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Remanufacturing electric vehicle battery supply chain under government subsidies and carbon trading: Optimal pricing and return policy

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HIGHLIGHTS

- A supply and return flow of EV batteries is considered under four decision makers of the Stackelberg game theory.
- The optimal decision consists in balancing total supply chain profit and environmental impacts.
- The increase in carbon trading price and decrease in government subsidy would drop the EV battery market demand.
- The return rate of used EV batteries can be enhanced by reinforcing a coordination partnership between green suppliers and third-party.

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ABSTRACT

The global electric vehicle (EV) market has experienced considerable growth over the last several decades to meet the demand for lower emissions and achieve sustainable development goals. This study considers the remanufactured electric vehicle battery (EVB) supply chain under government subsidies and carbon trading policies. The Stackelberg game theory model was used, in which four decision makers were specified to follow a given sequence. Regular EVB suppliers make decisions based on that of green EVB suppliers to finalize EVB wholesale prices, whereas EV manufacturers and third parties make decisions based on EV selling and return prices to maximize their profits. The results show that carbon trading regulations are important for managing carbon emissions and do not increase the return rate and remanufactured EVB production volume. Moreover, green suppliers obtain a higher profit under government subsidies, which leads to increased EVB return rates and reduces the market price and cost of materials. The total carbon emissions were reduced significantly by combining regular and recycled materials, which demonstrates that remanufacturing operations are among the most efficient methods of mitigating the environmental impacts of used batteries.

1. Introduction

Electric vehicles (EVs) present new engine generation technology compared to traditional internal combustion engine vehicles and thus have led to improved energy efficiency and reduced greenhouse gas (GHG) emissions. According to the International Energy Agency (IEA) (2022), global EV sales are projected to reach 200 million vehicles by 2030, accounting for >30% of global vehicles. The EV industry may face the challenge of a shortage of batteries owing to the lack of raw materials as well as high EV battery (EVB) costs, which account for over 30% of the total EV production costs [1]. Thus, as the EV market has grown, a sustainable development framework must be developed to achieve a balance between ecological and economic benefits [2]. However, an increase in the EV sales volume results in a large number of retired batteries, which is a crucial problem that might reduce the environmental and economic benefits of these vehicles if a proper management strategy for repurposing and recycling batteries is not developed. Therefore, the European Union, one of the largest EV markets, has proposed targets for collecting and recycling batteries of approximately 85% and 50%, respectively. Similarly, the Chinese government encourages a circular market for EVBs through collaboration among secondary consumers, manufacturers, remanufacturers, primary consumers, and recyclers.

A proper management strategy for remanufacturing EVBs would address the economic and environmental benefits of material recovery and energy storage applications. When the capacity degradation drops

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to 70–80% of the initial state, EVBs are replaced and moved to second-life applications [3]. On the one hand, high-quality batteries can extend service life, providing affordable energy storage for commercial buildings or residential households, especially storage systems for renewable energy production projects. On the other hand, low-quality batteries can be used as recycled materials for EVB production. Hence, the utilization of retired batteries would reduce natural material consumption and costs, increase sustainability when using recycled materials, and release 10% fewer GHG emissions compared with traditional production processes [4]. For instance, automotive manufacturers BMW, Nissan, and Sumitomo operate local EVB collection centers to encourage customers to return retired batteries that are used for storage facilities for second-life batteries [5]. Although recycling and remanufacturing EVBs have notable potential benefits, the position of different types of batteries in the market may become problematic through pricing and return policy optimization. New and remanufactured products are characterized by unit production cost differences; hence, dealing with pricing strategies implies an urgent need for remanufacturing EVBs [6]. Recent research has focused on collection models, such as manufacturer, retailer, and third-party collection models [7–9]. However, studies have not focused on issues related to pricing. Moreover, the quality of the returned batteries determines whether they are reused for energy storage purposes or to extract the materials (e.g., lithium, cobalt, and nickel) [10]. Consequently, pricing and return policies play a notable role in properly managing a large number of used batteries.

Recycling EVBs requires technological developments and government policies. For example, subsidies and carbon trading regulations are expected to promote the repurposing and remanufacturing of used batteries, especially because heavy metal pollution and geographic concentrations of critical minerals are emerging issues. However, whether subsidy efficiency can encourage the remanufacturing of EVBs or cause overproduction capacity remains unclear. Thus, another policy called carbon trading was introduced to effectively limit and control carbon emissions from EV and EVB production processes. According to the World Bank [11], stringent carbon regulations will contribute to reducing global emissions by 4% to meet the temperature reduction goal of the Paris Agreement by 2030. Carbon trading policies are critical parts of the international trading system because of the increasing pressure on industries and local manufacturers to reduce pollution. As material suppliers and manufacturers are involved in the strategy of sustainable development of EVB supply sources, business opportunities and environmental compliance challenges increase the competition between stakeholders (e.g., EVB suppliers, third parties, or other collection parties) [12,13]. A lack of cooperation among supply chain members can remarkably reduce profits and increase risks.

Under these circumstances, subsidy policies and carbon trading programs (e.g., cap-and-trade) are considered the primary external factors driving environmental objectives and ways to achieve economic targets and comply with regulations [14]. However, a limited number of studies have focused on pricing strategies that simultaneously consider the effects of these two factors (subsidy and carbon trading) on a holistic sustainable EVB supply chain. Furthermore, the competition between manufacturers and remanufacturers has not been considered in most studies.

Therefore, the game-theory method can be applied to address remanufacturing EVB supply chain problems:

(i) The relationship between government regulations (e.g., subsidies and carbon trading) and economic and environmental benefits (e.g., profits and carbon emissions reduction) can be investigated because remanufacturing has become a critical strategy for achieving sustainable development goal.
(ii) Adequate amounts of funds to be allocated to improve the performance of remanufacturing operations and achieve a balance between the supply of recycled materials and remanufactured battery demand can be identified.
(iii) The optimal pricing strategy and return rates for the battery supply chain can be determined while simultaneously considering subsidies and carbon trading policies.

The contributions of this study are as follows: First, the influence of EVB multi-supply sources on economic and environmental benefits was considered under government subsidies and carbon trading. The proposed model investigates not only the remanufactured EVB stream but also the new EVB stream by considering the market competitiveness between new and remanufactured products. Second, the economic and environmental impacts were integrated into stakeholder decisions to encourage the remanufacturing industry while maximizing profits. Moreover, this study conducted a comparative analysis of the supply chain of new batteries and the recycling of used batteries in terms of carbon emission reduction, with the analysis including and excluding remanufactured batteries. Finally, financial support from government subsidies and the carbon trading market is implemented to determine the optimal wholesale and retail prices, as well as the return rate of retired batteries. Among the key decisions, the optimal return rate contributes to helping the EVB industry reduce its dependency on virgin materials and facilitate more sustainable and profitable production than traditional production.

Moreover, while current research concentrates on supply chain pricing strategies with two to three decision makers, this study uses four decision makers (regular supplier, green supplier, EV manufacturer, and third-party) in the Stackelberg game theory model. The participation of third-party in the model strongly supports the manufacturer's decision that the production balance between new and remanufactured products relies on a return channel and an ordinary channel supply of third-party and regular suppliers, respectively. The proposed model simultaneously considers the handling strategy for used EVBs (recycling material and second-use) and the competitive mechanism for new and remanufactured EVBs. Existing studies have realized the role of carbon trading as the most important factor in recycling strategies. Conversely, this research shows that the market demand and return rate experience a downward trend and reduced remanufacturing activity performance at a certain carbon trading price.

The remainder of this paper is organized as follows: Section 2 reviews the relevant research. Section 3 describes the model in detail and derives the optimal wholesale prices, retail prices, and profits. Section 4 presents the experiments and analyses. Finally, Section 5 provides the conclusions and future research directions for this study.

2. Literature review

This section provides a comprehensive review of related studies on the different return policies of closed-loop supply chains (CLSCs). The following subsections describe relevant articles on remanufacturing, government subsidies, carbon trading, and pricing and return policies. Table 1 compares existing studies with this study in terms of the major factors.

2.1. Remanufacturing EVB supply chain

This study investigated the impact of supply flow and recycling of EVBs under government subsidies and carbon trading policies. By observing four decision makers (regular supplier, green supplier, EV manufacturer, and third party) in the Stackelberg game model, the major decisions focus on optimal supply chain profits, which include economic and environmental benefits. Although the optimal recycling and reuse of EVBs have been considered in previous research, few studies have addressed the competition between suppliers to supply new and remanufactured batteries. Moreover, the role of third-party decision makers in the reverse channel has been analyzed to a lesser degree in recent supply chain models.

Many studies have investigated the different aspects of recycling and

Table 1
Comparison between the proposed model and previous published works.

Author(s) (year)	Collector			Carbon regulation/ Emission policy			Sustainability dimension considered		CLSC competition		Decision maker	Government intervention type	Recycling products
	(Re) manufacturer	Retailer	Third-party	Carbon tax	CT	Carbon cost	Profit	Environmental quality	Recycling market (1)	Product-market (2)			
Xu and Wang [45]	●					●	●	●			2		ND
Wang et al. [35]			●				●		●		2	Reward-penalty on target collection rate	WEEE
Wang et al. [20]	●	●					●		●		2		ND
Wang et al. [4]			●			●							EVB
Ranjbar et al. [43]		●	●				●		●		3		WEEE
Dou and Cao [48]	●	●	●	●			●	●			2		ND
Wang et al. [37]		●			●		●	●			2		ND
Yang et al. [21]	●	●	●		●		●	●			2		ND
Zhu et al. [1]	●						●				2		EVB
Liu et al. [23]	●						●		●		2		EVB
Wu [44]	●						●	●	●		2	Tax and subsidy per remanufactured product	ND
Zhang et al. [24]	●	●	●				●				2, 3	Reward-penalty on target collection rate	EVB
Luo et al. [42]	●			●			●	●			2		ND
This study			●		●		●	●		●	4	Subsidy on units of remanufactured battery and CT	EVB

Note:
(1): Competitive collectors.
(2): New and remanufactured products.
WEEE: waste electrical and electronic equipment; ND: not determined; CT: carbon trading.

remanufacturing EVBs. For example, Li et al. [15] provided a summary of the technical processes involved in battery recycling and offered useful information on solid waste treatment. The recovery of lithium, graphite, cobalt, and other precious metals requires an understanding of the thermal and leaching processes, as reported by Wuschke et al. [16] and Yang et al. [17]. However, increasing research has focused on the economic and environmental benefits. By considering the recycling process, Ciez and Whitacre [18] explored more environmentally friendly recycling of batteries compared with landfill disposal, with studies showing that GHG emissions and energy consumption are reduced by approximately 10% and 35% via recycling, respectively [4,19]; moreover, recycling also provides a solution for the limited supply of raw materials due to the booming EV market. The aforementioned literature reveals the benefits of properly recycling EVBs, including less material consumption and fewer environmental issues. However, few studies have focused on the pricing and positioning of new and remanufactured EVBs in the market, which represent major factors for attracting investments from manufacturers and stakeholders.

With the increasing environmental concerns, several studies have investigated remanufacturing production problems, such as pricing strategies and supply chain configurations. Wang et al. [20] analyzed the effects of different collectors (remanufacturers, manufacturers, and outsourcing collectors) on optimal pricing strategies. Yang et al. [21] explored the influence of remanufacturing on carbon emission reduction and profit enhancement under cap-and-trade regulations. Three collection modes (manufacturer, retailer, and third-party collections) were examined, and the results indicated that the third-party collection mode had the lowest carbon emission level compared to the other collection modes. As the number of retired EVBs has increased recently, research on the recycling and reuse of used EVBs has also increased, thereby increasing the available literature [1,22,23]. By constructing an EVB recycling network, Wang et al. [4] indicated a reduction in the total cost and CO_2 emissions of approximately 5.7% and 21.8%, respectively. In addition to the recycling network, Zhang et al. [24] discussed the partnership of six collection modes with a single EV manufacturer: manufacturer, retailer, third party, manufacturer-retailer, manufacturer-third party, and retailer-third-party modes. The aforementioned studies did not examine multiple or competitive manufacturers in the remanufacturing supply chain, especially in the EVB supply chain. In contrast to this previous research, our current study concentrated on a CLSC under competitive supply sources of the two EVB manufacturers. The third-party collection mode was considered to further explore the role of third parties in promoting remanufacturing.

2.2. Government subsidy and carbon trading

Although concerns regarding recycling and remanufacturing have increased recently, several studies have concentrated on policies and government subsidies to accelerate EV penetration. Kester et al. [25] investigated appropriate policy mechanisms for the transition of EV in which governments can become front-runners in allocating subsidies. Thus, EV sales volume have increased because of both financial incentives and purchase taxes [26]. Investments in charging infrastructure and technological innovation are strongly recommended to promote EV purchase intention [27]. On the one hand, maintaining a certain national level of government subsidies (e.g., consumer subsidies and research and development subsidies) strongly supports the EV industry's sustainability with a larger economy of scale and significant carbon emission reduction [28,29]. On the other hand, remanufactured EVBs are dominated by the high profits earned when subsidies fall to zero [30]. From a practical perspective, while investigating the impact of consumer preferences (e.g., environmental awareness and battery duration), previous studies have indicated the potential for government subsidy reduction to promote the EV market [31]. Nonfinancial policies (such as charging and parking discounts) have been studied as effective strategies when financial debt pressure affects the number of subsidies [32]. Nonetheless, the aforementioned studies have not incorporated forward and reserve channels of EVBs, which should be considered for the EV industry sustainability and battery production.

When remanufacturing and reuse become essential activities in the CLSC, the government considers different mechanisms or incentives to encourage supply chain members to participate in environmentally friendly production. According to Gu et al. [33], an EVB-CLSC may earn less profits with more returned batteries. Hence, this research indicates that the higher the incentives from the government, the higher the recycling profit. Sinayi and Rasti-Barzoki [34] incorporated sustainable policies (tax and subsidy) into the supply chain of green products and explored the influence of these governmental policies on the final price of the product. Instead of providing incentives, Wang et al. [35] explored the reward-penalty mechanisms in a CLSC. Specifically, the collection rate target was stipulated, which determined whether a reward or penalty would be offered to the manufacturer. In related literature, Jauhari et al. [36] conducted further research on CLSC under take-back incentives and carbon taxes to minimize total costs and emissions. In another approach, Wang et al. [37] concentrated on profit optimization under different levels of carbon emission reductions and cap-and-trade regulations. Gu et al. [38] investigated the number of subsidies based on the return yields of used EVBs. Most existing studies use the collection rate as a condition for implementing government subsidies or penalties; however, such information would be difficult to obtain for small-scale production. Our study further considers government subsidies for CLSC based on the units of retired batteries returned to fill the gap associated with missing data. In addition to subsidies, a carbon trading policy was simultaneously considered to obtain optimal economic and environmental objectives.

2.3. Gaps in pricing and return policy

In the context of pricing and return policies, the remanufacturing industry involves green consumer awareness and CLSC design.

The presence of green consumers who purchase new and remanufactured products equally greatly affects the production decisions in terms of remanufacturing. Huang et al. [39] studied manufacturer pricing strategies and the social welfare obtained by considering partially and completely remanufactured products. Different pricing models demonstrate the market potential for producing remanufactured products, including a recycled material, remanufactured product, and hybrid strategy [40]. Another approach to the pricing model was conducted by Hong et al. [41], who examined single-product pricing and dual-product competition. From the perspective of economic benefits, previous studies have discussed the sustainable development of CLSC and remanufacturing channel performance [23,35,42–44]. Xu and Wang [45] analyzed customer preferences for optimal profits and their decisions and included a single manufacturer and a single retailer in the supply chain structure. Similarly, Liu et al. [23] proposed a used battery recovery model in which the leading role belongs to the battery supplier and the secondary role belongs to the EV manufacturer. Their approaches compared the profits of two recovery models, namely, the manufacturer-recovery and retailer-recovery models. Although prior studies on pricing models in the remanufacturing industry have been conducted, few studies have focused on the competition between new and remanufactured products from both economic and environmental perspectives.

Several studies have been devoted to the return channel of CLSC, in which the remanufacturer and third parties play key roles in handling and enhancing the value of used product returns. Dominguez et al. [46] analyzed the impacts of capacity restriction for both traditional and remanufacturing lines, and further investigations of third-party remanufacturers were conducted under demand uncertainty for remanufactured products [47]. In addition, Dou and Cao [48] and Yang et al. [21] used the carbon tax system to measure economic and environmental performance in three different collection modes, whereas Chai et al. [49] addressed the influence of carbon quotas and trading mechanisms on the ordinary and green markets of remanufacturing. Only a few studies have focused on both economic and environmental objectives, particularly in the remanufacturing channel. Hence, the number of decision makers was approximately two to three, and the manufacturer was always the leader. Based on these two types of products, this study supplies new and remanufactured products by regular and green suppliers and examines the competition between EVB suppliers in a CLSC model. Moreover, four decision-makers were considered in the Stackelberg model of the EVB supply chain.

The literature review indicates a lack of research on carbon trading and government subsidies for EVB supply chains via pricing strategies and return rate measurements. In addition, the existing supply chain ignores the role of third parties in enforcing used battery collection and remanufacturing. Along with the third party, our study differentiates itself from others by considering four decision makers: a regular battery supplier, a green battery supplier, an EV manufacturer, and a third party. The objective of this study was to address the influence of government subsidies and carbon trading on EVB CLSC in terms of pricing and system performance. Consequently, the importance of the government, carbon trading market, and third parties was explored to elaborate on and motivate sustainable development from economic and environmental perspectives.

3. Model description

A competitive EVB CLSC considers one regular battery supplier 1 (S_1), which uses natural materials; one green supplier 2 (S_2), which uses recycled material; one EV manufacturer (M), who buys batteries from both battery suppliers and sells them to the primary consumer (C_1); and a third party (TP), which collects and sorts used batteries from the primary consumer and delivers them to the secondary consumer (C_2) and the green battery supplier. Table 2 shows the notations used in the model.

Table 2
Notations.

Symbol	Description
Parameters	
M	EVB primary market size
α	Retail price elasticity coefficient of the new battery
β	Retail price elasticity coefficient of the remanufactured battery
ηw_r	Subsidy for each remanufactured battery
λ	High-quality returned battery for reusable market
c_{pn}	Unit production cost of a new battery
c_{mn}	Cost of purchasing raw materials for new battery production
c_{pr}	Unit production cost of a remanufactured battery
c_{mr}	Cost of purchasing a low-quality used battery as recycled material
p_m	Unit price for each used battery third-party collects from primary consumers.
p_u	Retail price of a reusable battery to the secondary market
D_n	$D_n(p_n, p_r) = M - \alpha p_n + \beta p_r$, the battery's demand for regular supplier
D_r	$D_r(p_n, p_r) = M - \alpha p_r + \beta p_n$, the battery's demand for green supplier
I_u	Investment parameter for used battery collection
I_r	Investment parameter for remanufacture
e_n	Emission parameter for producing a unit of regular battery
e_r	Emission parameter for producing a unit of remanufactured battery
p_c	Carbon trading price
E_n	Cap indicates the maximum emissions allowed for one regular battery supplier
E_r	Cap indicates the maximum emissions allowed for one green battery supplier
Δ	Unit cost savings of green production using recycled materials $\Delta = c_n - c_r$
Decision variables	
τ	Return rate that used batteries returned to the third-party
p_n	New battery retail price
p_r	Remanufactured battery retail price
w_n	Wholesale price when a regular battery supplier sells a battery to the EV manufacturer
w_r	Wholesale price when a green battery supplier sells a battery to the EV manufacturer

Fig. 1 illustrates the supply chain configuration, including the forward and reverse flows in the third-party collection mode. Upstream battery suppliers compete to fulfill the demand for EV from automobile manufacturers. A green supplier (using recycled materials) would have lower material costs, however, higher production costs. However, regular suppliers can benefit from the production scale without the limitation of material supply while considering the carbon trading policy. In the reverse flow, a third-party collects and sorts all the used batteries used from primary consumers. Returned batteries are sold to the secondary market for repurposing if the returned batteries meet a certain capacity standard (λ). Low-quality EVBs are subsequently transferred to green suppliers for remanufacturing. In a battery supply chain, the green supplier has sufficient power over other followers in employing remanufacturing. Hence, our study considered a leader-follower Stackelberg game theory model which focuses on the leader's commitment between the leader (green supplier) and followers (third-party, regular supplier, and manufacturer). First, the green supplier, as the leader, will determine the battery wholesale price for the EV manufacturer (considering profit and government subsidies). The regular supplier will then follow the leader's decision to determine the wholesale price produced by natural materials. Second, the EV manufacturer optimizes the two different retail prices of batteries. Finally, the third-party incorporates the behaviors of primary and secondary consumers, and green suppliers, to improve and enhance the quantity of returned batteries, increase the lifespan, and recycle used batteries.

3.1. Assumptions

Key assumptions were made during the development of the model, as listed below.

- The market demands are assumed to be a linear function of the retail prices, which are denoted by $D_n(p_n, p_r) = M - \alpha p_n + \beta p_r$ and $D_r(p_n, p_r) = M - \alpha p_r + \beta p_n$ [20]. This mechanism indicates that market demand for new batteries decreases as their retail price increases, however, increases as the remanufactured battery retail price increases, and vice versa.
- Remanufacturing production uses recycled materials that decrease production costs; that is, $c_{mn} > c_{mr}$[50].
- The channel structure considers competition between battery suppliers, where the green supplier is the leader and the regular supplier and other supply chain members follow.
- The returned battery quality is expressed as $\lambda \in [0, 1]$. A value of λ indicates the high-quality batteries, which is reusable in the secondary market or for remanufacturing.
- The quality of remanufactured and new batteries is the same in terms of performance specifications and consumer perspectives.
- Carbon emissions of new and remanufactured batteries measured during the regular manufacturing and remanufacturing processes, respectively, show that remanufacturing releases fewer carbon emissions because of the use of recycled materials ($e_n > e_r$), although the production costs are slightly higher [36].

3.2. Mathematical modeling

By using recycled materials, the green battery supplier receives a government subsidy for each unit (remanufactured battery). Thus, their profit function is expressed as follows:

$$\prod_{S2}(w_r) = \Big[(w_r - c_{pr})D_r + p_c(E_r - e_r D_r) + (\eta w_r + \Delta)D_r - c_{mr}\tau(D_r + D_n) - I_r(1-\lambda)^2\Big] \tag{1}$$

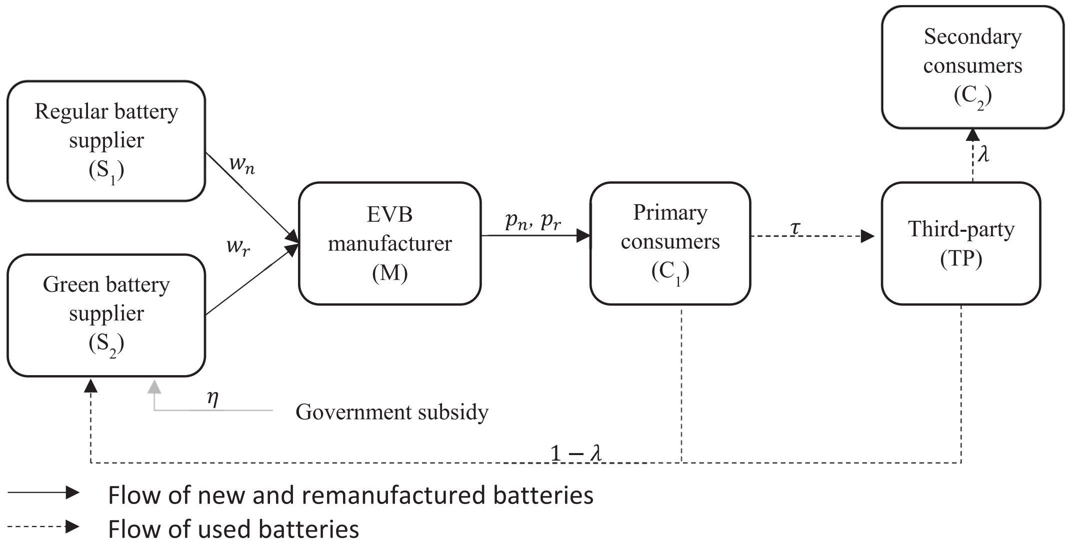

Fig. 1. CLSC with EVB supplier competition.

Eq. (1) describes the green supplier's profit, which can be calculated by the total profit from selling remanufactured batteries, the carbon credit trading revenue if the emissions are less than the allocation, the government subsidy and cost savings of using recycled materials based on the number of remanufactured batteries produced, the recycled material cost paid to a third-party collector, and the investment in remanufacturing.

During product market competition, a regular battery supplier provides only new batteries from natural materials. The profit of the regular supplier (Π_{S1}) consists of the profit from selling new batteries to automaker and carbon credit trading when the total carbon emission is less than their allocation. Thus, the regular battery supplier's profit function is described as follows:

$$\prod\nolimits_{S1}(w_n) = (w_n - c_{mn} - c_{pn})D_n + p_c(E_n - e_nD_n) \tag{2}$$

The EVB manufacturer's profit function (Π_M), which includes profit from selling new and remanufactured batteries to primary consumers, is calculated as follows:

$$\prod\nolimits_{M}(p_n, p_r) = (p_n - w_n)D_n + (p_r - w_r)D_r \tag{3}$$

Ultimately, the third-party profit demonstrates the impact of the reusable EVB market, recycled materials market, returned battery yield, and collection investment factors, as given by Eq.(4):

$$\prod\nolimits_{TP}(\tau) = p_u\tau\lambda(D_r + D_n) + c_{mr}\tau(1-\lambda)(D_r + D_n) - p_m\tau(D_n + D_r) - I_u\tau^2 \tag{4}$$

In the proposed model, the Stackelberg game leader is the green EVB supplier that determines the wholesale price (w_r), and then regular suppliers follow the leader's decision to optimize the wholesale price of the new EVB (w_n). Consequently, the retailer responds by setting the retail prices for new and remanufactured EVBs (p_n and p_r). Finally, the third-party, as a follower, determines the return rate (τ) based on the decisions of the green supplier and primary consumers. Using backward induction, we obtain the optimal results for the model, as described in the Appendix.

To express the formulas easily, we define $A_1 = (2\alpha^2 - \alpha\beta - \beta^2)c_{mr}\left[M(3\alpha+\beta) - \alpha(\alpha-\beta)(c_{mn} + c_{pn} + p_ce_n)\right]$, $A_2 = -(2\alpha^2 - \beta^2)(\Delta - c_{pr} - p_ce_r) + (1+\eta)(2M\alpha + M\beta + \alpha\beta c_{mn} + \alpha\beta c_{pn} + \alpha\beta p_ce_n)$, and $A_3 = c_{mr}(-2\alpha^2 + \alpha\beta + \beta^2)^2[(-1+\lambda)c_{mr} + p_m - \lambda p_u] - 8\alpha(2\alpha^2 - \beta^2)(1+\eta)I_u$.

The optimal decisions of the supply chain members under government subsidies and carbon trading are as follows:

$$w_r^* = \frac{-4\alpha A_2I_u + A_1[(-1+\lambda)c_{mr} + p_m - \lambda p_u]}{A_3} \tag{5}$$

$$w_n^* = \frac{1}{2\alpha}\left\{M + \frac{\beta\{-4\alpha A_2I_u + A_1[(-1+\lambda)c_{mr} + p_m - \lambda p_u]\}}{A_3} + \alpha(c_{mn} + c_{pn} + p_ce_n)\right\} \tag{6}$$

$$p_n^* = \frac{1}{4\alpha}\left\{M + \frac{2M\alpha}{\alpha-\beta} + \alpha(c_{mn} + c_{pn} + p_ce_n) + \frac{\beta\{-4\alpha A_2I_u + A_1[(-1+\lambda)c_{mr} + p_m - \lambda p_u]\}}{A_3}\right\} \tag{7}$$

$$p_r^* = \frac{1}{2}\left(\frac{M}{\alpha-\beta} + \frac{-4\alpha A_2I_u + A_1[(-1+\lambda)c_{mr} + p_m - \lambda p_u]}{A_3}\right) \tag{8}$$

$$\tau^* = \frac{1}{8\alpha A_3I_u}[(-1+\lambda)c_{mr} + p_m - \lambda p_u]\{-(2\alpha^2 - \alpha\beta - \beta^2)\{4\alpha A_2I_u + A_1[-(-1+\lambda)c_{mr} - p_m + \lambda p_u]\} - A_3[M(3\alpha+\beta) - \alpha(\alpha-\beta)(c_{mn} + c_{pn} + p_ce_n]\} \tag{9}$$

4. Results

The proposed model and relationships among parameters are analyzed as follows: (1) supply chain member profits and pricing decisions (under carbon trading regulations and government subsidies) are evaluated to determine how the self-price and competitive-price coefficients affect decision variables (which reflect green production promotion and sustainable development); and (2) the environmental impact of new and remanufactured battery production is analyzed.

To evaluate and provide managerial insights into the proposed model, the parameters for a new EVB market and EVB manufacturing were adopted from Wang et al. [20] and the IEA [51]. Parameters related to the remanufacturing and recycling of EBVs were obtained from the literature reviews of Gu et al. [38] and Xiong et al. [52]. Additionally, carbon trading prices were based on a report from the World Bank [11]. The setup parameters are listed as follows: M =

Table 3
Optimal decisions for the proposed model.

$w_r^* = 15,831$	$\tau^* = 0.75$	$\Pi_{S2} = 9.96\text{x}10^8$
$w_n^* = 16,818$	$\Pi_{TP} = 1.68\text{x}10^8$	$D_n = 91,354$
$p_n^* = 20,505$	$\Pi_{M_{EV}} = 7.7\text{x}10^8$	$D_r = 103,790$
$p_r^* = 20,012$	$\Pi_{S1} = 6.68\text{x}10^8$	

$600,000$, $\alpha = 25$, $\beta = 0.2$, $\eta = 0.1$, $\lambda = 0.6$, $c_{pn} = 1,860$, $c_{pr} = 1,950$, $p_m = 5,000$, $p_u = 8,500$, $c_{mn} = 7,500$, $c_{mr} = 5,500$, $I_u = 300,000,000$, $I_r = 90,000$, $e_n = 3$, $e_r = 2.7$, $E_n = 3,000$, $E_r = 3,000$, $p_c = 50$, and $\Delta = 2,000$.

Table 3 presents the major results obtained using the proposed model. First, the wholesale price of new batteries was slightly higher than that of remanufactured batteries owing to production costs, such as purchasing materials and ensuring a competitive advantage for remanufactured batteries, which represents an incentive for customers to choose environmentally friendly batteries. Moreover, the opportunity is offered for both regular and green suppliers to satisfy the market demand by considering competitive price coefficient $\beta = 0.2$. The system achieved a return rate of approximately 75%. It is likely that recycled materials and market demand will gradually balance each other out.

According to Gutman [53], the average cost of an EVB replacement is in the range of \$12,000 to \$22,000, depending on the manufacturer and battery pack capacity. Compared with our results, remanufactured EVBs can feasibly compete with new EVBs in the market. Investment in research and development, manufacturing between regions (e.g., the US, Europe, and Asia), and capacity expansion have resulted in a notable drop in battery prices over the last ten years. Therefore, from a practical perspective, the obtained solutions would encourage the remanufacturing industry based on its potential to promote sustainability and high competitiveness.

4.1. Effects of subsidies and carbon trading on the optimal decision

The effects of the carbon trading price and subsidies on the profits of supply chain members are illustrated in Fig. 2. Although the implementation of these two factors is expected to promote remanufacturing and enhance the profits of the entire supply chain, opposite profit change trends were observed. In Fig. 2 (a), the profit of the green battery supplier decreased slightly with increasing carbon prices, which will affect the upstream supply chain. Additionally, the other members retain the same profits, meaning that the operation of the supply chain is almost stable under the influence of carbon pricing. Fig. 2 (b) indicates that government subsidies increased the profits of all supply chain members, especially the supplier of green batteries, who directly received and shared financial support with other parties. The results show that the government's incentive encourages remanufacturing and brings profits to stakeholders rather than setting a higher price for carbon trading.

Fig. 3 shows the relationship between profit fluctuations and the self-price coefficient (α), competitive price coefficient (β), and recycled materials cost (c_{mr}). While the third-party nearly retained their economic benefits and only showed a small impact from these three factors, the other members reached different profit levels owing to their sensitivity to changes in α, β, and c_{mr}. The results showed that a lower α will provide a higher profit and narrow the profit gap between different supply chain members. Additionally, a change in β creates the opportunity to increase profits and improve the competitiveness of remanufactured EVBs on the market.

The recycled material cost (c_{mr}) negatively affected the profits of the green supplier and EV manufacturer relative to that of regular suppliers despite receiving subsidies from the government. In this case, the sustainable development of the EVB supply chain requires government financial support and purchasing cost management throughout the entire supply chain.

Table 4 shows the effects of the relevant parameters on the wholesale and retail prices of the two types of battery types. Among the external factors, government subsidies provide financial support to green suppliers. Subsequently, to satisfy the increased customer demand and obtain higher profits, EVB selling prices were reduced. However, increases in the carbon trading price limited the market demand for both battery suppliers and caused a notable increase in wholesale and retail prices. Although carbon emissions are managed by the carbon trading policy, such policies do not provide guarantees in a sustainable supply chain because increasing the carbon price is economically harmful. While recycled material costs only change the price of remanufactured batteries, raw material costs affect the market prices of new and remanufactured batteries. A certain change in material cost will change the market's competitiveness from new batteries to remanufactured batteries. Therefore, using recycled materials offers a reasonable price when material supply sources experience shortages or scarcity. Moreover, the government plays a leading role in balancing new and remanufactured EVBs to encourage battery recycling batteries and increase environmental awareness.

Fig. 4 shows the influence of related factors $(,\eta,\alpha,\beta,)$ on the return rate (τ) because of their important role in supplying materials for remanufacturing. The experimental results showed that p_c and α increased, which led to a lower return rate; thus, these parameters have a large effect on reducing profits and carbon emissions. In contrast, providing a moderate level of η and β might increase the percentage of

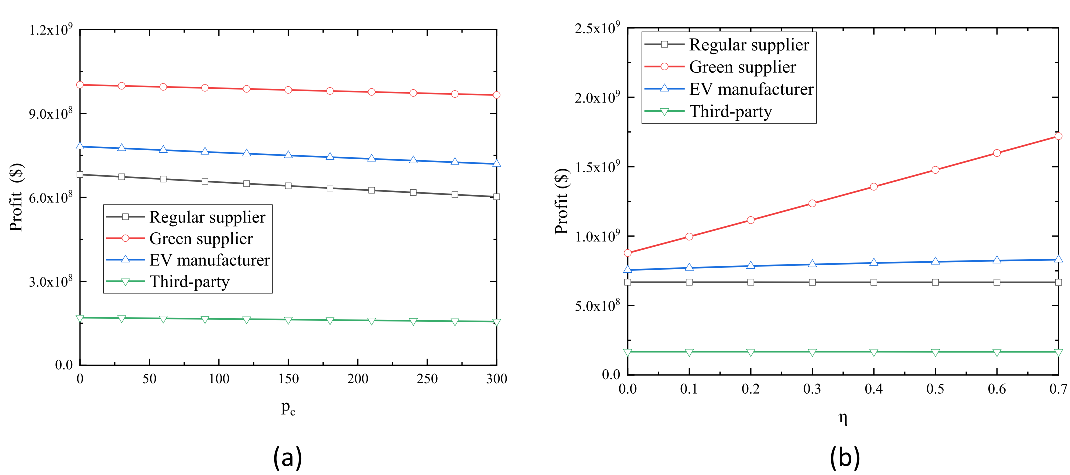

Fig. 2. Profits from regular and green suppliers of EVBs vs. carbon trading prices (p_c) and subsidies (η). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

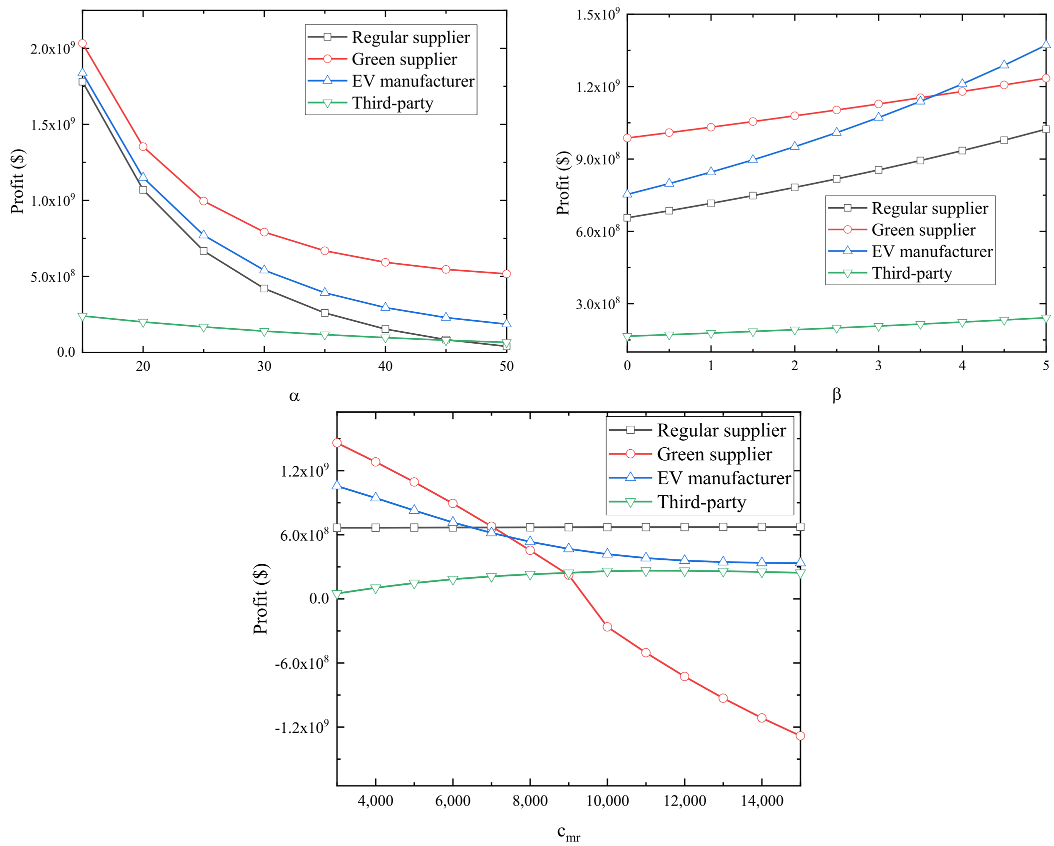

Fig. 3. Profit of regular and green suppliers of EVBs under α, β, and c_{mr}. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 4
Summary relationship between wholesale price, retailer price, and parameters.

	η	p_c	c_{mr}	c_{mn}
w_r	↓	↑	↑	↓
w_n	↓	↑	–	↑
p_r	↓	↑	↑	↓
p_n	↓	↑	–	↑

Note: ↑ or ↓ represents the positive or negative correlation.

used batteries returned and improve the ability to meet the increased demand for green battery suppliers. Therefore, a suitable incentive from government subsidies can be useful for supply chains to adapt to the growth in carbon emission restrictions and environmental concerns. Additionally, the curve in Fig. 4 (e) indicates a quadratic correlation between c_{mr} and τ. Notably, higher recycled material costs attract primary consumers to return used batteries. However, the return rate gradually decreases as the cost increases above the ideal material cost.

Fig. 5 shows the relationship between the market demand for different carbon trading prices and subsidies. Fig. 5 (a) shows that an increase in carbon prices drastically decreases market demand for regular and remanufactured EVBs. However, when a certain carbon trading regulation is applied to the supplier, the growth in government subsidies provides financial support to the green supplier; thus, demand increases sharply (Fig. 5 (b)). Additionally, the demand for regular batteries remains approximately the same regardless of subsidy changes. Thus, a higher subsidy provides more opportunities to encourage environmentally friendly production methods. Again, the results indicate a strong impact of both carbon trading policies and government subsidies on the entire supply chain performance, especially on profits, wholesale prices, retail prices, return rate, and market demand.

In summary, profits, demand, and return rates continue to increase when subsidies are considered. Thus, the supply of recycled materials is ensured by a substantially greater supply of retired batteries. Moreover, remanufacturing can achieve economic targets while satisfying market demand.

4.2. Environmental performance comparison

Fig. 6 (a) shows that total carbon emissions decreased significantly with increasing carbon trading prices. Compared to traditional production, the combination of regular and green production results in lower carbon emissions (approximately 21.8%) and thus less damage to the environment. Regardless of market development and customer demand, the environmental impacts are mitigated by carbon trading regulations. As the demand for both batteries decreased (Fig. 5 (a)), a lower production quantity resulted in lower carbon emissions. Nevertheless, an optimal solution must be comprehensively considered from the perspectives of sustainability and market development. The solution should also promote an environmentally friendly production approach and fulfill consumer demand. Therefore, carbon trading regulations do not provide ideal suggestions for those who set ambitious sustainability goals as a long-term strategy.

Fig. 7 (a) shows the effect of carbon trading on the total profits and carbon emissions for the two EVB suppliers. The amount of carbon emissions decreased significantly with an increase in carbon trading price but was relatively high as the subsidies increased, as shown in Fig. 7(b). The results provide conflicting solutions for carbon emissions under green supplier incentives. The market demand pattern shows that if the government encourages supply chain members through subsidies, then more batteries, especially remanufactured batteries, will be produced to satisfy the market. Expanding the total production capacity

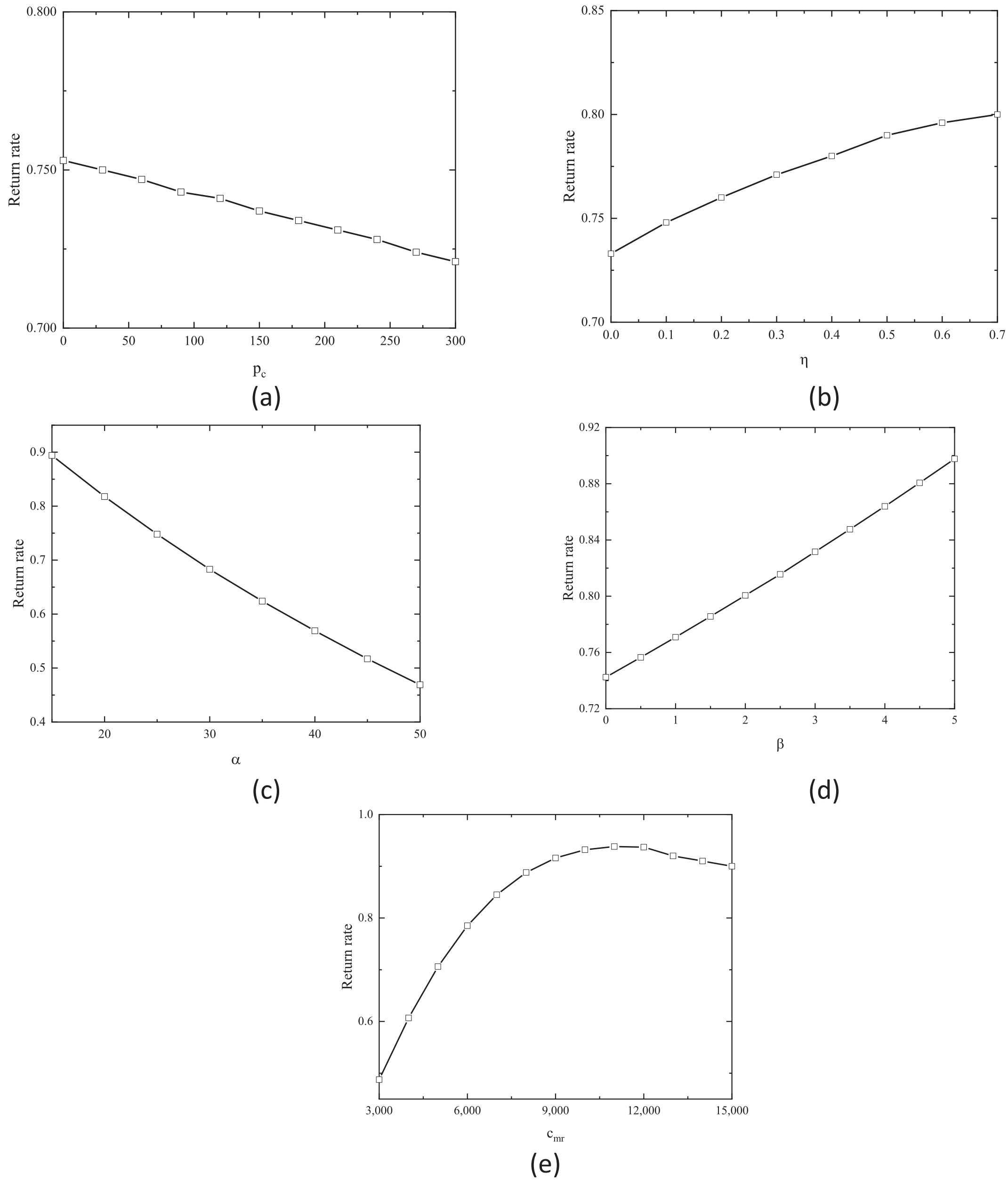

Fig. 4. Relationship between return rate and related parameters.

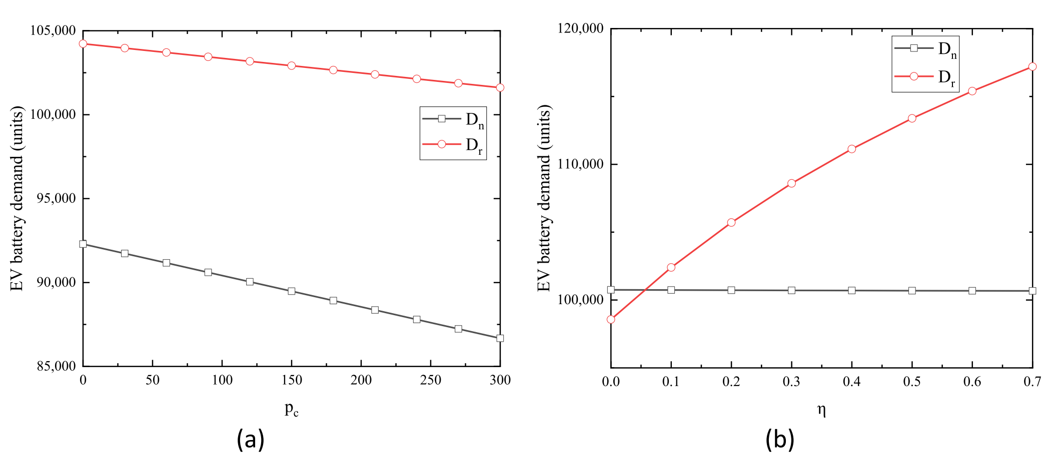

Fig. 5. Market demand vs. carbon trading price (a) and subsidy (b).

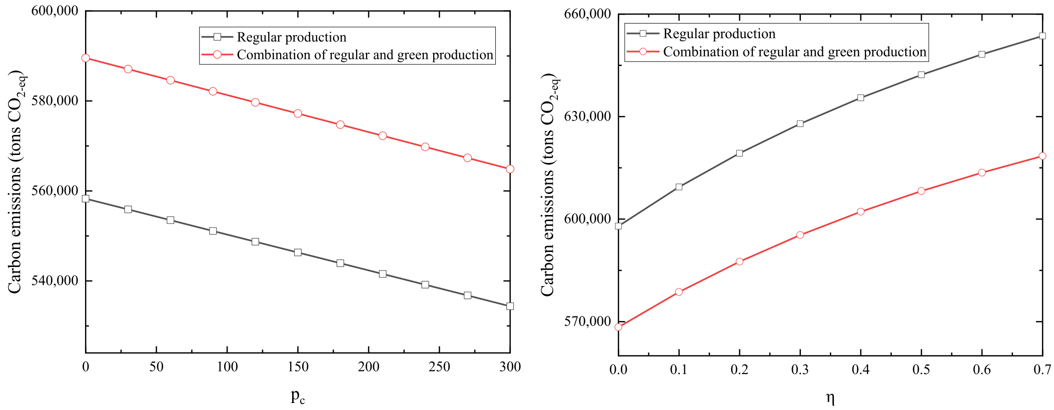

Fig. 6. Impact of p_c and η on total carbon emissions.

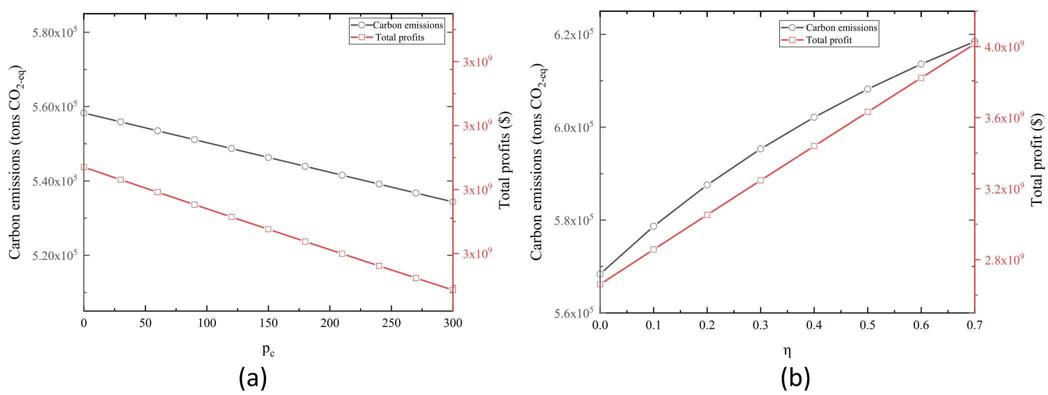

Fig. 7. Relationship between total supply chain profits and total carbon emissions under different carbon trading prices (a) and subsidies (b).

results in increased carbon emissions; however, the emissions are still lower relative to those emitted during new battery production. This situation reinforces and enhances the competitive advantage of green EVB production. Additionally, it provides a solution for sustainable battery development when the EV market is forecasted to grow exponentially in the coming decades with the increased number of retired batteries.

In summary, the supply chain performance (including two EVB suppliers) was analyzed based on profits, total carbon emissions, and potential consumer demand. Although carbon trading regulations are the core factors in reducing carbon production, they require integration with government subsidies. This would balance and maintain green manufacturing navigation while also producing lower carbon emissions compared to that in the regular production process.

This study provides several key managerial insights into remanufacturing EVB supply chains. First, government subsidies lead to remanufacturers who rely on government support, face overproduction, and exceed their carbon quotas. Thus, a remarkable reduction in the EVB market price will lead to lower competitiveness among battery types and faster degradation of remanufacturing operations owing to over-subsidies. Second, a supportive mechanism between government subsidies and carbon trading can enhance sustainability goals while encouraging more batteries to be returned from customers. Finally, the Stackelberg game model reflects the strong influence of upstream (remanufacturer) pricing decisions on third-party downstream members, especially in terms of EVB return rate.

5. Concluding Remarks

This study proposes a remanufacturing EVB supply chain model that comprehensively considers the battery supply, collection, and recycling processes. Owing to the dynamics of the global EV market, the proper management of retired EVBs would benefit the secondary battery market and reduce the pressure on raw material supply sources. These two competitive aspects would lead to the provision of new and remanufactured batteries to EV manufacturers at different wholesale prices. Retired batteries with degraded capacity are collected by a third party and then sold to the secondary market and green suppliers for repurposing and remanufacturing. Price and return rates are determined based on the optimal profit of supply chain members, with the green supplier representing the leader of the supply chain network. This analysis focused on government subsidies and carbon trading regulations as two key factors influencing profit, pricing strategy, and return rate. The competition between new and remanufactured batteries was also investigated, and the findings will provide suppliers and governments with appropriate incentives for the sustainable development of the EV market. The major findings are as follows.

- Government subsidies and carbon trading have positive and negative effects on the profits of all supply chain members, particularly the two EVB suppliers. A sustainable supply chain tends to balance and encourage green production to offer lower wholesale and retail prices under subsidies because of the competitive market between regular and green battery suppliers. A high carbon trading price decreases profits because of the rapid drop in market demand and

higher wholesale and retail prices. This finding indicates that subsidies are preferred to increase carbon trading prices to encourage battery remanufacturing.
- The lower the carbon emissions required to achieve a balance between economic and environmental development regarding carbon emissions, the higher the carbon trading price. Government subsidies encourage the production of remanufactured batteries and increase the collection rate compared to carbon trading regulations. Production increases may exceed the carbon emission quotas allowed by suppliers, who buy carbon credits to fulfill regulations.
- Based on the environmental assessment and sustainability, a notable amount of carbon emissions (approximately 21.8% less than that produced by the consumption of new materials alone) would be eliminated under this study's model and assumptions. The results also indicated that government subsidies should be shared with supply chain members to collect and sort retired batteries for energy storage or recycled materials. Therefore, this model considers third parties as followers that collect and preprocess used batteries before delivering them to secondary users and green EVB suppliers. An increase in the return rate under the government subsidy policy reduces the environmental impact of retired batteries. It also enhances the green production market demand and provides an advantage for remanufactured batteries in competitive markets.
- The return rate has a quadratic relationship with the cost of recycled materials. Hence, a reasonable recycled material cost leads to an optimal return rate; otherwise, the return rate decreases. This finding raises concerns regarding the relationship between third parties and green suppliers because the number of retired batteries increases with increased profit-sharing between supply chain members.

Although applying government subsidies and carbon trading policies would benefit development goals in the EV industry, certain limitations should be addressed. First, this study only examined the influence of financial incentives (including government subsidies) and carbon trading on the sustainable supply chain of EVs. Financial incentives may place heavy financial debt pressure on policymakers. Thus, exploring the interaction between financial and non-financial resources represents a practical direction for future research. Second, in a competitive market for regular and remanufactured products, the proposed model does not consider consumer preferences for remanufactured products. Thus, including consumers' preferences for remanufactured EVBs in the model would help assess and mitigate the bias of market demand and production capacity because of over-subsidies. Finally, this study assumes that the quality of returned batteries is predetermined. Several factors lead to uncertainty in returned batteries in different market segments (e.g., new batteries, remanufactured batteries, and secondary batteries). Nonetheless, developing a quality evaluation mechanism based on mathematical models is an effective method of providing practical guidance for the remanufacturing industry.

CRediT authorship contribution statement

Yu-Chung Tsao: Writing – review & editing, Writing – original draft, Validation, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Ho Thi Thu Ai:** Writing – review & editing, Writing – original draft, Validation, Software, Methodology, Conceptualization.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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Appendix A. Appendix

The decision objective function of the third-party collector is formulated as follows:

$$\prod\nolimits_{TP}(\tau) = p_u\tau\lambda(D_r+D_n) - p_m\tau(D_n+D_r) + c_{mr}\tau(1-\lambda)(D_r+D_n) - I_u\tau^2 \tag{A1}$$

By the first order derivative of Π_{TP} with respect to τ, we obtained the following:

$$\frac{\partial_{\Pi_{TP}}}{\partial_\tau} = -2\tau I_u - [2M - (\alpha-\beta)(p_n+p_r)][(-1+\lambda)c_{mr} + p_m - \lambda p_u]$$

and

$$\frac{\partial^2_{\Pi_{TP}}}{\partial_\tau{}^2} = -2I_u < 0 \tag{A2}$$

Thus, by solving these derivatives to zero, the optimal return rate was obtained:

$$\tau^* = -\frac{[(-1+\lambda)c_{mr} + p_m - \lambda p_u][2M_n - (\alpha-\beta)(p_n+p_r)]}{2I_u} \tag{A3}$$

The objective function of EV manufacturer was expressed as follows:

$$\prod\nolimits_M(p_n,p_r) = [(p_n-w_n)D_n + (p_r-w_r)D_r] \tag{A4}$$

Similarly, taking the first-order derivative of Π_M with respect to p_n and p_r, we can obtain:

$$\frac{\partial_{\Pi_M}}{\partial_{p_n}} = M_n - 2\alpha p_n + 2\beta p_r + \alpha w_n - \beta w_r \tag{A5}$$

$$\frac{\partial_{\Pi_M}}{\partial_{p_r}} = M_n + 2\beta p_n - 2\alpha p_r - \beta w_n + \alpha w_r \tag{A6}$$

The corresponding Hessian matrix of Eq. (A4) was expressed as follows:

$$H(p_n, p_r) = \begin{bmatrix} \frac{\partial^2_{\Pi_M}}{\partial_{p_n}{}^2} & \frac{\partial^2_{\Pi_M}}{\partial_{p_n}\partial_{p_r}} \\ \frac{\partial^2_{\Pi_M}}{\partial_{p_r}\partial_{p_n}} & \frac{\partial^2_{\Pi_M}}{\partial_{p_r}{}^2} \end{bmatrix} = \begin{bmatrix} -2\alpha & 2\beta \\ 2\beta & -2\alpha \end{bmatrix}$$

(A7)

The determinant is $4\alpha^2 - 4\beta^2 > 0$ by $\alpha > \beta$, which indicates that the retail price of a new battery has a larger effect on the demand than that of the remanufactured battery. Thus, the objective function is concave. By computing $\frac{\partial_{\Pi_M}}{\partial_{pn}} = 0$ and $\frac{\partial_{\Pi_M}}{\partial_{pr}} = 0$, we found that

$$p_n{}^* = \frac{1}{2}\left(\frac{M}{\alpha - \beta} + w_n\right) \tag{A8}$$

$$p_r{}^* = \frac{1}{2}\left(\frac{M}{\alpha - \beta} + w_r\right) \tag{A9}$$

Then, p_n^* and p_r^* we can formulate the regular and green EV suppliers' profits, respectively, as follows:

$$\prod\nolimits_{S1}(w_n) = \frac{1}{2}\left[\left(c_{mn} + c_{pn} + p_c e_n - w_n\right)\left(-M + \alpha w_n - \beta w_r\right) + 2p_c E_n\right] \tag{A10}$$

Taking the first-order derivative of Π_{S1} with w_n, we can derive the following:

$$\frac{\partial_{\Pi_{S1}}}{\partial_{w_n}} = \frac{1}{2}\left[M + \alpha\left(c_{mn} + c_{pn} + p_c e_n - 2w_n\right) + \beta w_r\right] \tag{A11}$$

And, $\frac{\partial^2_{\Pi_{S1}}}{\partial_{w_n}{}^2} = -\alpha < 0$. Thus, we have

$$w_n{}^* = \frac{\alpha\left(c_{mn} + c_{pn} + p_c e_n\right) + M_n + \beta w_r}{2\alpha} \tag{A12}$$

In addition to identifying the optimal value of the remanufactured-battery wholesale price, the profit objective function with $w_n{}^*$, p_n^* and p_r^* is as follows:

$$\begin{aligned}\prod\nolimits_{S2}(w_r) = \frac{1}{32}\Bigg\{ & -32(-1+\lambda)^2 I_r - \frac{8\left(c_{pr} - w_r\right)\left(2M\alpha + M\beta + \alpha\beta c_{mn} + \alpha\beta c_{pn} + \alpha\beta p_c e_n - 2\alpha^2 w_r + \beta^2 w_r\right)}{\alpha} + \frac{1}{\alpha^2 I_u} c_{mr}[(-1+\lambda)c_{mr} \\ & + p_m - \lambda p_u]\left[3M\alpha + M\beta + \alpha(-\alpha+\beta)c_{mn} + \alpha(-\alpha+\beta)c_{pn} - \alpha^2 p_c e_n + \alpha\beta p_c e_n - 2\alpha^2 w_r + \alpha\beta w_r + \beta^2 w_r\right]^2 \\ & + \frac{8\left(2M\alpha + M\beta + \alpha\beta c_{mn} + \alpha\beta c_{pn} + \alpha\beta p_c e_n - 2\alpha^2 w_r + \beta^2 w_r\right)(\Delta + \eta w_r)}{\alpha} + \frac{8p_c\left[4\alpha E_r - e_r\left(2M\alpha + M\beta + \alpha\beta c_{mn} + \alpha\beta c_{pn} + \alpha\beta p_c e_n - 2\alpha^2 w_r + \beta^2 w_r\right)\right]}{\alpha}\Bigg\}\end{aligned} \tag{A13}$$

Hence, equating the first-order derivative of Π_{S2} to zero with respect to w_r, we obtained the following:

$$\begin{aligned}\frac{\partial_{\Pi_{S2}}}{\partial_{w_r}} = -\frac{1}{16\alpha^2 I_u}\Big\{ & -4\alpha I_u\big[(-2\alpha^2 + \beta^2)\Delta + M(2\alpha+\beta)(1+\eta) + \alpha\beta(1+\eta)c_{mn} + \alpha\beta(1+\eta)c_{pn} + 2\alpha^2 c_{pr} - \beta^2 c_{pr} + \alpha\beta p_c e_n + \alpha\beta\eta p_c e_n + 2\alpha^2 p_c e_r - \beta^2 p_c e_r \\ & - 2\left(2\alpha^2 - \beta^2\right)(1+\eta)w_r\big] + (\alpha-\beta)(2\alpha+\beta)(-1+\lambda)c_{mr}^2\left\{M(3\alpha+\beta) - (\alpha-\beta)\left[\alpha\left(c_{mn} + c_{pn} + p_c e_n\right) + (2\alpha+\beta)w_r\right]\right\} \\ & + (\alpha-\beta)(2\alpha+\beta)c_{mr}(p_m - \lambda p_u)\left\{M(3\alpha+\beta) - (\alpha-\beta)\left[\alpha\left(c_{mn} + c_{pn} + p_c e_n\right) + (2\alpha+\beta)w_r\right]\right\}\Big\}\end{aligned} \tag{A14}$$

In addition, $\frac{\partial^2_{\Pi_{S2}}}{\partial_{w_r}{}^2} = -\frac{\left(2\alpha^2 - \beta^2\right)(1+\eta)}{2\alpha}$. If $2\alpha^2 > \beta^2$, then $\frac{\partial^2_{\Pi_{S2}}}{\partial_{w_r}{}^2} < 0$. Thus, the optimal solution for w_r is expressed as follows:

$$\begin{aligned}w_r{}^* = \Big\{ & \left(2\alpha^2 - \alpha\beta - \beta^2\right)(-1+\lambda)c_{mr}^2\left[M(3\alpha+\beta) - \alpha(\alpha-\beta)\left(c_{mn} + c_{pn} + p_c e_n\right)\right] + (p_m - \lambda p_u)\left(2\alpha^2 - \alpha\beta - \beta^2\right)c_{mr}\left[M(3\alpha+\beta) - \alpha(\alpha-\beta)\left(c_{mn} + c_{pn} + p_c e_n\right)\right] \\ & - 4\alpha I_u\left[-\left(2\alpha^2 - \beta^2\right)\left(\Delta - c_{pr} - p_c e_r\right) + (1+\eta)\left(2M\alpha + M\beta + \alpha\beta c_{mn} + \alpha\beta c_{pn} + \alpha\beta p_c e_n\right)\right]\Big\} \Big/ \Big[c_{mr}\left(-2\alpha^2 + \alpha\beta + \beta^2\right)^2[(-1+\lambda)c_{mr} + p_m - \lambda p_u] \\ & - 8\alpha\left(2\alpha^2 - \beta^2\right)(1+\eta)I_u\Big]\end{aligned} \tag{A15}$$

By denoting $A_1 = \left(2\alpha^2 - \alpha\beta - \beta^2\right)c_{mr}\left[M(3\alpha+\beta) - \alpha(\alpha-\beta)\left(c_{mn} + c_{pn} + p_c e_n\right)\right]$, $A_2 = -\left(2\alpha^2 - \beta^2\right)\left(\Delta - c_{pr} - p_c e_r\right) + (1+\eta)\left(2M\alpha + M\beta + \alpha\beta c_{mn} + \alpha\beta c_{pn} + \alpha\beta p_c e_n\right)$, and $A_3 = c_{mr}\left(-2\alpha^2 + \alpha\beta + \beta^2\right)^2[(-1+\lambda)c_{mr} + p_m - \lambda p_u] - 8\alpha\left(2\alpha^2 - \beta^2\right)(1+\eta)I_u$, the expression of $w_r{}^*$ can be described as follows

$$w_r^* = \frac{-4\alpha A_2 I_u + A_1[(-1+\lambda)c_{mr} + p_m - \lambda p_u]}{A_3} \tag{A16}$$

Substituting Eq. (A15) into Eq. (A12), we can identify the formula of $w_n{}^*$ as follows:

$$w_n^* = \frac{1}{2\alpha}\left\{M + \frac{\beta\{-4\alpha A_2 I_u + A_1[(-1+\lambda)c_{mr} + p_m - \lambda p_u]\}}{A_3} + \alpha(c_{mn} + c_{pn} + p_c e_n)\right\} \tag{A17}$$

Substituting Eqs. (A16) and (A17) into Eqs. (A8) and (A9), the p_n^* and p_r^* values are obtained as follows:

$$p_n^* = \frac{1}{4\alpha}\left\{M + \frac{2M\alpha}{\alpha-\beta} + \alpha(c_{mn} + c_{pn} + p_c e_n) + \frac{\beta\{-4\alpha A_2 I_u + A_1[(-1+\lambda)c_{mr} + p_m - \lambda p_u]\}}{A_3}\right\} \tag{A18}$$

$$p_r^* = \frac{1}{2}\left(\frac{M}{\alpha-\beta} + \frac{-4\alpha A_2 I_u + A_1[(-1+\lambda)c_{mr} + p_m - \lambda p_u]}{A_3}\right) \tag{A19}$$

Substituting Eqs. (A18) and (A19) into Eq. (A3), the optimal return rate is as follows:

$$\tau^* = \frac{1}{8\alpha A_3 I_u}[(-1+\lambda)c_{mr} + p_m - \lambda p_u]\{-(2\alpha^2 - \alpha\beta - \beta^2)\{4\alpha A_2 I_u + A_1[-(-1+\lambda)c_{mr} - p_m + \lambda p_u]\} - A_3[M(3\alpha+\beta) - \alpha(\alpha-\beta)(c_{mn} + c_{pn} + p_c e_n]\} \tag{A20}$$

Finally, we can obtain the results of Π_{S2}, Π_{S1}, Π_M, and Π_{TP}. Owing to its tedious nature, we do not present a specific expression here.

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