented as $\frac{ke^2}{2}$, and k represents the recycling cost coefficient. e represents the effort level of the recycler.

Assumption 8: Factors affecting the EV batteries recycling amount include the recycling capability of the recycler, the effort level of the recycler, the recycling market characteristics, and consumer environmental awareness $S(r) = a + C_i e_{ij} + \varepsilon$. a represents free returns by consumers, C_i represents the true recycling capability of the recycler, e_{ij} represents the effort level of the recycler reporting as j when their actual effort level is i , ε represents the uncertain quantity of the recycling market, which follows a normal distribution with mean 0 and variance σ^2 .

Assumption 9: The battery manufacturer needs help to directly observe detailed market information or understand the capabilities of the recycler. There is asymmetric information between the EV battery manufacturer and the recycler (Zhang et al., 2023b). To incentivize the recycler to recycle, the EV battery manufacturer adopts a linear profit-sharing mechanism to allocate profits as $T_j = s_j + t_j q$. s_j represents the fixed reward, and t_j represents the reward per unit of retired EV battery recycled by the C_j recycling type recycler. In addition, the recycler receives a reservation profit π_0 when they do not participate in the contract coordination. The symbols used in this paper and their meanings are shown in Table 1.

Table 1 Model symbols and meanings

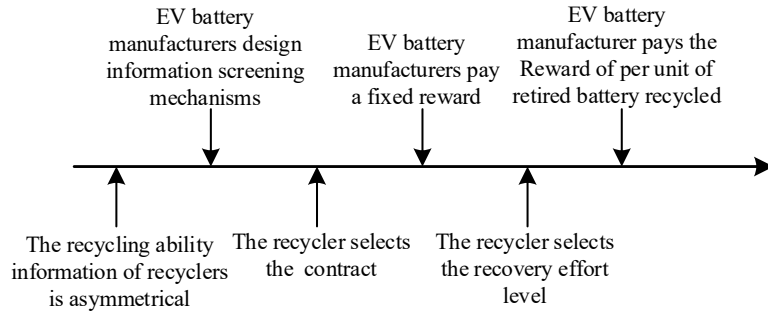
Notation	Meaning	Notation	Meaning
p	Average selling price of power battery	w	Power battery factory price
A	Fixed cost for recycling a single scrap battery	\tilde{V}	Energy storage capacity of scrapped battery pack units
k	Difficulty in recycling retired power batteries	t	Transfer payment price for used power battery
c_m	Power battery unit manufacturing cost	a	Free returns by consumers
c_r	Recycling and remanufacturing costs of retired power battery	Δ	Benefits of cascade utilization of scrapped power battery
r	Waste power battery recycling quotation	ϕ	Market demand for power battery
b	Consumers' price sensitivity to power battery	G	Government subsidies for used batteries per unit capacity
P	Probability of high-capacity recyclers	k	Recycling cost coefficient
η	Net cascade utilization profitability per unit EV battery	θ	Consumer's sensitivity to EV's selling price
e	Effort level of the recycler	s_j	Fixed reward

C_H High-capability recycler	C_L Low-capability recycler
Source(s): Authors' own creation	

4. Contract design

Section 3 provides a detailed description of the research questions addressed in this paper and establishes the corresponding models. This section will also design a contract to mitigate the issue of information asymmetry. Adverse selection arises when recyclers conceal their true recycling capabilities before entering contracts, while moral hazard occurs when recyclers fail to exert maximum effort in recycling activities after contract signing. Battery manufacturers are thus confronted with a dual asymmetry challenge, grappling with both adverse selection and moral hazard issues (Merk et al., 2019; Wagner and Zizzamia, 2022). This paper endeavors to tackle these challenges by exploring the design of contracts that incentivize recyclers to accurately report their actual recycling capacities and to enhance their recycling efforts post-contract signing. By devising contractual mechanisms that align the interests of all stakeholders and mitigate the risks associated with information asymmetry.

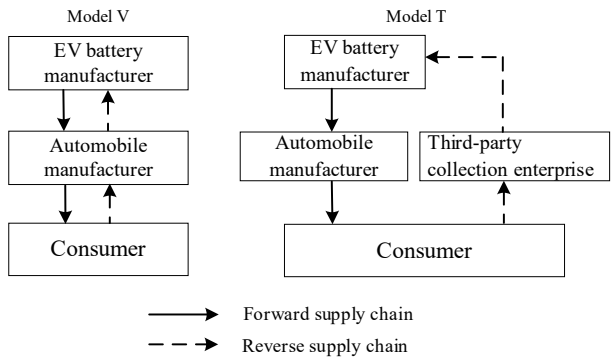
The design of contracts necessitates a nuanced understanding of the various types of recyclers and must encompass mechanisms to incentivize them to fulfill their recycling obligations both before and after contract signing. As depicted in Figure 2, this paper adopts a contract design framework to explore the creation of bespoke contracts tailored to each type of recycler. The overarching objective is to facilitate information screening and incentivize recyclers to intensify their recycling efforts. The contract design process can be conceptualized as a Stackelberg game, wherein the battery manufacturer assumes the role of the leader, strategically devising contracts that anticipate the responses of different types of recyclers. By customizing contract terms and incentives to suit the specific characteristics and capabilities of each recycler type. The detailed contract design mechanism is described below: The EV battery manufacturer first designs a contract (s_j, t_j) based on the reported recycling capabilities C_j of the recyclers. Where s_j represents the fixed remuneration paid to the recycler, and t_j is the reward paid to the recycler for recycling each set of batteries. Then the recyclers select the corresponding contract based on their actual recycling capabilities. Each recycler signs a contract with a fixed compensation s_j based on their true recycling capabilities and chooses an effort level e_{ij} to maximize their interests. The EV battery manufacturer pays a reward t_j to the recycler for each recycled EV battery unit. Finally, the EV battery manufacturer recycles the retired EV batteries for remanufacturing.



Source(s): Authors' own creation

Figure 2 Supply chain decision sequence

When facing recyclers with different recycling abilities, the EV battery manufacturer designs a contract to ensure that the recyclers truthfully report their recycling ability level C_i first. Secondly, the contract design also needs to make recyclers earn more than no contracts. Additionally, to induce the recyclers to adopt the optimal effort level, the contract also needs to satisfy the incentive compatibility constraint. The EV battery manufacturer designs the contract $\{(s_L, t_L), (s_H, t_H)\}$. The expected condition is that low-ability recyclers select the contract (s_L, t_L) designed for low-ability recyclers. Where s_L represents the fixed remuneration paid to the low-ability recycler, and t_j is the reward paid to the low-ability recycler for recycling each set of batteries. And high-ability recyclers choose the contract (s_H, t_H) designed for high-ability recyclers. Where s_H represents the fixed remuneration paid to the high-ability recycler, and t_H is the reward paid to the high-ability recycler for recycling each set of batteries. It indicates that the contract is self-selecting, and recyclers with different recycling abilities not be motivated to pretend to have other types of recycling abilities. Since there are two types of recyclers in practice, automobile manufacturers and third-party collection enterprises, this paper discusses two situations separately, as shown in Figure 3.



Source(s): Authors' own creation

Figure 3 Recovery situation diagram

4.1 Automobile manufacturer recovery situation (Model V)

Based on the assumptions and contract design presented in this article, we will establish the profit functions for each recovery entity in two scenarios: recovery by the automobile manufacturer and recovery by a third-party collection enterprise. The battery manufacturer's profit function can be derived as equation (1). The first part of the profit function of the power battery manufacturer represents the profit of power battery wholesale in the forward supply chain, the second part represents the profit of power battery recycling under high capacity of the recycler in the reverse supply chain, and the third part represents the profit of recycling under low capacity of the recycler.

$$\begin{aligned} \Pi_M^V = & (w - c_m)(\phi - \theta p) + P[(\Delta - t_{VH} + G\tilde{V})(a + C_{VH}e_{VHH} + \varepsilon) - s_{VH}] \\ & + (1 - P)[(\Delta - t_{VL} + G\tilde{V})(a + C_{VL}e_{VLL} + \varepsilon) - s_{VL}] \end{aligned} \quad (1)$$

From Equation (1), we can derive the expected profit for the battery manufacturer, as presented in Equation (2).

$$\begin{aligned} E(\Pi_M^V) = & (w - c_m)(\phi - \theta p) + P[(\Delta - t_{VH} + G\tilde{V})(a + C_{VH}e_{VHH}) - s_{VH}] \\ & + (1 - P)[(\Delta - t_{VL} + G\tilde{V})(a + C_{VL}e_{VLL}) - s_{VL}] \end{aligned} \quad (2)$$

Where C_{VH} indicates the high-ability automobile manufacturer recycler, e_{VHH} represents the high-ability automobile manufacturer making their true effort, t_{VH} represents the reward per unit of EV battery recycled for high-ability automobile manufacturer recycler, t_{VL} represents the reward per unit of EV battery recycled for low-ability automobile manufacturer recycler, G refers to the government subsidy for recycled power batteries per unit capacity, \tilde{V} is the remaining capacity per unit retired EV battery and complies with normal distribution, s_{VH} denotes the fixed reward for high-ability automobile manufacturer recycler, s_{VL} denotes the fixed reward for low-ability automobile manufacturer recycler, P is the probability of high-capacity recyclers.

The profit function and expected profit function of the automobile manufacturer are shown in equations (3) and (4). The first part of the automobile manufacturer's profit function represents the profit from the retail of power batteries in the forward supply chain, the second part represents the profit from the recycling of power batteries in the reverse supply chain, the third part represents the fixed reward for recycling, and the fourth part represents the cost of the recycling effort.

$$\Pi_V^V = (\phi - \theta p)(p - w) + (a + C_i e_{ij} + \varepsilon)(t_j - A) + s_j - \frac{ke_{ij}^2}{2} \quad (3)$$

$$E(\Pi_V^V) = (\phi - \theta p)(p - w) + (a + C_i e_{ij})(t_j - A) + s_j - \frac{ke_{ij}^2}{2} \quad (4)$$

The essence of the contract is to attempt to coordinate the information asymmetry between the EV battery manufacturer and recycler through the contractual agreement. The contract must satisfy the individual participation and incentive compatibility constraints while maximizing the principal's utility. Based on the above analysis, the recycling decision model under the automobile manufacturer recycling scenario can be established as shown in equations (5) to (7). Equation (5) represents the maximization of the profit function of the EV battery manufacturer, equation (6) represents the maximization of the profit function of the automobile manufacturer, and equation (7) represents the condition that the profit obtained by the automobile manufacturer from signing the contract is not less than its reserved profit, which is also a prerequisite for the automobile manufacturer to participate the contract.

$$\begin{aligned} \text{Max}E(\Pi_M^V) = & (w - c_m)(\phi - \theta p) + P[(\Delta - t_{VH} + G\bar{V})(a + C_{VH}e_{VHH}) - s_{VH}] \\ & + (1 - P)[(\Delta - t_{VL} + G\bar{V})(a + C_{VL}e_{VLL}) - s_{VL}] \end{aligned} \quad (5)$$

s. t.

$$\text{Max}E(\Pi_V^V) = (\phi - \theta p)(p - w) + (a + C_i e_{ij})(t_j - A) + s_j - \frac{ke_{ij}^2}{2} \quad (6)$$

$$(\phi - \theta p)(p - w) + (a + C_i e_{ij})(t_j - A) + s_j - \frac{ke_{ij}^2}{2} \geq \pi_0 \quad (7)$$

Equation (8) represents the expected profit of a high-ability recycler reporting as a high-ability recycler, equation (9) represents the expected profit of a high-ability recycler falsely reporting as a low-ability recycler, equation (10) represents the profit of a low-ability recycler reporting as a low-ability recycler, and equation (11) represents the profit of a low-ability recycler falsely reporting as a high-ability recycler.

$$E(\Pi_{VHH}^V) = (\phi - \theta p)(p - w) + (a + C_{VH}e_{VHH})(t_{VH} - A) + s_{VH} - \frac{ke_{VHH}^2}{2} \quad (8)$$

$$E(\Pi_{VHL}^V) = (\phi - \theta p)(p - w) + (a + C_{VH}e_{VHL})(t_{VL} - A) + s_{VL} - \frac{ke_{VHL}^2}{2} \quad (9)$$

$$E(\Pi_{VLL}^V) = (\phi - \theta p)(p - w) + (a + C_{VL}e_{VLL})(t_{VL} - A) + s_{VL} - \frac{ke_{VLL}^2}{2} \quad (10)$$

$$E(\Pi_{VLH}^V) = (\phi - \theta p)(p - w) + (a + C_{VL}e_{VLH})(t_{VH} - A) + s_{VH} - \frac{ke_{VLH}^2}{2} \quad (11)$$

Where C_{VH} indicates the high-ability automobile manufacturer recycler, e_{VHH} represents the high-

ability automobile manufacturer making their true effort, e_{VHL} represents the high-ability automobile manufacturer make less effort, e_{VLL} represents the low-ability automobile manufacturer making their true effort, e_{VLH} represents the low-ability automobile manufacturer making high effort. t_{VH} represents the reward per unit of EV battery recycled for high-ability automobile manufacturer recycler, t_{VL} represents the reward per unit of EV battery recycled for low-ability automobile manufacturer recycler, G refers to the government subsidy for recycled power batteries per unit capacity, \tilde{V} is the remaining capacity per unit retired EV battery and complies with normal distribution, s_{VH} denotes the fixed reward for high-ability automobile manufacturer recycler. The prerequisite for the automobile manufacturer to participate in the contract is that the expected profit from participating in the contract is greater than the expected profit without any contract coordination, i.e., $E(\pi_{VHH}^*) \geq \pi_0$, $E(\pi_{VLL}^*) \geq \pi_0$.

The contract design in automobile manufacturers' recycling situation is shown in equations (12) to (18). Equation (12) represents the maximization of the expected profit of the EV battery manufacturer. Equations (13) and (14) represent the expected profit maximization functions of automobile manufacturers with different recycling abilities. Equations (15) and (16) ensure that it is more advantageous for automobile manufacturers to share truthful information than to report false information. Equations (17) and (18) are the constraint conditions for the automobile manufacturers to accept the contract, ensuring that the profit obtained by the automobile manufacturers after accepting the contract is not less than the profit obtained under the situation without accepting the contract, ultimately ensuring the information screening process.

$$\begin{aligned} \text{Max}E(\Pi_M^V) = & (w - c_m)(\phi - \theta p) + P[(\Delta - t_{VH} + G\tilde{V})(a + C_{VH}e_{VHH}) - s_{VH}] \\ & + (1 - P)[(\Delta - t_{VL} + G\tilde{V})(a + C_{VL}e_{VLL}) - s_{VL}] \end{aligned} \quad (12)$$

s. t.

$$\text{Max}E(\Pi_{VHH}^V) = (\phi - \theta p)(p - w) + (a + C_{VH}e_{VHH})(t_{VH} - A) + s_{VH} - \frac{ke_{VHH}^2}{2} \quad (13)$$

$$\text{Max}E(\Pi_{VLL}^V) = (\phi - \theta p)(p - w) + (a + C_{VL}e_{VLL})(t_{VL} - A) + s_{VL} - \frac{ke_{VLL}^2}{2} \quad (14)$$

$$\begin{aligned} & (\phi - \theta p)(p - w) + (a + C_{VH}e_{VHH})(t_{VH} - A) + s_{VH} - \frac{ke_{VHH}^2}{2} \\ & \geq (\phi - \theta p)(p - w) + (a + C_{VH}e_{VHL})(t_{VL} - A) + s_{VL} - \frac{ke_{VHL}^2}{2} \end{aligned} \quad (15)$$

$$\begin{aligned}
& (\phi - \theta p)(p - w) + (a + C_{VL}e_{VLL})(t_{VL} - A) + s_{VL} - \frac{ke_{VLL}^2}{2} \\
& \geq (\phi - \theta p)(p - w) + (a + C_{VL}e_{VLH})(t_{VH} - A) + s_{VH} - \frac{ke_{VLH}^2}{2}
\end{aligned} \tag{16}$$

$$(\phi - \theta p)(p - w) + (a + C_{VH}e_{VHH})(t_{VH} - A) + s_{VH} - \frac{ke_{VHH}^2}{2} \geq \pi_0 \tag{17}$$

$$(\phi - \theta p)(p - w) + (a + C_{VL}e_{VLL})(t_{VL} - A) + s_{VL} - \frac{ke_{VLL}^2}{2} \geq \pi_0 \tag{18}$$

All the meanings of the above are consistent with those in the above text.

4.2 Third-party collection enterprise recovery situation (Model T)

Under the third-party collection enterprise recovery situation, the battery manufacturer's profit function and expected profit function can be obtained as shown in Equations (19) and (20).

$$\begin{aligned}
\Pi_M^T &= (w - c_m)(\phi - \theta p) + P[(\Delta - t_{TH} + G\bar{V})(a + C_{TH}e_{THH} + \varepsilon) - s_{TH}] \\
&\quad + (1 - P)[(\Delta - t_{TL} + G\bar{V})(a + C_{TL}e_{TLL} + \varepsilon) - s_{TL}]
\end{aligned} \tag{19}$$

$$\begin{aligned}
E(\Pi_M^T) &= (w - c_m)(\phi - \theta p) + P[(\Delta - t_{TH} + G\bar{V})(a + C_{TH}e_{THH}) - s_{TH}] \\
&\quad + (1 - P)[(\Delta - t_{TL} + G\bar{V})(a + C_{TL}e_{TLL}) - s_{TL}]
\end{aligned} \tag{20}$$

The profit function and expected profit function of the automobile manufacturer are shown in equations (21) and (22), respectively.

$$\Pi_V^T = (\phi - \theta p)(p - w) \tag{21}$$

$$E(\Pi_V^T) = (\phi - \theta p)(p - w) \tag{22}$$

The third-party collection enterprise's profit function and expected profit function are shown in formulas (23) and (24), respectively.

$$\Pi_T^T = (a + C_i e_{ij})(t_j - A) + s_j - \frac{ke_{ij}^2}{2} \tag{23}$$

$$E(\Pi_T^T) = (a + C_i e_{ij})(t_j - A) + s_j - \frac{ke_{ij}^2}{2} \tag{24}$$

The expected revenue of the third-party collection enterprise is affected by its recycling ability and whether it truthfully reports its recycling level. Equation (25) represents the expected profit that a high-ability recycler reporting its recycling ability as high. Equation (26) represents the expected profit that a high-ability recycler reporting its recycling ability as low. Equation (27) represents the expected profit that

a low-ability recycler reporting its recycling ability as low. Equation (28) represents the expected profit that a low-ability recycler reporting its recycling ability as high.

$$E(\Pi_{THH}^T) = (a + C_{TH}e_{THH})(t_{TH} - A) + s_{TH} - \frac{ke_{THH}^2}{2} \quad (25)$$

$$E(\Pi_{THL}^T) = (a + C_{TH}e_{THL})(t_{TL} - A) + s_{TL} - \frac{ke_{THL}^2}{2} \quad (26)$$

$$E(\Pi_{TLL}^T) = (a + C_{TL}e_{TLL})(t_{TL} - A) + s_{TL} - \frac{ke_{TLL}^2}{2} \quad (27)$$

$$E(\Pi_{TLH}^T) = (a + C_{TL}e_{TLH})(t_{TH} - A) + s_{TH} - \frac{ke_{TLH}^2}{2} \quad (28)$$

According to the model assumption, it can be known that the expected profit of the recycler under contract coordination is greater than the expected profit without contract coordination, $E(\pi_{THH}^*) \geq \pi_0$, $E(\pi_{TLL}^*) \geq \pi_0$. Based on the above analysis, the decision model for third-party collection enterprise under contract coordination can be obtained, as shown in Equations (29)-(36).

$$\begin{aligned} \text{Max}E(\Pi_M^T) = & (w - c_m)(\phi - \theta p) + P[(\Delta - t_{TH} + G\bar{V})(a + C_{TH}e_{THH}) - s_{TH}] \\ & + (1 - P)[(\Delta - t_{TL} + G\bar{V})(a + C_{TL}e_{TLL}) - s_{TL}] \end{aligned} \quad (29)$$

s. t.

$$\text{Max}E(\Pi_V^T) = (\phi - \theta p)(p - w) \quad (30)$$

$$\text{Max}E(\Pi_{THH}^T) = (a + C_{TH}e_{THH})(t_{TH} - A) + s_{TH} - \frac{ke_{THH}^2}{2} \quad (31)$$

$$\text{Max}E(\Pi_{TLL}^T) = (a + C_{TL}e_{TLL})(t_{TL} - A) + s_{TL} - \frac{ke_{TLL}^2}{2} \quad (32)$$

$$\begin{aligned} & (a + C_{TH}e_{THH})(t_{TH} - A) + s_{TH} - \frac{ke_{THH}^2}{2} \\ & \geq (a + C_{TH}e_{THL})(t_{TL} - A) + s_{TL} - \frac{ke_{THL}^2}{2} \end{aligned} \quad (33)$$

$$\begin{aligned} & (a + C_{TL}e_{TLL})(t_{TL} - A) + s_{TL} - \frac{ke_{TLL}^2}{2} \\ & \geq (a + C_{TL}e_{TLH})(t_{TH} - A) + s_{TH} - \frac{ke_{TLH}^2}{2} \end{aligned} \quad (34)$$

$$(a + C_{TH}e_{THH})(t_{TH} - A) + s_{TH} - \frac{ke_{THH}^2}{2} \geq \pi_0 \quad (35)$$

$$(a + C_{TL} e_{LL})(t_{TL} - A) + s_{TL} - \frac{ke_{TLL}^2}{2} \geq \pi_0 \quad (36)$$

Equation (29) represents the optimal decision function for the battery manufacturer. Equation (30) represents the optimal decision function for the automobile manufacturer. Equations (31) and (32) ensure that third-party collection enterprise with different capabilities make optimal efforts. Equations (33) and (34) ensure that it is more advantageous for recyclers to share truthful information rather than misreport it. Equations (35) and (36) are the constraints that third-party collection enterprise accept the contract.

4.3 The effectiveness of contract coordination

This paper has designed the coordination mechanism in the EV battery recycling closed chain. However, it is not confirmed the effectiveness of the mechanism in solving the information asymmetry problems. Therefore, we further examined the effectiveness of the information screening mechanism in the EV battery recycling closed chain from different perspectives.

Proposition 1 In the closed-loop supply chain under information asymmetry, the reward per unit EV battery recycled will increase with the government subsidy. In addition, government subsidies can encourage the recycler to make more effort in recycling.

Proposition 1 shows that the government subsidy policy can not only strengthen the effect of the contract by increasing recycling incentives but also promote recyclers to make more efforts. Therefore, the government can enhance the performance of the contract. This is because government subsidies directly increase the economic benefits of recyclers, making recycling activities more economically attractive. The increased income can offset the costs incurred during the recycling process, thereby increasing the overall benefits of recyclers.

Proposition 2 In a closed-loop supply chain of power battery recycling with asymmetric information, regardless of whether the recycler is a vehicle manufacturer or a third-party recycler, the power battery manufacturer's contractual reward to the recycler for each unit of retired power battery recycled is the same, and the fixed remuneration to the vehicle manufacturer in the contractual contract is smaller than the fixed remuneration to the third-party recycler.

Proposition 2 indicates that under the incentive mechanism, the automobile manufacturer and the third-party collection enterprise receive the same reward per unit of EV battery recycled. However, the automobile manufacturer's fixed reward is lower than that of the third-party collection enterprise. It is because the EV battery manufacturer cooperates with the automobile manufacturer in the forward and

reverse supply chains. While EV battery manufacturer cooperates with the third-party collection enterprise only in the reverse supply chain. A lower fixed reward for the automobile manufacturer can achieve the same incentive effect as for the third-party collection enterprise.

Proposition 3 Under contract coordination, whether the automobile manufacturer recycles or the third-party collection enterprise recycles, it is more profitable for low-ability recyclers to truthfully report their recycling ability. In contrast, high-ability recyclers have the same profit from falsely reporting information and truthfully reporting information. With the increasement in the proportion of high-ability recyclers in the market, the profit of recyclers who falsely report their recycling ability will decrease. The reward per unit of EV battery recycled received by high-ability recyclers has no relationship with the proportion of high-ability recyclers in the market. However, the reward per unit EV battery recycled received by low-ability recyclers will decrease with the higher proportion of high-ability recyclers in the market.

Proposition 4 Increase the reward per unit EV battery recycled, and the recycler will be inspired to make more effort. In addition, the recycling effort of the recycler will increase with their recycling ability. The reward per unit EV battery recycled for low-ability recyclers increases with their recycling ability. The reward of per unit EV battery recycled for high-ability recyclers will not change with their recycling ability.

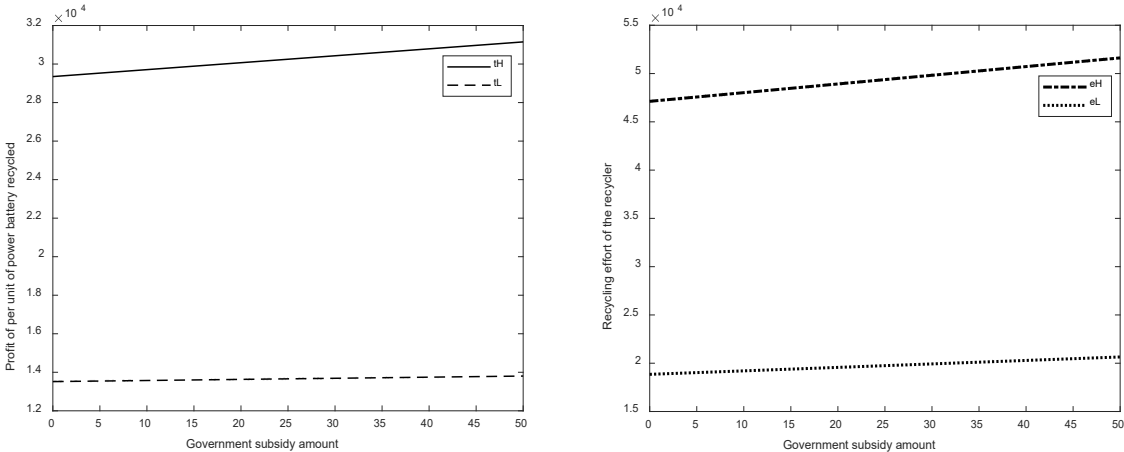
Proposition 5 As the proportion of high-ability recyclers increases, the total profits of high-ability and low-ability recyclers will decrease. The profit of cattery manufacturer is influenced by the proportion of recycling ability types of recyclers in the market. The higher the proportion of high-ability recyclers, the greater the profit of Battery manufacturer. Conversely, the higher the proportion of low-ability recyclers, the smaller the profit of Battery manufacturer.

5. Numerical analysis

The previous section analyzed the theoretical design and effects of contract coordination. This section will further verify the propositions through numerical examples, incorporating actual market operations and dynamic changes. Referring to existing literature and combining with practical experience, we set the parameters as follows: Take the best-selling model BYD Song as an example, its battery capacity is 59kWh. Decommissioned batteries usually have 60% remaining capacity (Zhang et al., 2023b), and the average profitability of cascade utilization is 304 yuan /kWh (Lin et al., 2023), so the profitability of cascade utilization per unit of EV battery is $59 \times 0.8 \times 304 = 14349$ yuan. The manufacturing cost using raw materials is $c_m = 82000$ yuan (Zhang et al., 2022). The unit cost of remanufacturing the recycled battery into a new

battery is $c_r=67000$ yuan (Kamath et al., 2023). Therefore, the total revenue per unit of waste battery recycling $\Delta=(82000-67000)+14349=29349$ yuan. The market demand for electric vehicles is $\phi=300000$ (Tang et al., 2019). According to the study by Wu et al. (2024a), the price sensitivity coefficient of consumers to power batteries is $\theta=1.6$, recovery cost coefficient $k=1.1$. The retained revenue of the recycler under the non-recycling contract is $\pi_0=13$ (Wang et al., 2023b). The recycling capability of high-ability recyclers $C_H=5$ and low-ability recyclers $C_L=2$ (Wang et al., 2017). After setting the above parameters, this paper uses Matlab software to perform sensitivity analysis on key parameters and observe the dynamic impact of changes in key parameters on the system.

Figure 4 (a) is plotted with the government subsidy amount as the horizontal axis and the reward per unit EV battery recycled as the vertical axis. In the figure, the solid line t_H represents the reward for high-capacity recyclers for recycling each set of power batteries, while the dashed line t_L indicates the reward for low-capacity recyclers for recycling each set of power batteries. Figure 4 (b) is plotted with the government subsidy amount as the horizontal axis and the recycling effort of recyclers as the vertical axis, which describes the optimal recycling effort level of recyclers against the government subsidy amount. e_H and e_L represent the recycling effort levels of high-capacity recyclers and low-capacity recyclers, respectively. As shown in Figure 4 (a), as the increase of the reward per unit of EV battery recycled received by high-ability and low-ability recyclers from min to max, the subsidy amount increases by 20000 yuan. Similarly, Figure 4 (b) illustrates that recyclers' recycling effort also increases with the subsidy amount, as government subsidies for excess capacity increased from 0 to 50, the recycling efforts of high-capacity recyclers rose from 47,500 to 52,500, while those of low-capacity recyclers increased from 17,500 to 21,000. This confirms Proposition 1.



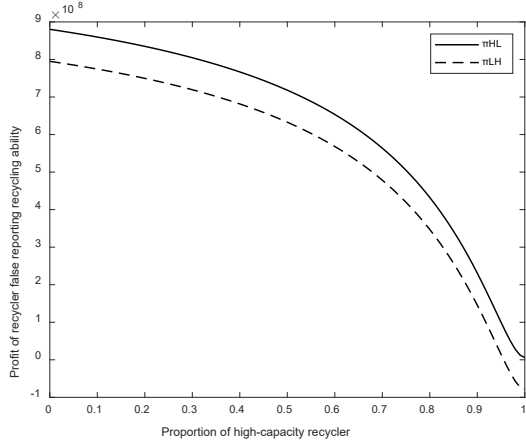
(a) Reward of per unit EV battery recycled change with a subsidy amount (b) The variation of recycling effort with changes in subsidy amount

Source(s): Authors' own creation

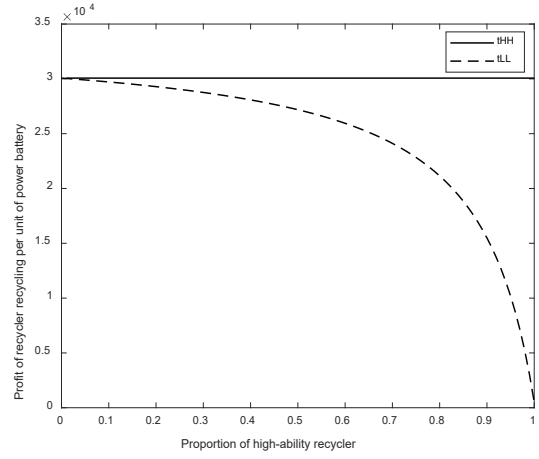
Figure 4 The variation of reward of per unit EV battery recycled and recycling effort with changes in subsidy amount

Figure 5 (a) shows the change in recyclers' total profits who report false recycling ability with the proportion of high-ability recyclers. In the figure, the horizontal axis represents the variation in the proportion of high-capacity recyclers, while the vertical axis indicates the profit level of recyclers misreporting their recycling capabilities. The solid line π_{HL} represents the profit of high-capacity recyclers misreporting as low-capacity recyclers, while π_{HL} represents the profit of low-capacity recyclers misreporting as high-capacity recyclers. As the proportion of high-ability recyclers increases from 0 to 1, the profits obtained by recyclers who report false recycling ability decrease from 9×10^8 and 8×10^8 to 0. Proposition 3 is examined. For low-ability recyclers who report falsely as high-ability, the increased proportion of high-ability recyclers intensifies competition, thus their profits decrease. On the other hand, for high-ability recyclers reporting falsely as low-ability, the increased proportion of high-ability recyclers leads to decreased competitiveness for low-ability recyclers, resulting in a decrease in their recycling profits.

Figure 5 (b) illustrates the change in recyclers' reward per unit EV battery recycled with the change in the proportion of high-ability recyclers. The horizontal axis represents the proportion of high-capacity recyclers, while the vertical axis indicates the revenue from recycling each set of power batteries. In the figure, the solid line t_{HH} represents the share received by high-capacity recyclers when reporting as high-capacity, while t_{LL} represents the share received by low-capacity recyclers when reporting as low-capacity. It can be concluded that the reward per unit EV battery recycled by high-ability recyclers does not change with the increasement in the proportion of high-ability recyclers. However, the reward per unit of EV battery recycled by low-capacity recyclers decreases from 30,000 to 0 as the proportion of high-capacity recyclers increases from 0 to 1. The result is consistent with Proposition 3. It is because more high-ability recyclers will be entrusted, and less reward will be given to low-ability recyclers.



(a) False reporting recycling ability recycler's profit



(b) Recyclers' reward per unit EV battery recycled

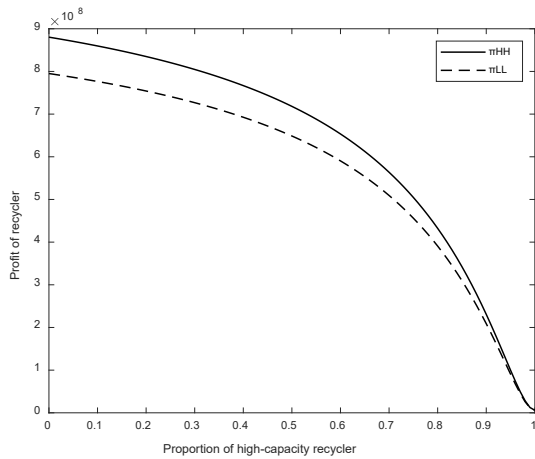
Source(s): Authors' own creation

Figure 5 The change of false reporting recycling ability recycler's profit and recyclers' reward per unit EV battery recycled with the change of proportion of high-ability recyclers

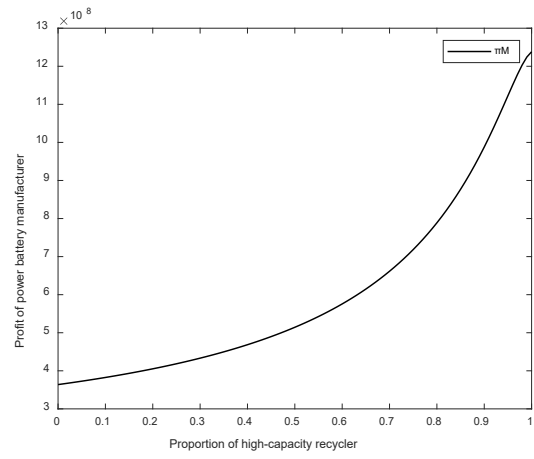
Figure 6 (a) displays the change in recyclers' total profits who report true recycling ability with the proportion of high-ability recyclers. The horizontal axis represents the proportion of high-capacity recyclers, while the vertical axis indicates the profit level of the recyclers. π_{HH} represents the profit level of high-capacity recyclers reporting as high-capacity, while π_{LL} indicates the profit level of low-capacity recyclers reporting as low-capacity. It can be concluded that as the proportion of high-capacity recyclers increases from 0 to 1, the total profits of high-capacity recyclers and low-capacity recyclers decrease from 9×10^8 and 8×10^8 to 0, respectively. The competition among high-ability recyclers will intensify due to the higher proportion of high-ability recyclers. As a result, and total profits of high-ability recyclers will decrease due to the intensification of competition. For low-ability recyclers, their recycling market will be occupied by high-recycler. In addition, their reward of per unit EV battery recycled also decreased. Therefore, the total profit of low-ability recyclers will decrease. Proposition 3 is confirmed.

Figure 6 (b) shows the change in the EV manufacturer's total profits with the proportion of high-ability recyclers. In this case, the horizontal axis represents the proportion of high-capacity recyclers, while the vertical axis indicates the profit level of battery manufacturers. The curve π_M in the figure represents the total profits of EV manufacturers. The results indicate that increasing the proportion of high-capacity recyclers from 0 to 1 raises the total profit of electric vehicle manufacturers from 4×10^8 to 12×10^8 . It is because less reward will be given to recyclers due to the increasement in the proportion of high-ability

recyclers. Proposition 5 is confirmed.



(a) Recyclers' total profits who report true recycling ability



(b) EV manufacturer's total profits

Source(s): Authors' own creation

Figure 6 The change of the recyclers' total profits who report true recycling ability and EV manufacturer's total profits with the proportion of high-ability recyclers

Table 2 is intended to provide a clear presentation of the key points associated with each proposition, along with the supporting empirical evidence, thereby facilitating a more efficient understanding of the main findings of the research for the readers.

Table 2 Summarizes of propositions

Proposition	Contents	Figure
Proposition 1	The reward per unit EV battery recycled and recycler's effort will increase with the government subsidy	Figure 4
Proposition 2	Reward to the recycler for each unit of battery recycled is the same, and the fixed remuneration to the vehicle manufacturers smaller than the third-party recycler.	
Proposition 3	Contractual coordination can motivate recyclers to truthfully report their actual recycling ability	Figure 5, Figure 6 (a)
Proposition 4	Contracts can inspire low-ability recyclers to improve their recycling ability	
Proposition 5	Promoting the recycling ability of recyclers is beneficial for the recycling profits	Figure 6 (b)

Source(s): Authors' own creation

6. Conclusions

This paper delves into the intricate supply chain coordination challenges stemming from asymmetric information regarding recyclers' recycling capabilities and efforts within the power battery recycling supply chain. Drawing upon insights from principal-agent theory, the paper constructs distinct information screening mechanisms tailored to scenarios where the recycler is either the automobile manufacturer or a

third-party entity. Through rigorous modeling and analysis, the optimal solutions for decision variables are derived, shedding light on effective strategies for addressing information asymmetry and enhancing supply chain coordination. Upon solving the model, the paper conducts comprehensive comparisons and analyses of the obtained results, providing insights into the effectiveness and implications of different information screening mechanisms across various supply chain configurations. Furthermore, the conclusions drawn from the analysis are validated through illustrative examples, bolstering the robustness and applicability of the proposed approaches.

The key findings of this study can be summarized as follows: The findings of Wang et al. (2017) suggest that information screening contracts can help manufacturers assess the recycling efforts of retailers. This study's results indicate that information screening mechanisms are crucial tools for automotive manufacturers and third-party collection companies, enabling them to accurately evaluate and disclose their recycling capabilities. By promoting transparency and accountability, these mechanisms can enhance trust and facilitate effective coordination within the supply chain. Government subsidy policies can complement information screening mechanisms by incentivizing recyclers to enhance their recycling efforts. Increasing the rewards for recycling each unit of electric vehicle batteries provides tangible incentives for recyclers to maximize their recycling activities, thereby amplifying the impact of information screening mechanisms on supply chain coordination and efficiency. This conclusion supports the role of government subsidies in addressing information asymmetry and is consistent with the findings of Song and Wang (2022). Under the optimal coordination of information screening mechanisms, recyclers benefit more from accurately reporting their recycling levels than from making false statements. Honest reporting fosters trust and collaboration among supply chain partners, ultimately leading to better outcomes for all stakeholders. This conclusion aligns with the findings of Wu et al. (2021). Consistent with the findings of Yang et al. (2018) regarding the heterogeneous effects of principal-agent contracts on different types of recyclers, this study reveals that in an optimally coordinated information screening mechanism, market dynamics indicate that as the proportion of high-capacity recyclers increases, the rewards received by low-capacity recyclers for each unit of electric vehicle battery recycled decrease. Consequently, the total profits of low-capacity recyclers diminish, while the profits of high-capacity recyclers may also decline due to intensified competition. However, as market dynamics evolve, the overall profits of power battery manufacturers tend to increase.

Consistent with the research of Chandra et al. (2023) on mechanisms that enhance supply chain recycling efficiency, the study finds that under an optimal information screening mechanism, increasing the rewards for recycling each unit of electric vehicle batteries effectively incentivizes recyclers to intensify their efforts. Recyclers with greater capacity are inherently more inclined to leverage these incentives, contributing to improved overall recycling performance within the supply chain. The improvement in the recycling capabilities of low-capacity recyclers leads to an increase in the rewards for recycling each unit of electric vehicle batteries, motivating them to enhance their recycling processes. In contrast, for high-capacity recyclers, the rewards for recycling each unit are unaffected by changes in their recycling capabilities, as they are already operating at optimal efficiency. Cheng et al. (2024) also suggest designing differentiated contracts for different types of firms to eliminate double marginalization in their study. Regarding the interactions of changes in recycling capabilities among recyclers, the growth in the recycling capabilities of low-capacity recyclers does not affect the rewards high-capacity recyclers receive for recycling each unit of electric vehicle batteries. Conversely, the rewards for low-capacity recyclers decrease as the recycling capabilities of high-capacity recyclers increase. This finding is consistent with the study by Li et al. (2019).

Based on the above conclusions, the following management implications can be drawn:

(1) Enhance Transparency and Accountability: The government should promote the implementation of robust information screening mechanisms within the power battery recycling supply chain. This can be achieved by standardizing reporting practices and encouraging both automobile manufacturers and third-party recyclers to adopt transparent disclosure of their recycling capabilities. Providing guidelines and support for these practices will foster trust and facilitate better coordination among supply chain partners.

(2) Implement Targeted Subsidy Programs: To maximize the effectiveness of recycling efforts, the government should design targeted subsidy programs that reward recyclers based on their performance in recycling electric vehicle (EV) batteries. By increasing the reward per unit recycled, the government can incentivize recyclers, particularly those with lower capabilities, to enhance their recycling processes and efficiency. This will not only boost overall recycling rates but also align with the goals of the information screening mechanism.

(3) Encourage Collaboration Among Recyclers: The government should foster collaboration and knowledge-sharing among recyclers, particularly between high-ability and low-ability recyclers. By

creating platforms for partnerships, workshops, and joint initiatives, low-ability recyclers can learn best practices and innovative techniques from their more experienced counterparts. This collaborative approach can help elevate the overall recycling capabilities within the supply chain, leading to improved efficiency and effectiveness in recycling operations.

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Competing interests

The authors declare no competing interests.

Data availability statement

The datasets generated during and analyzed during the current study are available from the corresponding author upon reasonable request.

Ethical Approval

This work does not require any ethical approval.

Consent to Participate

Not applicable.

Consent to Publish

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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Solution to Models

(1) Automobile manufacturer recycling situation

When the automobile manufacturer undertakes to recycle work, the EV battery manufacturer acts as the leader in the supply chain. The decision sequence of the model is as follows: Firstly, the EV battery manufacturer gives the batteries' wholesale price w ; Then, automobile manufacturers give selling prices based on battery prices and costs. The EV battery manufacturer provides the automobile manufacturer with a fixed recycling incentive, s_{VH} , and s_{VL} . The recycling efforts of automobile manufacturers are respectively e_{VHH} and e_{VLL} based on the contract and maximizing their interests. The EV battery manufacturer provides reward t_{VH} , and t_{VL} per unit of EV batteries recycled.

Recyclers with different recycling capacities determine their effort levels based on the contracts they choose to maximize their interests. Using the inverse induction method, the optimal effort levels for recyclers with true recycling abilities of C_{VH}^V and C_{VL}^V can be obtained respectively as $e_{VHH}^{V*} = \frac{C_{VH}^V(t_{VH}-A)}{k}$ and $e_{VLL}^{V*} = \frac{C_{VL}^V(t_{VL}-A)}{k}$. The optimal effort level is $e_{VHL}^* = \frac{C_{VH}^V(t_{VL}-A)}{k}$ for C_{VH}^V recycling ability type recycler who report as C_{VL}^V . Similarly, the optimal effort level is $e_{VLH}^* = \frac{C_{VL}^V(t_{VH}-A)}{k}$ for C_{VL}^V recycling ability type recyclers who report as C_{VH}^V . The original model can be transformed by substituting these values into the objective function, as shown in equations (37)-(41).

$$\begin{aligned} \text{Max}E(\Pi_M^V) = & (w - c_m)(\phi - \theta p) + P[(\Delta - t_{VH} + G^{\square})(a + \frac{C_{VH}^2(t_{VH}-A)}{k}) - s_{VH}] \\ & + (1 - P)[(\Delta - t_{VL} + G^{\square})(a + br + \frac{C_{VL}^2(t_{VL}-A)}{k}) - s_{VL}] \end{aligned} \quad (37)$$

s. t.

$$\begin{aligned} (\phi - \theta p)(p - w) + (a + \frac{C_{VH}^2(t_{VH}-A)}{k})(t_{VH} - A) + s_{VH} - \frac{C_{VH}^2(t_{VH}-A)^2}{2k} & \geq \\ (\phi - \theta p)(p - w) + (a + br + \frac{C_{VH}^2(t_{VL}-A)}{k})(t_{VL} - A) + s_{VL} - \frac{C_{VH}^2(t_{VL}-A)^2}{2k} & \end{aligned} \quad (38)$$

$$(\phi - \theta p)(p - w) + (a + br + \frac{C_{VL}^2(t_{VL} - A)}{k})(t_{VL} - A) + s_{VL} - \frac{C_{VL}^2(t_{VL} - A)^2}{2k} \geq \quad (39)$$

$$(\phi - \theta p)(p - w) + (a + \frac{C_{VL}^2(t_{VH} - r - A)}{k})(t_{VH} - A) + s_{VH} - \frac{C_{VL}^2(t_{VH} - A)^2}{2k}$$

$$(\phi - \theta p)(p - w) + (a + \frac{C_{VH}^2(t_{VH} - r - A)}{k})(t_{VH} - A) + s_{VH} - \frac{C_{VH}^2(t_{VH} - A)^2}{2k} \geq \pi_0 \quad (40)$$

$$(\phi - \theta p)(p - w) + (a + \frac{C_{VL}^2(t_{VL} - r - A)}{k})(t_{VL} - A) + s_{VL} - \frac{C_{VL}^2(t_{VL} - A)^2}{2k} \geq \pi_0 \quad (41)$$

According to Equations (38) and (41), we can obtain

$$\begin{aligned} & (\phi - \theta p)(p - w) + (a + \frac{C_{VH}^2(t_{VH} - A)}{k})(t_{VH} - A) + s_{VH} - \frac{C_{VH}^2(t_{VH} - A)^2}{2k} \\ & \geq (\phi - \theta p)(p - w) + (a + \frac{C_{VH}^2(t_{VL} - A)}{k})(t_{VL} - A) + s_{VL} - \frac{C_{VH}^2(t_{VL} - A)^2}{2k} \\ & = (\phi - \theta p)(p - w) + (a + \frac{C_{VL}^2(t_{VL} - A)}{k})(t_{VL} - A) + s_{VL} + \frac{C_{VL}^2(t_{VL} - A)^2}{2k} + \frac{(C_{VH}^2 - C_{VL}^2)(t_{VL} - A)^2}{2k} \\ & \geq \pi_0 + \frac{(C_{VH}^2 - C_{VL}^2)(t_{VL} - A)^2}{2k} \end{aligned}$$

Using the Lagrange multiplier method to solve for the parameters. Introducing Lagrange factors λ , μ , and γ corresponding to equations (38), (39), and (41), the following Kuhn-Tucker optimality conditions from equations (42) to (45) can be obtained:

$$\frac{\partial L}{\partial s_{VH}} = -P + \lambda - \mu = 0 \quad (42)$$

$$\frac{\partial L}{\partial s_{VL}} = -(1 - P) - \lambda + \mu + \gamma = 0 \quad (43)$$

$$\frac{\partial L}{\partial t_{VH}} = P[-(a + \frac{C_{VH}^2(t_{VH} - A)}{k}) + \frac{(\Delta - t_{VH} + G\bar{V})C_{VH}^2}{k}] + \lambda[\frac{C_{VH}^2(t_{VH} - A)}{k} + a + br] - \mu[a + \frac{C_{VL}^2(t_{VH} - A)}{k}] = 0 \quad (44)$$

$$\begin{aligned} \frac{\partial L}{\partial t_{VL}} &= (1 - P)[-(a + \frac{C_{VL}^2(t_{VL} - A)}{k}) + \frac{(\Delta - t_{VL} + G\bar{V})C_{VL}^2}{k}] - \lambda[\frac{C_{VH}^2(t_{VL} - A)}{k} + a] \\ &+ \mu[(a + \frac{C_{VL}^2(t_{VL} - A)}{k})] + \gamma[(a + \frac{C_{VL}^2(t_{VL} - A)}{k})] = 0 \end{aligned} \quad (45)$$

Based on equations (41) and (42), we know that $\gamma = 1 > 0$ and $\mu + P > 0$. Furthermore, from the Kuhn-Tucker optimality conditions, we can conclude that $\mu = 0$. Since $\gamma = 1 > 0$, equation (40) holds with equality, and thus equation (46) can be derived:

$$E(\pi_{VLL}^*) = \pi_0 \quad (46)$$

From the values of λ , μ , γ and equations (43), the optimal reward value per unit EV battery recycled

for high-ability recycler can be described as equation (47):

$$t_{VH}^* = \Delta + G\tilde{V} \quad (47)$$

From equation (44), the optimal reward value per unit of EV battery recycled for a low-ability recycler can be expressed by equation (48):

$$t_{VL}^* = \frac{C_{VL}^2(G\tilde{V}+\Delta)(1-P)+PA(C_{VH}^2-C_{VL}^2)}{PC_{VH}^2-C_{VL}^2(2P-1)} \quad (48)$$

From equation (45), the optimal fixed reward value for a low-ability recycler can be expressed by equation (49):

$$s_{VL}^* = \pi_0 + \frac{C_{VL}^2(t_{VL}^*-A)^2}{2k} - (t_{VL}^*-A)\left[a + \frac{C_{VL}^2(t_{VL}^*-A)}{2k}\right] - (\phi - \theta p)(p - w) \quad (49)$$

Because $\lambda = P > 0$, equation (38) is an equal sign. Combine with t_{VH}^* , t_{VL}^* , and s_{VL}^* , the optimal fixed reward value for a high-ability recycler can be expressed by equation (49):

$$s_{VH}^* = s_{VL}^* + a(t_{VL}^* - t_{VH}^*) + \frac{C_{VH}^2(t_{VL}^*-A)^2}{2k} - \frac{C_{VH}^2(t_{VH}^*-A)^2}{2k} \quad (50)$$

According to equation (42), the selling price response function can be derived as equation (51):

$$p^{v_i} = \frac{\phi + \theta w}{2\theta} \quad (51)$$

Substituting the response function into equation (41), the optimal wholesale price and retail price are given by equations (52) and (53), respectively:

$$w^{v^*} = \frac{\phi + \theta c_m}{2\theta} \quad (52)$$

$$p^{v^*} = \frac{3\phi + \theta c_m}{4\theta} \quad (53)$$

(2 Third-party collection enterprise recycling situation

In a closed-loop supply chain in which third-party collection enterprise are responsible for the recycling work; the EV battery manufacturer takes a leading position in the supply chain. The decision sequence of the model is as follows: The EV battery manufacturer provides a fixed recycling incentive, s_{TH} , and s_{TL} , to the third-party collection enterprise, and the third-party collection enterprise determines the optimal effort levels, e_{THH} and e_{TLL} , based on the contract and their interests; the EV battery manufacturer provides the unit recycling reward, t_{TH} , and t_{TL} , to the recyclers.

Under information asymmetry, recyclers with different abilities determine their effort levels that

maximize their interests based on their chosen contracts. By using the backward induction method, we can obtain the optimal effort levels of the recyclers with true recycling abilities of C_{TH} and C_{TL} , respectively, as $e_{THH}^* = \frac{C_{TH}(t_{TH}-A)}{k}$, and $e_{TLL}^* = \frac{C_{TL}(t_{TL}-A)}{k}$. Meanwhile, the recycler with the actual recycling ability of C_H but reports C_L chooses the contract (s_{TL}, t_{TL}) to maximize their interests, their optimal effort level is $e_{THL}^* = \frac{C_{TH}(t_{TL}-A)}{k}$. Similarly, a recycler with the actual recycling ability of C_{TL} but reports C_{TH} chooses the contract (s_{TH}, t_{TH}) to maximize their interests, their optimal effort level is $e_{TLH}^* = \frac{C_{TL}(t_{TH}-A)}{k}$. The original model can be transformed into equations (54)-(58) by substituting these results into the objective function.

$$\begin{aligned} \text{Max}E(\Pi_M^T) = & (w - c_m)(\phi - \theta p) + P[(\Delta - t_{TH} + G\bar{V})(a + \frac{C_{TH}^2(t_{TH}-r-A)}{k}) - s_{TH}] + (1-P)[(\Delta - t_{TL} + G\bar{V}) \\ & (a + \frac{C_{TL}^2(t_{TL}-A)}{k}) - s_{TL}] \end{aligned} \quad (54)$$

s. t.

$$\begin{aligned} & (a + br + \frac{C_{TH}^2(t_{TH}-r-A)}{k})(t_{TH} - A) + s_{TH} + \frac{C_{TH}^2(t_{TH}-A)^2}{2k} \\ & \geq (a + \frac{C_{TH}^2(t_{TL}-A)}{k})(t_{TL} - A) + s_{TL} + \frac{C_{TH}^2(t_{TL}-A)^2}{2k} \end{aligned} \quad (55)$$

$$\begin{aligned} & (a + \frac{C_{TL}^2(t_{TL}-r-A)}{k})(t_{TL} - A) + s_{TL} + \frac{C_{TL}^2(t_{TL}-A)^2}{2k} \\ & \geq (a + \frac{C_{TL}^2(t_{TH}-A)}{k})(t_{TH} - A) + s_{TH} + \frac{C_{TL}^2(t_{TH}-A)^2}{2k} \end{aligned} \quad (56)$$

$$(a + \frac{C_{TH}^2(t_{TH}-A)}{k})(t_{TH} - A) + s_{TH} + \frac{C_{TH}^2(t_{TH}-A)^2}{2k} \geq \pi_0 \quad (57)$$

$$(a + \frac{C_{TL}^2(t_{TL}-A)}{k})(t_{TL} - A) + s_{TL} + \frac{C_{TL}^2(t_{TL}-A)^2}{2k} \geq \pi_0 \quad (58)$$

Using the same calculation method as that for the automobile manufacturer recycling case, the expected profit function of a low-ability third-party collection enterprise, which accurately reports its recycling capacity, is given by equation (59):

$$E(\pi_{TLL}^*) = \pi_0 \quad (59)$$

In the context of information asymmetry, a third-party collection enterprise is entrusted with recycling, and the optimal contract $\{(s_{TL}, t_{TL}), (s_{TH}, t_{TH})\}$ designed by the battery manufacturer for high-ability and low-ability recyclers is given by equations (60)-(63):

$$t_{TH}^* = \Delta + G\bar{V} \quad (60)$$

$$t_{TL}^* = \frac{C_{VL}^2(G\bar{V} + \Delta)(1-P) + PA(C_{VH}^2 - C_{VL}^2)}{PC_{VH}^2 - C_{VL}^2(2P-1)} \quad (61)$$

$$s_{TL}^* = \pi_0 + \frac{C_{VL}^2(t_{TL}^* - A)^2}{2k} - (t_{TL}^* - A)[a + \frac{C_{VL}^2(t_{TL}^* - A)}{2k}] \quad (62)$$

$$s_{TH}^* = s_{TL}^* + a(t_{TL}^* - t_{TH}^*) + \frac{C_{TH}^2(t_{TL}^* - A)^2}{2k} - \frac{C_{TH}^2(t_{TH}^* - A)^2}{2k} \quad (63)$$

Under the scenario of third-party battery recycling, the optimal wholesale and selling prices for electric vehicle batteries are shown in equations (64) and (65), respectively.

$$w^{T*} = \frac{\phi + \theta c_m}{2\theta} \quad (64)$$

$$p^{T*} = \frac{3\phi + \theta c_m}{4\theta} \quad (65)$$