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A decision-making model for echelon utilization of retired batteries in competitive duopoly: the role of government subsidy

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Abstract

As the wave of retirements in the new energy vehicle sector approaches, China's emphasis on echelon utilization has grown to optimize battery reuse and recycling. However, the burgeoning industry will inevitably face the challenges of competition, influencing stakeholders across the supply chain. In this study, we employ game theoretic models to investigate the interplay between competitive dynamics and government subsidy policies within this industry. Through the development of a competitive duopoly echelon utilization supply chain model, our analysis offers valuable insights and recommendations for the advancement of the industry. We find that increases in echelon utilization costs prompt adjustments in retail prices by echelon utilization enterprises, third-party recyclers, and new energy vehicle manufacturers. As competition intensifies, overall supply chain profitability diminishes, resulting in a lose-lose situation, favoring only third-party recyclers, who raise wholesale prices as new energy vehicle manufacturers reduce transfer payments. Conversely, government subsidies stimulate higher total demand, benefiting subsidized echelon utilization enterprises, which enhance consumer and social value. Non-subsidized enterprises are compelled to raise retail prices. Given the positive impact of subsidies, governments should prioritize support for enterprises demonstrating superior echelon utilization practices.

Keywords: Battery recycling, echelon utilization, competition, government subsidies

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INTRODUCTION

In recent years, the global new energy vehicle market, encompassing regions such as China and Europe, has seen remarkable growth driven by environmental concerns and industrial green transformation efforts[1]. With the rapid growth of the new energy vehicle industry, the first wave of retirement for core components, namely new energy batteries, is approaching[2,3]. These batteries primarily consist of ternary lithium and lithium iron phosphate batteries[4]. Inadequate processing of retired batteries poses a significant risk, as heavy metal elements found in both battery types can lead to water, soil, and air pollution, severely harming the ecological environment and hindering the achievement of environmental goals associated with promoting new energy vehicles[5]. Failing to attain the desired environmental benefits may result in resource wastage and heightened environmental pollution.

Echelon utilization offers an effective means to manage the retirement of used batteries from new energy vehicles, mitigating environmental pollution concerns and fostering a positive corporate image[6]. Echelon utilization involves classifying and reusing used batteries based on their remaining volume[7]. High-volume used batteries can be directly sold to consumers after minimal treatment, while low-volume ones can have their heavy metal elements extracted for remanufacturing[8,2]. Simultaneously, it presents eco-friendly solutions to the used battery dilemma, alleviating anxieties surrounding the new energy automobile industry's development and further propelling its growth.

In practice, the Chinese regulation named "New Energy Vehicle Industry Development Plan (2021-2035)" highlights the accelerated development of Chinese new energy vehicles[9] (http://www.gov.cn/zhengce/content/2020-11/02/content5556716.htm). Another regulation named "Administrative Measures for the Echelon Utilization of New Energy Vehicle Power Batteries" further encourages the collaboration between members of the supply chain. In addition, the EU formulated a medium and long-term development plan for carbon reduction in the battery industry chain and developed a carbon footprint management approach for the entire battery chain[2]. Currently, 52 firms have met the Chinese standards outlined in the "Industry Standard Conditions for Comprehensive Utilization of Waste Power Batteries for New Energy Vehicles", indicating a growing number of enterprises in this field. It is anticipated that due to the ongoing efforts of the government, increasing echelon utilization enterprises will meet the stipulated criteria.

As the adoption of electric vehicles and renewable energy continues to rise, the importance of these enterprises in managing the life cycle of power batteries will only grow, making the industry increasingly competitive. The competition among power battery echelon utilization enterprises is driven by factors such as investment in cost-efficient battery recycling systems[10], technological innovation[7], environmental responsibility[11], market demand, and subsidy[12,13]. The continuous endeavors of echelon utilization enterprises are poised to generate a noteworthy challenge in the form of heightened competition within the industry. For example, in China, GEM and ZCycle are two prominent companies that engage in competition within the specialized field of power battery echelon utilization. GEM claims that it has built a new energy full life cycle value chain of "waste battery recycling - raw material remanufacturing - material remanufacturing - battery pack remanufacturing - reuse - echelon utilization" (https://en.gem.com.cn/). ZCycle boasts advanced wet extraction technology and customizes safe application scenarios based on different types of retired batteries, committed to environmentally friendly waste power battery treatment with a low-carbon footprint(https://www.zcycle.com/). Competition significantly shapes the decision-making process of both GEM and ZCycle, and the introduction of government subsidies and incentive policies further complicates their decision-making behavior.

Currently, in order to promote the further development of the recycling and echelon utilization of power batteries, China's central government has launched the "Promote the Power Battery Industry Development Action Plan (2017)", "Administrative Measures for Echelon Utilization of Power Batteries of New Energy Vehicles (2021)", and other support management policies (http://www.mofcom.gov.cn/article/zcfb/zcwg/202201/20220103246981.shtml). Some local governments have also introduced subsidy or incentive policies, such as "Shanghai Interim Measures to Encourage the Purchase and Use of New Energy Vehicles" and "Shenzhen New Energy Vehicle Financial Support Policy"[14]. Implementing these subsidy and incentive policies can reduce the cost of recycling, improve the recycling rate, achieve social optimization, and solve environmental pollution[15]. For example, Tang *et al.* studied the impact of three kinds of government policies: no policy intervention, subsidy mechanism, and reward-penalty mechanism on recycling used batteries. They found that both subsidy and reward-penalty mechanisms can improve the recycling rate of used batteries, thus reducing the harm of used batteries to the environment. Under the subsidy system, government subsidies increase social welfare by increasing consumer surplus and manufacturers' profits[15]. Therefore, government subsidies are considered to be an important means for electric vehicle manufacturers to adjust their production strategies.

In examining the real practices, questions surrounding decision-making under competition, the impact of the competitive environment on decisions, and the highly efficient strategic use of government subsidies for promoting echelon utilization have emerged. Although the existing scholars have studied the competition under the closed-loop supply chain and the content related to government subsidies, they have not considered the impact of government subsidies on the competition among the echelon utilization enterprises of waste batteries, especially how the government subsidizes the echelon utilization enterprises with different costs to maximize environmental benefits. Based on this observation and to mirror real-world dynamics, this paper aims to investigate the firms' echelon utilization strategies in a competitive duopoly environment. Furthermore, to investigate the government's role, we initially analyze firms' echelon utilization strategies without government subsidies, establishing a benchmark. Subsequently, we delve into their echelon utilization strategies in the presence of government subsidies. To be specific, this study primarily focuses on echelon utilization enterprises, constructing a competitive duopoly supply chain to address three key issues:

(1) Examining equilibrium scenarios in the echelon utilization competitive game, both with and without government subsidies.
(2) Investigating how changes in the echelon utilization enterprise environment influence decision-making and outcomes.
(3) Assessing the effects of government subsidies on echelon utilization enterprises and providing recommendations for effective subsidy strategies.

To meet the research objectives, we employ game theory methodology to analyze real-world dynamics and provide managerial recommendations. These models involve a multi-party game supply chain that includes two battery echelon utilization enterprises, one new energy vehicle manufacturer, one third-party recycler, and government entities. In this competitive environment, two echelon utilization companies engage in a game to define their echelon utilization strategies. By analyzing the model, this study conducts a comparative analysis of the game equilibrium outcomes in the absence of government subsidies and with the inclusion of government subsidies. The contribution of this paper is to expand the existing closed-loop supply chain model by considering the influence of the competition among the echelon utilization enterprises and government subsidies. Moreover, our research examines how third-party recyclers can improve their own profits in the face of enterprise competition and government subsidies, which makes up for the lack of consideration of third-party recyclers in the existing literature. By analyzing the changes and interrelationships among various segments of the supply chain, we gain deeper insights into the intensified competition and the effects of subsidy policies on the entire industry. The research findings indicate that government subsidy policies stimulate market demand to some extent, particularly for subsidized enterprises. However, this also leads to a decline in profitability along the supply chain, resulting in a situation where both sides lose. Furthermore, the study reveals the benefits experienced by third-party recyclers under government subsidy policies. They obtain higher profits by increasing wholesale prices, indicating the positive impact of subsidy policies on the development of the recycling industry.

The remainder of this paper is organized as follows. Section "LITERATURE REVIEW" briefly summarizes and reviews the previous research related to this research. Section "MODEL DESCRIPTION AND CONSTRUCTION" describes the research problem in detail and establishes the competitive duopoly supply chain models in two cases according to the relevant assumptions. Section "MODEL RESULTS AND ANALYSIS" calculates the equilibrium situations in two cases and preliminarily analyzes the influence of the internal and external environment of echelon utilization enterprises and the subsidies. Section "NUMERICAL EXPERIMENTS" further analyzes the impact of the environment and subsidies through numerical experiments and gives some relevant management suggestions. Section "CONCLUSIONS AND PROSPECTS FOR FUTURE RESEARCH" summarizes the main conclusions and proposes the shortcomings of the research. We also give an outlook on possible future research directions.

LITERATURE REVIEW

This section reviews previous research in three primary categories: competition, government subsidies in closed-loop supply chains, and the management of new energy battery recycling and echelon utilization.

Research related to competition in or between closed-loop supply chain

Over the past decade, numerous scholars have delved into research concerning competition within and between closed-loop supply chains. Additionally, studies have examined competition among manufacturers and retailers. For instance, Jena and Sarmah (2014) investigated the effects of various cooperation models with retailers in the context of manufacturer competition[16]. Likewise, Liu *et al*. (2017) explored the interplay between channel structure and price- and quality-based competition among two manufacturers characterized by customer loyalty asymmetry[17]. In the realm of retailer competition research, Savaskan *et al*. (2006) pioneered the examination of competition intensity's influence on decision-making within the context of retailer competition in closed-loop supply chains[18]. Similarly, Guo *et al*. (2020) investigated the impact of retail competition on developing green products, revealing that heightened market competition intensity leads to a lower optimal level of greenness[19]. Zhang *et al*. (2023) constructed a two-period pricing game that involves two competing platforms to investigate the influence of network effects on optimal pricing strategies and profits[20].

Numerous scholars have researched competition within the recycling sector. Liu *et al*. (2017) explored reverse channel choice decisions involving collection competition under three recycling options. Their findings suggest that manufacturers consistently benefit from the joint recycling mode with recyclers[17]. In the context of echelon utilization, Tang *et al*. (2018) investigated mechanisms and policies under various recycling modes, including both single and competitive dual recycling channel modes[21]. Wang *et al*. (2019) focused on remanufacturing space, exploring recycling competition between remanufacturers and recyclers and between recyclers and retailers[22]. Giri and Dey (2019) addressed decision-making issues involving manufacturer-built recycling channels and traditional competition among recyclers[23], while Wei *et al*. (2019) analyzed the remanufacturer's decision-making in the context of dual recycling channels[24]. Zhou *et al*. (2023) investigated channel leadership and performance in a closed-loop supply chain that involves the competition among an electric vehicle manufacturer, an electric vehicle recycler, and a third-party recycler[25]. Suvadarshini *et al*. (2023) studied a closed-loop supply chain consisting of an original equipment manufacturer (OEM), a retailer and a third-party vendor where the OEM designs an efficient multi-channel recollection structure when recollection agents competitively recollect used products[26].

While competition has been explored extensively from various angles, such as customer service perspective by Boyaci and Gallego (2004)[27], Cournot competition among supply chains considering leader position and cost structure as investigated by Majumder and Srinivasan (2008)[28], and the influence of competition on product pricing strategy by Wang *et al*. (2017)[29], relatively limited attention has been given to competition among echelon utilization enterprises. Our research breaks new ground by introducing competitive conditions into the echelon utilization domain, shedding light on its impact on decision-making within the supply chain.

While existing research has explored competition in various aspects of supply chains, including manufacturer, retailer, recycler, and supply chain competition, there has been limited investigation into the introduction of competition in echelon utilization. Furthermore, research on competition among echelon utilization enterprises is scarce. Our paper innovatively introduces the concept of competition into echelon utilization and uniquely centers on echelon utilization enterprises as the primary agents of competition.

Research related to government subsidizing the sustainable supply chain

Considerable research has examined the effects of various government subsidies on supply chains. Mitra and Webster (2008) examined the impact of government subsidies on promoting remanufacturing activities, suggesting that partial subsidies to manufacturers could be effective[30]. Mo *et al*. (2009) proposed the use of recycling tax incentives as a means for government intervention, based on their field investigations[31]. Aksen *et al*. (2009), meanwhile, established supportive and legislative models, discovering that the supportive model necessitates more subsidies when recycling rates and profitability are the same[32]. In a recent study, Zhang *et al*. (2020) suggested strategic options that account for the effects of tax policy, subsidy policy, and tax-subsidy policy on the supply chain[33].

In green products and innovation, Li *et al*. (2018) find that consumption subsidies can improve social welfare and replacement subsidies can promote environmental protection[34]. Yi *et al*. (2021) also introduced a novel extended producer responsibility (EPR) system emphasizing resource conservation[35]. They argue that a combined tax subsidy approach can optimize social welfare and foster ecological innovation. Bai *et al*. (2021) introduce a three-stage Stackelberg game model to find the optimal allocation of the subsidy budget among multiple products covered by the trade-in program[12].

Bai *et al*. (2019) asserted that government R&D subsidies play a significant role in promoting green innovation among energy-intensive enterprises[13], although Yu *et al*. (2016) reached the opposite conclusion[36]. Chang *et al*. (2019) highlighted the role of the joint tax-subsidy mechanism in incentivizing ecological innovation by manufacturers[37]. Wang *et al*. (2020) investigated the impact of government subsidies and altruistic preferences on decision-making in a low-carbon e-commerce closed-loop supply chain[38]. Zhang and Yu (2022) considered mode selection and coordination in a low-carbon closed-loop supply chain under compound government subsidies from a long-term dynamic perspective[39].

Despite the abundance of research into the mechanism of government subsidies in various industries, there has been little exploration of the role of these subsidies in battery echelon utilization and into how the government should best disburse the subsidies. A major innovation of our research is in its study of how government subsidies in echelon utilization affect the decision-making of echelon utilization enterprises.

Research related to the management of echelon utilization

The last decade has seen the emergence of a robust literature related to used battery recycling and echelon utilization.

Most recently, Lai *et al.* (2021) researched echelon utilization in the context of battery recycling; they systematically reviewed the echelon utilization and recycling of the retired lithium-ion batteries (LIBs) and proposed two valuable sorting methods to improve the rapidity and accuracy of the LIB sorting[40]. While Turner and Nugent (2016) analyzed how EPR policies address problems of the environmental cost and benefits of end-of-life management in the European Union, Canada, and the United States, they argued that for such policies to be effective, they need to be extended to address waste collection practices, the life cycle consequences of EOL management, and the quality of recovered materials[41]. Gu *et al.* (2017) studied the vehicle manufacturer's decision-making problem regarding the battery recycling rate under conditions of government subsidies; they found that either subsidy or battery recycling can offset the negative effects of loss aversion on the optimal production quantity and expected utility[42]. Gu *et al.* (2018) subsequently found that compared to new battery manufacturing, battery recycling and reusing would contribute to lowering raw material consumption and, hence, reducing environmental impact, but may not gain financial benefits[43]. Zhang *et al.* (2020) considered the Chinese echelon utilization policy from the two perspectives of basic policy tools and the industrial chain process. They suggested that the government should increase the use of interactive impact instruments, optimize their classification, and emphasize the matching between basic policy instruments and the recycling industry chain[6].

The above summary highlights that the present literature lacks a focus on the companies involved in echelon utilization practices. As a response, our paper focuses on the decision-making process of echelon utilization and how it can be influenced by the business environments and government subsidies. Our article is most similar to (Zhang *et al.* 2022). They also explored the impact of government policies and third-party recycling on echelon utilization enterprises and new energy vehicle manufacturers, but they did not examine the impact of competition among echelon utilization enterprises on the recycling of used batteries[14]. Secondly, regarding government policies, they overlooked the impact of government subsidies on the competition between enterprises and environmental factors. Overall, our article investigates the combined effects of competition among echelon utilization enterprises and government subsidies to maximize environmental benefits on supply chain members.

MODEL DESCRIPTION AND CONSTRUCTION

Model description

This research focuses on evaluating the influence of the internal and external business environment and government subsidies on echelon utilization enterprises in a competitive setting. To achieve this, a competitive duopoly supply chain for echelon utilization is established, which comprises a new energy vehicle manufacturer, a third-party recycler, and two competing echelon utilization enterprises. The manufacturer sells new energy vehicles to consumers, and the echelon utilization enterprises entrust the third-party recycler to handle used battery recycling. The third-party recycler collects the used power batteries from customers, resells the echelon-utilizable batteries to the echelon utilization enterprise, and disposes of those excess used batteries. The echelon utilization enterprises 1 and 2 process the echelon-utilizable batteries into echelon utilization products for sale and transfer the non-echelon-utilizable power batteries and the post-echelon-utilized residues to the manufacturer for extracting raw materials.

In view of the nascent stage of echelon utilization for used new energy batteries in China, it is assumed that the number of used batteries reclaimed by recyclers exceeds the demand from the two echelon utilization enterprises. Consequently, the excess used batteries must be managed by the third-party recycler to avert potential ecological pollution. The used batteries are sold by the two echelon utilization enterprises to specialized consumers (e.g., power plants) for the initial stage of the echelon utilization process, encompassing dismantling, testing, and sorting. Subsequently, the processed used batteries are recycled and supplied to the new energy vehicle manufacturer for remanufacturing.

In this process, the new energy vehicle manufacturer holds a dominant position due to its influence on the entire process. The manufacturer determines the retail price, denoted as P for new energy vehicles. For model simplification, we assume that the actual recycling ratio and the unit recycling price of recyclers are exogenous. Consequently, the third-party recycler solely determines the wholesale price of used batteries (w), while the two echelon utilization enterprises independently establish retail prices for their respective used batteries (p_1, p_2). The specific flow chart of the model is shown in Figure 1.

In Figure 1, the solid line illustrates the journey of new energy vehicles; a new energy vehicle manufacturer provides products to consumers at the retail price P, and the third-party recycler collects used batteries from consumers at the recycling price h. In contrast, the dotted line delineates the recycling of used batteries after the initial echelon utilization stage; the manufacturer then decides the transfer payment price F for the remanufactured materials. To simplify the model, C_1 and C_2 in Figure 1 denote the unit costs associated with echelon utilization. These costs encompass activities such as dismantling, detection, classification, and recovery, and they are contingent solely upon the echelon utilization level of each enterprise.

Model construction

Based on the descriptions in Section "Model description", we establish the decision-making sequence for all parties within the supply chain. Initially, the new energy vehicle manufacturer determines the sales price for its vehicles. Subsequently, the third-party recycler sets the wholesale price for used batteries. Finally, the two echelon utilization firms independently establish the retail prices for their respective used batteries.

The model's relevant symbols and the decision variables for each party are detailed in Table 1.

To align the model with real-world dynamics and facilitate the generation of meaningful results, this paper incorporates the following assumptions in the model construction, drawing inspiration from the work of Tang *et al*. (2018)[21].

Assumption 1. In the model constructed in this paper, the new energy vehicle manufacturer is in the leading position, with the third-party recycler and echelon utilization enterprises being the followers. The third-party recycler makes decisions before the echelon utilization enterprises[6,11]. This is because, based on the research of Liu *et al*. (2022), compared to the collector-dominated supply chain, the manufacturer can improve the product collection rate and increase the total profit in the manufacturer-dominated model. Therefore, it is reasonable to assume that manufacturers occupy a dominant position in the model[44].

Assumption 2. All parties in the dynamic game are profit-maximizing and exhibit complete rationality while possessing full information[6,45].

Assumption 3. Since echelon utilization is still in its initial phase in China, we assume that the demand for it is less than the actual number of batteries in need of recycling, with third-party recyclers needing to

Table 1. Symbols and decision variables

		Definition
Symbol	Q	The actual market demand for new energy vehicles
	a	The basic market demand for new energy vehicles
	b	Price sensitivity of new energy vehicles
	G	The actual recycling amount of used batteries
	θ	Recycling ratio of used batteries
	T_i	The market demand of the ith echelon utilization enterprise, i = 1, 2
	e	The basic market demand for echelon utilization
	β	Price sensitivity of echelon utilization
	γ	The competition intensity of echelon utilization
	π_m, π_r, π_i	The vehicle manufacturer's (third-party recycler's, ith echelon utilization enterprise's) profit, i = 1, 2
	C_m	Unit manufacturing cost of new energy vehicles
	C_r	Unit remanufacturing cost of new energy vehicles
	h	The unit recycling price of the third-party recycler
	C_0	Unit disposal cost of the third-party recycler
	C_i	The total unit cost of echelon utilization of the ith echelon utilization enterprise, i = 1, 2
	S	The unit government subsidy for the echelon utilization enterprise
Decision variable	P	Unit selling price of new energy vehicles
	F	Unit transfer payment for remanufactured materials
	p_i	The price of the ith echelon utilization enterprise's echelon utilization product, i = 1, 2
	w	The wholesale price of used batteries from the third-party recycler

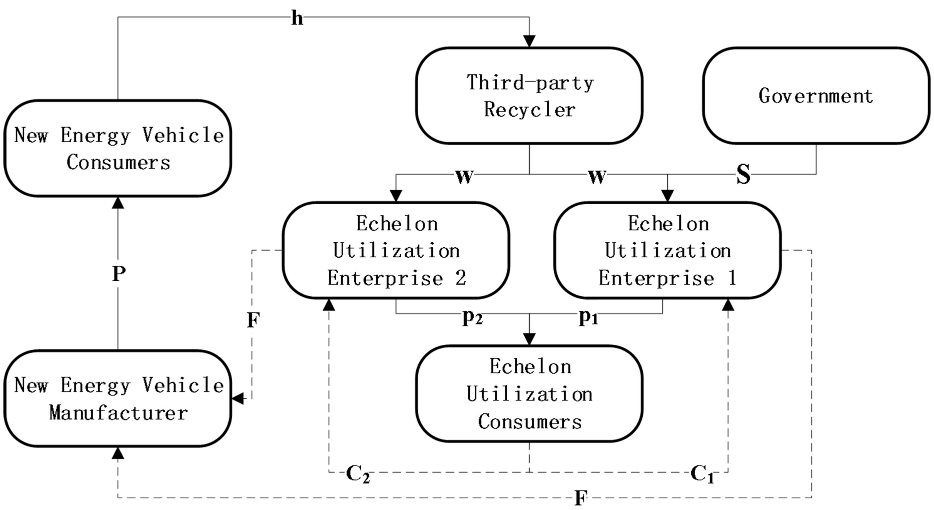

Figure 1. Flow chart of new energy battery echelon utilization.

handle the resulting excess[6]. Therefore, the relationship between the actual amount of recycling and the demand for echelon utilization services is as follows.

$$G > T_1 + T_2$$

Assumption 4. To make the model's conclusions more reasonable and in line with reality, there is a range of competition intensity between two echelon utilization enterprises. This constraint mainly means that the demand for a product is more sensitive to the changes in its own sale price than to the changes in the sale price of the other competitive product, which is reasonable in reality[46].

$$\gamma < \beta$$

Assumption 5. For simplicity of representation, our model uses a linear function to express market demand for new energy vehicles and echelon utilization[5,6,45].

$$Q = a - b * P$$
$$T_1 = e - \beta * p_1 + \gamma * p_2$$
$$T_2 = e - \beta * p_2 + \gamma * p_1$$

Assumption 6. To facilitate calculation and highlight the focus of our research, we assume that the third-party recycler chooses the reasonable recycling ratio and the unit recycling price according to their actual situation and experience. In other words, θ and h are exogenous. The third-party recycler also provides one uniformly wholesale price of used batteries for two echelon utilization enterprises. Simultaneously, both echelon utilization enterprises are privy to this pricing information. Consequently, the actual amount of recycling can thus be expressed as[6,8]

$$G = \theta * Q$$

This study follows the aforementioned assumptions and employs a literature review approach, drawing insights from previous research and model construction. We utilize the backward induction method within a dynamic game with complete information to derive the decision-making process and relevant parameters at equilibrium. Subsequently, we apply sensitivity analysis and numerical experiments to explore the influence of the supply chain's internal dynamics. Lastly, we analyze the effects of government subsidies and offer managerial recommendations.

Model formulation without government subsidies

The profit functions of each party without government subsidies are as follows.

Profit function of the new energy vehicle manufacturer:

$$\pi_m = (P - C_m) * Q + (C_m - C_r - F) * (T_1 + T_2) \quad (1)$$

which consists of two parts: the profit obtained from selling new energy vehicles in the forward supply chain and the additional income through remanufacturing.

Profit function of the third-party recycler:

$$\pi_r = (w - h) * (T_1 + T_2) - C_0 * (G - T_1 - T_2) \quad (2)$$

which comprises two parts: The first half is the profit made by selling used batteries and the additional cost incurred by having to dispose of excess recycled batteries.

Profit function of echelon utilization enterprises:

$$\pi_1 = (p_1 - w - C_1 + F) * T_1 \tag{3}$$

$$\pi_2 = (p_2 - w - C_2 + F) * T_2 \tag{4}$$

Echelon utilization enterprises generate profits from sales revenue in the marketplace and from transfer payments obtained from the new energy vehicle manufacturer.

Model formulation with government subsidies

Based on our research into the relevant policy documents, we consider the case in which the government subsidizes one echelon utilization firm based on the quantity of the echelon utilization product. To maintain symmetry, we study only the case where the government subsidizes echelon utilization enterprise 1, with the profit function as follows.

$$\pi_1{}^s = (p_1{}^s - w^s - C_1 + F^s + S) * T_1{}^s \tag{5}$$

The profit function expressions of other parties are similar to those in Section "Model formulation without government subsidies".

MODEL RESULTS AND ANALYSIS

This section uses the backward induction method in game theory to obtain the equilibrium outcomes for the two modes. Our analysis focuses on the decision-making of echelon utilization enterprises and assesses the impact of the business environment and subsidy levels.

The equilibrium situation without government subsidies

The equilibrium situation without government subsidies is provided in Proposition 1.

Proposition 1. The equilibrium situations of the game without government subsidies are:

$$P^* = \frac{a + bC_m}{2b}$$

$$F^* = \frac{-2e + 2h\beta - 2h\gamma - 2(\beta-\gamma)C_0 + (\beta-\gamma)C_1 + \beta C_2 - \gamma C_2 + 2\beta C_m - 2\gamma C_m - 2\beta C_r + 2\gamma C_r}{4(\beta-\gamma)}$$

$$w^* = \frac{2e + 6h\beta - 6h\gamma - 6(\beta-\gamma)C_0 + (-\beta+\gamma)C_1 - \beta C_2 + \gamma C_2 + 2\beta C_m - 2\gamma C_m - 2\beta C_r + 2\gamma C_r}{8(\beta-\gamma)}$$

$$p_1{}^* = \frac{1}{8(\beta-\gamma)(4\beta^2-\gamma^2)}(28e\beta^2 + 4h\beta^3 - 2e\beta\gamma - 2h\beta^2\gamma - 8e\gamma^2 - 2h\beta\gamma^2 + 2\beta(-2\beta^2 + \beta\gamma + \gamma^2)C_0 + \beta(10\beta^2 - 13\beta\gamma + 3\gamma^2)C_1 - 6\beta^3C_2 + 11\beta^2\gamma C_2 - 5\beta\gamma^2C_2 - 4\beta^3C_m + 2\beta^2\gamma C_m + 2\beta\gamma^2C_m + 4\beta^3C_r - 2\beta^2\gamma C_r - 2\beta\gamma^2C_r)$$

$$p_2{}^* = \frac{1}{8(\beta-\gamma)(4\beta^2-\gamma^2)}(28e\beta^2 + 4h\beta^3 - 2e\beta\gamma - 2h\beta^2\gamma - 8e\gamma^2 - 2h\beta\gamma^2 + 2\beta(-2\beta^2 + \beta\gamma + \gamma^2)C_0 + \beta(-6\beta^2 + 11\beta\gamma - 5\gamma^2)C_1 + 10\beta^3C_2 - 13\beta^2\gamma C_2 + 3\beta\gamma^2C_2 - 4\beta^3C_m + 2\beta^2\gamma C_m + 2\beta\gamma^2C_m + 4\beta^3C_r - 2\beta^2\gamma C_r - 2\beta\gamma^2C_r)$$

Proof. See the Supplementary Materials.

By substituting the optimal decision variables P^*, F^*, w^*, $p_1{}^*$, and $p_2{}^*$ into the defined functions of each variable, we get the actual market demand for new energy vehicles $Q^* = 1/2(a - bC_m)$ and the actual recycling amount of used batteries $G^* = 1/2\theta(a - bC_m)$. Based on these variables, we can get the demand of the two echelons of utilization and the profit of each member of the supply chain at this time. Because the formula is too complicated, we will not show it here, and readers can see it in Supplementary Table 1.

From Proposition 1, two corollaries can be derived. Corollary 1 evaluates how unit echelon utilization costs affect the optimal decision variables related to echelon utilization products. This analysis offers insights into whether echelon utilization enterprises should adjust their retail prices, whether the third-party recycler should modify wholesale prices for used batteries, and whether the new energy vehicle manufacturer should change transfer payments in response to fluctuations in unit echelon utilization costs.

Corollary 1. The influence of the total unit cost of echelon utilization on the optimal decision variables related to echelon utilization products is given in Table 2.

Proof. See the Supplementary Materials.

Table 2 reveals several significant findings. First, it demonstrates that when the costs of one echelon utilization enterprises increase, the competitor tends to lower their retail prices to capture a larger market share. Conversely, when the costs of one echelon utilization enterprises decrease, the competitor tends to raise retail prices to safeguard their profits. This result can be explained as follows: Increased costs signifies a weaker competitive position, allowing competitors to raise their retail prices of echelon utilization products while maintaining a competitive edge.

Second, as the unit cost of echelon utilization increases, the wholesale price of used batteries for the third-party recycler will decrease. This shows that as its unit cost rises, the third-party recycler tends to reduce the price, benefitting the echelon utilization industry by ensuring market demand. When the unit cost of echelon utilization services declines, the third-party recycler tends to protect their interests by raising their retail prices.

Table 2. The influence of unit cost on the optimal decision variables

	$0 < \gamma < \beta$
p_1^* changes with C_1	↗
p_1^* changes with C_2	↘
p_2^* changes with C_1	↘
p_2^* changes with C_2	↗
w^* changes with C_1 and C_2	↘
F^* changes with C_1 and C_2	↗

↗ indicates increasing with the increase of C_1 and C_2; ↘ indicates decreasing with the increase of C_1 and C_2.

Third, the effect of echelon utilization costs on transfer payments for remanufactured materials can be derived and represented in Figure 2, where we let a = 3,000, b = 1.6, C_m = 800, C_r = 600, C_0 = 3, θ = 0.8, e = 100, β = 2, h = 100, and γ = 0.8. According to Figure 2, as the cost of echelon utilization escalates, the new energy vehicle manufacturer will elevate the transfer payments to ease the pressure on echelon utilization enterprises. The new energy vehicle manufacturer hopes to maintain demand in the echelon utilization market, thereby stabilizing the resource of remanufactured materials. It should be noted here that the setting of this and subsequent parameters are obtained by partly referring to the research of Tang *et al.* (2019) and satisfying the basic constraints of the model[15].

Corollary 2 evaluates the impact of unit echelon utilization costs on the optimal profits of two echelon utilization enterprises.

Corollary 2. The profits earned by echelon utilization firms vary according to their operating costs, expressed as follows.

(1) When $C_1 < C_1^*$, π_1^* decreases with the increase of C_1; When $C_1 > C_1^*$, π_1^* increases with C_1.
(2) When $C_2 < C_2^*$, π_1^* decreases with the increase of C_2; When $C_2 > C_2^*$, π_1^* increases with C_2.
(3) When $C_1 < C_3^*$, π_2^* decreases with the increase of C_1; When $C_1 > C_3^*$, π_2^* increases with C_1.
(4) When $C_2 < C_4^*$, π_2^* decreases with the increase of C_2; When $C_2 > C_4^*$, π_2^* increases with C_2.

In which C_i^*, i = 1, 2, 3, and 4 are defined below.

$$C_1^* = \frac{1}{10\beta^2 + 3\beta\gamma - 5\gamma^2}((4\beta^2 - 2\beta\gamma - 2\gamma^2)C_0 + (6\beta^2 + 5\beta\gamma - 3\gamma^2)C_2 + 2(2\beta + \gamma)(e - h\beta + h\gamma + (\beta - \gamma)C_m + (-\beta + \gamma)C_r))$$

$$C_2^* = \frac{1}{6\beta^2 + 5\beta\gamma - 3\gamma^2}(2(-2\beta^2 + \beta\gamma + \gamma^2)C_0 + (10\beta^2 + 3\beta\gamma - 5\gamma^2)C_1 - 2(2\beta + \gamma)(e - h\beta + h\gamma + (\beta - \gamma)C_m + (-\beta + \gamma)C_r))$$

$$C_3^* = \frac{1}{6\beta^2 + 5\beta\gamma - 3\gamma^2}(2(-2\beta^2 + \beta\gamma + \gamma^2)C_0 + (10\beta^2 + 3\beta\gamma - 5\gamma^2)C_2 - 2(2\beta + \gamma)(e - h\beta + h\gamma + (\beta - \gamma)C_m + (-\beta + \gamma)C_r))$$

$$C_4^* = \frac{1}{10\beta^2 + 3\beta\gamma - 5\gamma^2}((4\beta^2 - 2\beta\gamma - 2\gamma^2)C_0 + (6\beta^2 + 5\beta\gamma - 3\gamma^2)C_1 + 2(2\beta + \gamma)(e - h\beta + h\gamma + (\beta - \gamma)C_m + (-\beta + \gamma)C_r))$$

Proof. See the Supplementary Materials.

Corollary 2 explores how changes in the unit cost of echelon utilization impact the profits of echelon utilization enterprises. It shows that as echelon utilization costs increase, profits earned by the echelon utilization firms always decrease first and then increase later. This is because the change in cost affects both the retail price and the number of echelon utilization products. In the actual situation, considering the non-negativity of demand, price, and cost, these profits tend to change monotonically with the changes of C_1 and C_2, that is, monotonically increasing or decreasing.

The equilibrium situation with government subsidies

According to the relevant proof method in Proposition 1, we can obtain the equilibrium situations with government subsidies as given in Proposition 2.

Proposition 2. The equilibrium situations of the game with government subsidies are:

$$P^{S*} = \frac{a + bC_m}{2b}$$

$$F^{S*} = \frac{-2e + 2h\beta - S\beta - 2h\gamma + S\gamma - 2(\beta - \gamma)C_0 + (\beta - \gamma)C_1 + \beta C_2 - \gamma C_2 + 2\beta C_m - 2\gamma C_m - 2\beta C_r + 2\gamma C_r}{4(\beta - \gamma)}$$

$$w^{S*} = \frac{2e + 6h\beta + S\beta - 6h\gamma - S\gamma - 6(\beta - \gamma)C_0 + (-\beta + \gamma)C_1 - \beta C_2 + \gamma C_2 + 2\beta C_m - 2\gamma C_m - 2\beta C_r + 2\gamma C_r}{8(\beta - \gamma)}$$

$$p_1{}^{S*} = \frac{1}{8(\beta - \gamma)(4\beta^2 - \gamma^2)}(28e\beta^2 + 4h\beta^3 - 10S\beta^3 - 2e\beta\gamma - 2h\beta^2\gamma + 13S\beta^2\gamma - 8e\gamma^2 - 2h\beta\gamma^2 - 3S\beta\gamma^2 + 2\beta(-2\beta^2 + \beta\gamma + \gamma^2)C_0 + \beta(10\beta^2 - 13\beta\gamma + 3\gamma^2)C_1 - 6\beta^3C_2 + 11\beta^2\gamma C_2 - 5\beta\gamma^2C_2 - 4\beta^3C_m + 2\beta^2\gamma C_m + 2\beta\gamma^2C_m + 4\beta^3C_r - 2\beta^2\gamma C_r - 2\beta\gamma^2C_r)$$

$$p_2{}^{S*} = \frac{1}{8(\beta - \gamma)(4\beta^2 - \gamma^2)}(28e\beta^2 + 4h\beta^3 + 6S\beta^3 - 2e\beta\gamma - 2h\beta^2\gamma - 11S\beta^2\gamma - 8e\gamma^2 - 2h\beta\gamma^2 + 5S\beta\gamma^2 + 2\beta(-2\beta^2 + \beta\gamma + \gamma^2)C_0 + \beta(-6\beta^2 + 11\beta\gamma - 5\gamma^2)C_1 + 10\beta^3C_2 - 13\beta^2\gamma C_2 + 3\beta\gamma^2C_2 - 4\beta^3C_m + 2\beta^2\gamma C_m + 2\beta\gamma^2C_m + 4\beta^3C_r - 2\beta^2\gamma C_r - 2\beta\gamma^2C_r)$$

Proof. Similar to the proof of Proposition 1.

By substituting the optimal decision variables P^{S*}, F^{S*}, w^{s*}, $p_1{}^{S*}$, and $p_2{}^{S*}$ into the defined functions of each variable, we get the actual market demand for new energy vehicles $Q^{S*} = 1/2(a - bC_m)$ and the actual recycling amount of used batteries $G^{S*} = 1/2\theta(a - bC_m)$. As before, we again do not show the demand of the echelon utilization firm and the profit of each member of the supply chain, and readers can see it in

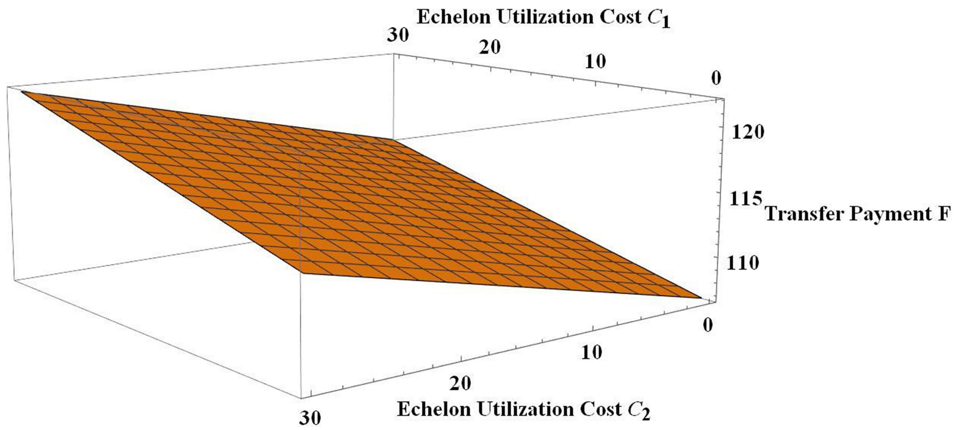

Figure 2. Impact of costs on transfer payments.

Supplementary Table 2.

From Proposition 2, some corollaries can be derived. Corollary 3 assesses the impact of government subsidy on the optimal decision variables related to echelon utilization products. This analysis offers insights into whether echelon utilization enterprises should adjust their retail prices, whether the third-party recycler should modify wholesale prices for used batteries, and whether the new energy vehicle manufacturer should change transfer payments in response to government subsidy changes.

Corollary 3. The influence of the government subsidy (S) on the optimal decision variables related to echelon utilization products is presented in Table 3.

Proof. See the Supplementary Materials.

Table 3 indicates several important findings. First, as government subsidies increase, the subsidized echelon utilization firm 1 will reduce its retail price, while unsubsidized firm 2 will raise it. This indicates that the more government subsidies, the more the subsidized enterprises will lower their retail prices to stimulate demand in the echelon utilization market. Conversely, unsubsidized firms raise their prices to protect their profits.

Second, the wholesale price of used batteries from third-party recyclers increases with government subsidies. This suggests that these third-party recyclers will raise their price in the hopes of earning some dividends from the increased subsidies.

Third, the new energy vehicle manufacturer similarly seeks to benefit from the subsidies. The impact of government subsidies on transfer payments is illustrated in Figure 3. We set a = 3,000, b = 1.6, C_m = 800, C_r = 600, C_0 = 3, θ = 0.8, e = 100, β = 2, h = 100, and γ = 0.8, C_1 = 9, C_2 = 5 in Figure 3. With the gradual increase in government subsidies, the new energy vehicle manufacturer will pay lower transfer payments.

The following Corollary 4 can be obtained by a sensitivity analysis of the equilibrium situation obtained in Proposition 2.

Table 3. The influence of government subsidy on the optimal decision variables

	$0 < \gamma < \beta$
p_1^{S*} changes with S	↘
p_2^{S*} changes with S	↗
w^{S*} changes with S	↗
F^{S*} changes with S	↘

↗ indicates increasing with S; ↘ indicates decreasing with the increase of S.

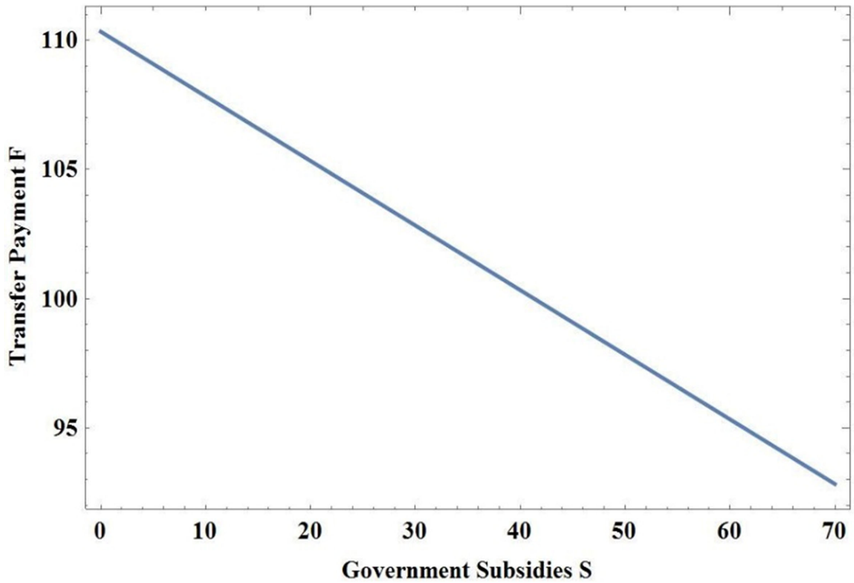

Figure 3. Impact of government subsidies on transfer payments.

Corollary 4. The profits earned by the echelon utilization enterprises change with government subsidies as follows.

(1) When $S < S_1^*$, π_1^{S*} decreases with the increase of government subsidies S; When $S > S_1^*$, π_1^{S*} increases with the government subsidies S.
(2) When $S < S_2^*$, π_2^{S*} decreases with the increase of government subsidies S; When $S > S_2^*$, π_2^{S*} increases with the government subsidies S.

In which S_i^*, $i = 1, 2$, are defined below.

$$S_1^* = \frac{1}{10\beta^2 + 3\beta\gamma - 5\gamma^2}(-4e\beta + 4h\beta^2 - 2e\gamma - 2h\beta\gamma - 2h\gamma^2 + 2(-2\beta^2 + \beta\gamma + \gamma^2)C_0 + (10\beta^2 + 3\beta\gamma - 5\gamma^2)C_1 - 6\beta^2 C_2 - 5\beta\gamma C_2 + 3\gamma^2 C_2 - 4\beta^2 C_m + 2\beta\gamma C_m + 2\gamma^2 C_m + 4\beta^2 C_r - 2\beta\gamma C_r - 2\gamma^2 C_r)$$

$$S_2^* = \frac{1}{6\beta^2 + 5\beta\gamma - 3\gamma^2}(4e\beta - 4h\beta^2 + 2e\gamma + 2h\beta\gamma + 2h\gamma^2 + (4\beta^2 - 2\beta\gamma - 2\gamma^2)C_0 + (6\beta^2 + 5\beta\gamma - 3\gamma^2)C_1 - 10\beta^2 C_2 - 3\beta\gamma C_2 + 5\gamma^2 C_2 + 4\beta^2 C_m - 2\beta\gamma C_m - 2\gamma^2 C_m - 4\beta^2 C_r + 2\beta\gamma C_r + 2\gamma^2 C_r)$$

Proof. See the Supplementary Materials.

Corollary 4 evaluates the impact of government subsidy on the optimal profits of two echelon utilization enterprises. It shows that as government subsidies rise, industry profits always decrease first and then increase later because the subsidies affect not only the price of echelon utilization products but also the demand for them. In the actual situation, considering the non-negativity of demand, price, cost, and government subsidies, echelon utilization company profits tend to change monotonically with the S variations, that is, monotonically increasing or decreasing.

NUMERICAL EXPERIMENTS

This section employs numerical analysis to delve deeper into the equilibrium outcomes and derive pertinent managerial insights.

Influence of competition intensity on echelon utilization

This section considers the effect of competition intensity on echelon utilization enterprises and third-party recyclers in the absence of subsidies. By referring to relevant literature and meeting the constraints of the model, we set a = 3,000, b = 1.6, C_m = 800, C_r = 600, C_0 = 3, C_1 = 9, C_2 = 5, θ = 0.8, e = 100, β = 2, h = 100 and substitute them in Proposition 1 to get Figures 4-6. Observation 1 can be drawn from the three Figures.

Observation 1. With the increase in competition intensity (γ), echelon utilization firms will raise retail prices (p_1, p_2), leading to a decline in demand for their products and then in company profits. At the same time, third-party recycler profits will rise in proportion to the competition intensity- the higher it is, the faster profits will rise.

Figures 4-6 and Observation 1 show that: (1) According to Figure 4, since we assume that the cost of enterprise 1 is higher than that of enterprise 2, it is reasonable for enterprise 2 to have higher profits under the same competition intensity; (2) According to Figure 5, we find that with the increase of competition intensity, the demand of both firm 1 and Firm 2 continues to decline. This is because the increasing intensity of competition makes enterprises increase the retail price of products excessively, which leads to consumers becoming less and less willing to buy their products and ultimately results in a lose-lose situation; (3) Finally, based on Figure 4, we can find that the profits of third-party recycling enterprises are on the rise with the competition intensity. On the one hand, due to the fierce competition, the retail price of products keeps rising, enabling the third-party recycling enterprises to charge higher wholesale prices to obtain higher profits. On the other hand, the fierce competition makes both enterprises want to obtain more products from third-party enterprises to increase their competitive advantage, which invisibly gives third-party recycling enterprises greater bargaining power.

Influence of echelon utilization costs on the supply chain

This section investigates the influence of echelon utilization costs on the entire supply chain in the absence of government subsidies. We set $\pi^* = \pi_m^* + \pi_r^* + \pi_1^* + \pi_2^*$ to represent the total profit of the supply chain, with the numerical settings in this section consistent with those in Section "Influence of competition intensity on

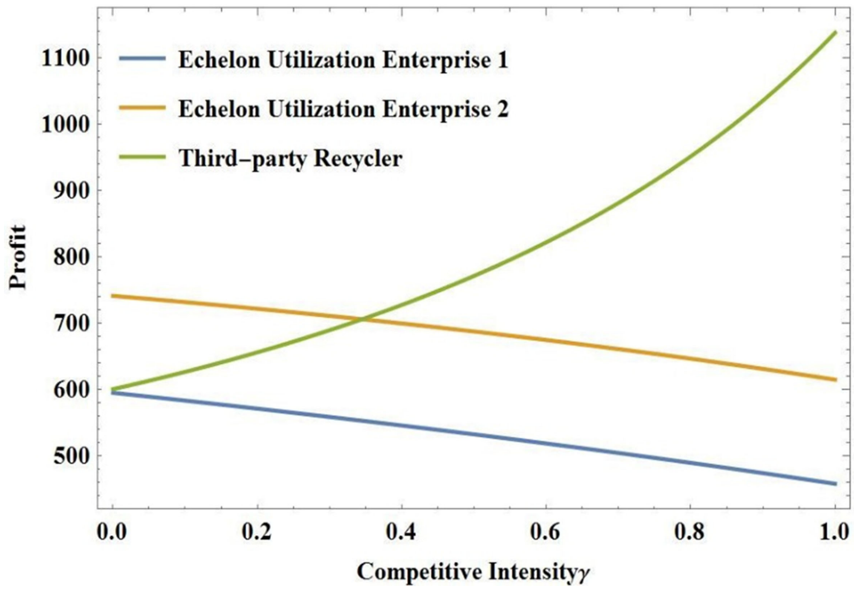

Figure 4. Influence of competitive intensity on profits.

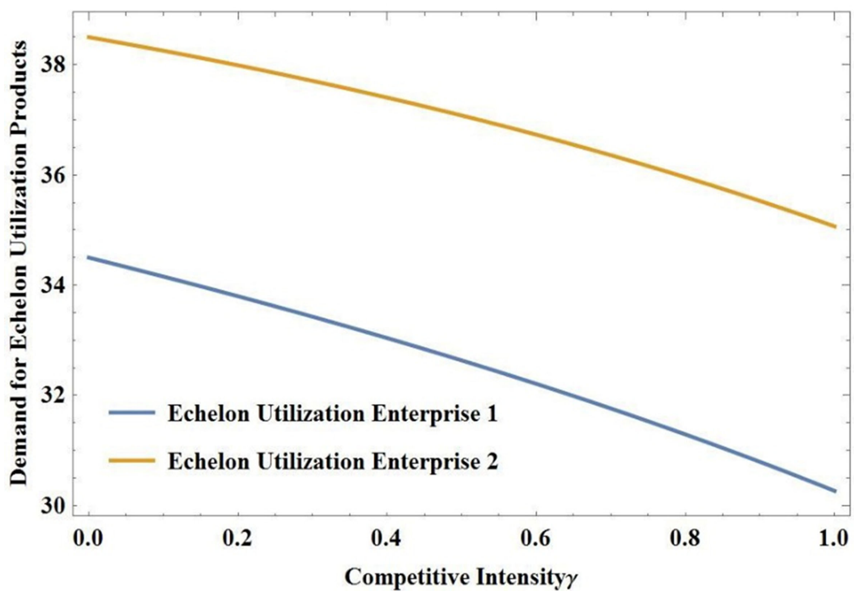

Figure 5. Influence of competitive intensity on demand.

echelon utilization”. It should be noted that we set that $\gamma = 0.8$, with the result of the numerical experiment shown in Figure 7, from which Observation 2 can be drawn.

Observation 2. The total profit of the supply chain (π^*) will diminish as the echelon utilization costs (C_1, C_2) of both echelon utilization firms increase. In general, excessive echelon utilization costs will hurt the overall supply chain.

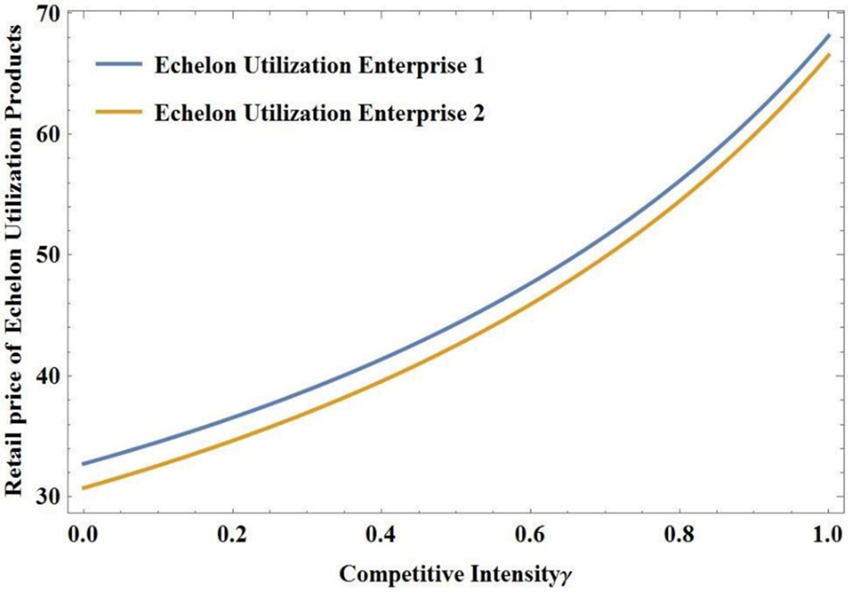

Figure 6. Influence of competitive intensity on retail price.

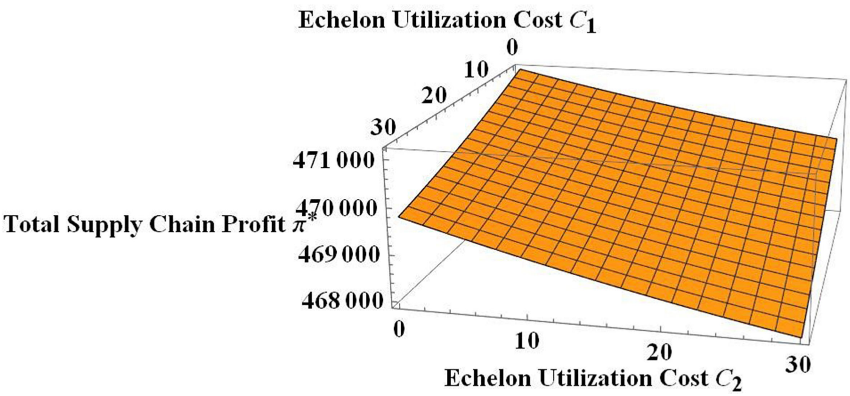

Figure 7. Influence of costs on profits in the supply chain.

Figure 7 and Observation 2 demonstrate that, from the standpoint of the overall supply chain, it is logical that an increase in the echelon utilization cost of any echelon utilization enterprise under competition will decrease the total profit of the supply chain. Hence, even within a competitive environment, echelon utilization enterprises with superior echelon utilization capabilities, meaning lower echelon utilization costs, should be preferred for cooperation.

Influence of government subsidies on echelon utilization enterprises

This section discusses the influence of government subsidies on market demand, retail price, and echelon utilization enterprise profits, with numerical settings consistent with those in Section "Influence of competition intensity on echelon utilization". For the convenience of expression, we set the additional demand after government subsidies as $\Delta T_1 = T_1^{S*} - T_1^*$, $\Delta T_2 = T_2^{S*} - T_2^*$, set the changes in the retail prices of echelon utilization products as $\Delta p_1 = p_1^{S*} - p_1^*$, $\Delta p_2 = p_2^{S*} - p_2^*$, and set the competing firms' additional profits as $\Delta \pi_1 = \pi_1^{S*} - \pi_1^*$, $\Delta \pi_2 = \pi_2^{S*} - \pi_2^*$. The results of the numerical experiments are presented in Figures 8-10. According to these figures, we can get the corresponding Observations 3-5.

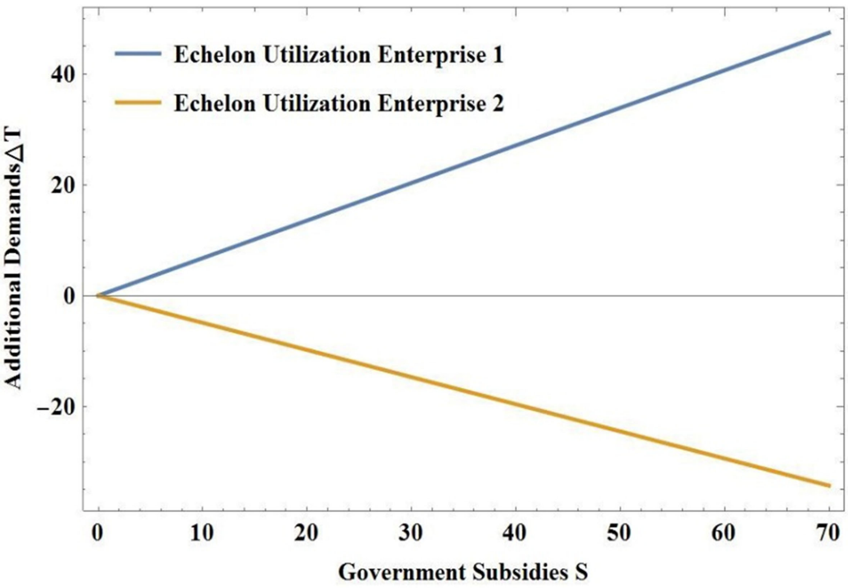

Figure 8. Impact of government subsidies on additional demand.

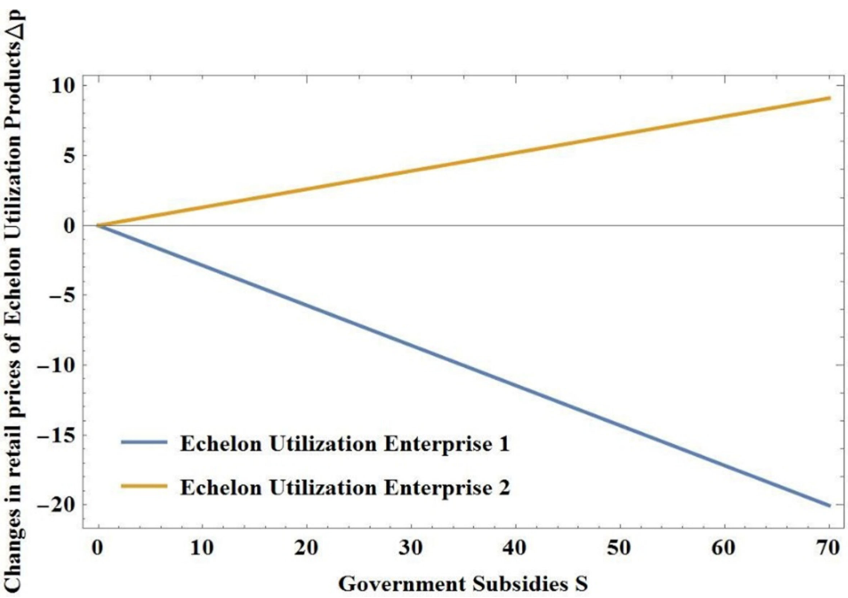

Figure 9. Impact of government subsidies on changes in retail price.

Observation 3. Government subsidies will increase demand for the subsidized echelon utilization firm and reduce demand for the unsubsidized firm, but the overall demand will increase. In other words, ΔT_1 increases with the government subsidies, and ΔT_2 decreases as subsidies increase.

Observation 3 shows that government subsidies do affect competition such that the subsidized firm will increase market demand and gain market share while the unsubsidized firm will lose it. Yet, from the perspective of the entire market, government subsidies are beneficial overall because they can increase total demand and promote the development of the echelon utilization industry. Even subsidizing the firm with the higher costs will also increase total demand. When taken together with Observation 2, it becomes clear

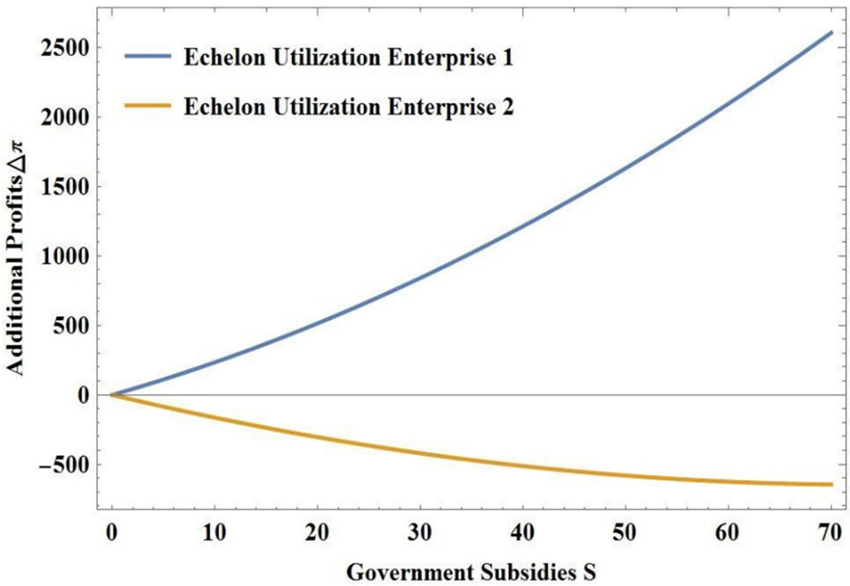

Figure 10. Impact of government subsidies on additional profits.

that the government should prioritize offering subsidies to the firm with the lower echelon utilization costs, so that the echelon utilization market can be further regulated and accelerated.

Observation 4. Government subsidies will cause the recipient enterprise to lower its retail price, but will also lead its unsubsidized competitor to raise its retail price, with the resulting price decrease greater than the increase. Or, written another way, Δp_1 decreases as government subsidies increase, and Δp_2 increases with the subsidies.

Observation 4 shows that government subsidies can significantly affect the retail prices of echelon utilization competitors, with the subsidized echelon enterprise reducing its price to benefit consumers, while the unsubsidized one increases its own in order to maintain its profits. For the unsubsidized firm, government subsidies relax its willingness to compete and put it at a competitive disadvantage. From the perspective of the subsidized firm, government subsidies increase its willingness to compete but can also ultimately benefit consumers. This once again shows that when the government selects subjects for its subsidy policies, it should select the enterprises with the strongest capabilities, as determined by a thorough investigation. Doing so can optimize consumer benefit, thereby promoting the development of the industry efficiently.

Observation 5. Government subsidies will lead to higher profits for the recipient echelon utilization firm but reduced profits for the unsubsidized one, causing total market revenue to rise. Or, $\Delta\pi_1$ increases with the government subsidies, and $\Delta\pi_2$ decreases as subsidies increase.

Observation 5 shows that government subsidies can significantly affect the potential of echelon utilization competitors to earn additional profits. The subsidy recipient will obtain obvious additional profits, and the greater the subsidies, the faster the growth rate. At the same time, the unsubsidized firm will suffer additional losses, but the growth rate will gradually slow down as subsidies increase. When looking at the whole market, it becomes clear that subsidies can increase the total profit and play an important role in promoting development. Similar to the suggestions mentioned in Observations 4 and 5, Figure 10 further illustrates that the government should be cautious from the perspective of industry profits when selecting subject firms to receive subsidies.

CONCLUSIONS AND PROSPECTS FOR FUTURE RESEARCH

Due to the rapid development of new energy vehicles, there is great potential for the echelon utilization of waste batteries in China, with various policies being introduced to support this. Although many scholars have studied the competition among different members of the supply chain, few have focused on the competition related to the echelon utilization of waste batteries. Based on this observation, this paper establishes a closed-loop competitive duopoly supply chain consisting of one new energy vehicle manufacturer, one third-party recycler, and two echelon utilization enterprises. It contributes to the literature on echelon utilization of retired batteries by drawing attention to closed-loop supply chains with competitive duopoly and taking the influence of the government subsidy into consideration. By comparing and analyzing the decisions and equilibrium outcomes of each member in the supply chain, we find that:

1. Without government subsidies, the echelon utilization enterprise will reduce retail prices to gain market share when costs rise for its competitors. When the costs of echelon utilization increase, the echelon utilization enterprise tends to raise retail prices to ensure its profit while the third-party recycler tends to reduce the wholesale price to ensure demand. Similarly, the new energy vehicle manufacturer tends to augment the transfer payment to stabilize the source of remanufactured materials.

2. In the case of government subsidies, the recipient echelon utilization enterprise is more likely to reduce the retail price to increase demand as subsidies increase which is similar to the findings of Gu *et al*. (2017), while the unsubsidized competitor's demand will be falling due to too high retail price[42]. This is still beneficial from the perspective of the market, however, as subsidies will lead to a rise in total demand. In addition, we found that the larger the amount of government subsidies, the faster the growth of subsidized enterprises. In contrast, businesses without subsidies will suffer additional losses. In other words, the more government subsidies a competitor receives, the lower the growth rate of a company without subsidies.

3. As government subsidies increase, the profits of echelon utilization firms will theoretically decrease first and then increase. This viewpoint differs from existing research (Li *et al*., 2018; Mitra and Webster, 2008), suggesting that government subsidies always benefit manufacturers[34,30]. The third-party recycler will raise wholesale prices as government subsidies increase as it hopes to enjoy its share of dividends from the subsidies. The new energy vehicle manufacturer, for its part, will reduce the transfer payment to enjoy its own share of dividends.

4. With an increase in competition intensity, competing echelon utilization enterprises will raise retail prices in order to ensure their profits, which, in turn, may reduce market demand and eventually create a lose-lose situation. However, subsidies can ease the competitive willingness of non-subsidized competitive enterprises and avoid vicious competition. At the same time, the subsidized competitors and the third-party recycler will gain an advantage over their competition and generate additional revenue from the opportunity, which will benefit Echelon utilization consumers in the end.

5. As far as the supply chain is concerned, the rise in echelon utilization costs will lead to a decline in total profits. For this reason, governments may consider prioritizing support for enterprises demonstrating superior echelon utilization practices.

Since our research focuses on echelon utilization enterprises, this paper may have the following deficiencies and parts that could be expanded in the future. (1) To simplify the model and highlight the key points, we set the recycling ratio and the unit recycling price as constants. In the future, we can treat them as decision variables; (2) Our research focuses on the initial stage of echelon utilization. In the future, there may be further discussions where the supply and the demand are in balance or where the supply is less than the demand; (3) In our research, the sources of remanufactured materials all come from echelon utilization enterprises. It is possible to study the impact on echelon utilization enterprises when the third-party recycler or both the third-party recycler and echelon utilization enterprises provide remanufactured raw materials; (4) Many factors still need to be considered during the industrial process, such as supply chain dynamics, international trade policies, and so on. The closed-loop supply chain involves a wider range of objectives and stakeholders, making its environment more complex, dynamic and uncertain, so improving the dynamics of the closed-loop supply chain is particularly important. Additionally, on a global scale, promoting the development of the power battery recycling industry has become a hot topic. For example, new energy vehicle power battery manufacturers entering the European Union should provide ingredient descriptions, carbon footprint labels, and battery "digital passports" in line with the European Union's harmful substance content limit standard. Therefore, waste battery echelon utilization enterprises still have great room for progress. We need to consider more factors to match the development of the actual situation.

DECLARATIONS

Author's contributions

Conceptualization, methodology, formal analysis, supervision, writing - review and editing: Zhao S
Methodology, formal analysis: Wang M
Software, methodology: Ma C

Availability of data and materials

Not applicable.

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Conflicts of interest

All authors declared that there are no conflicts of interest.

Ethical approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

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