Developing Pricing Strategy in a Closed-Loop Supply Chain for Electric Vehicle Batteries With a Government Reward and Punishment Mechanism

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ABSTRACT

Electric vehicles are expected to become a major means of transportation in the future, but entail the challenge of collecting used electric vehicle batteries. This article examines pricing strategies in a closed-loop dual-channel supply chain for electric vehicle batteries both with and without a governmental reward and punishment mechanism. The discussion considers the optimal pricing strategy considering the competition between dual collecting channels, both with the government's reward and punishment mechanism and without it. The degree of influence of government mechanisms, echelon utilization, and EV battery collection on a) collection price, b) collection capacity, and c) the profit obtained by participants are also examined. The discussion shows that collection capacity, collection price, and recycler profits in the closed-loop EV battery supply chain could be improved with a government reward and punishment mechanism. Finally, the robustness of the proposed model was verified through numerical examples.

KEYWORDS

Closed-Loop Supply Chain, Echelon Utilization, Electric Vehicle Battery, Government Reward and Punishment Mechanism, Pricing Decision

INTRODUCTION

Electric vehicles (EVs) are expected to become a major means of transportation in the future, despite the challenge they entail in collecting and recycling used EV batteries.

An EV battery is a critical component of an electric vehicle and accounts for 50% of the cost of an EV. Additionally, the EV battery must be replaced when its charging capacity decreases by 70% or 80% of the maximum (McIntire-Strasburg, 2015). It is worth noting that an EV battery at the end of its life in its primary capacity remains valuable for echelon, or secondary, utilization. This further utilization of the collected battery takes advantage of the diminished but still-present capacity of a high-quality collected battery. Even when completely depleted, the collected battery, upon disassembly, can be converted into raw materials.

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An increasing number of EV batteries will need to be replaced given the growing popularity of EVs. Yu et al. (2019) point out that in this case, the used EV battery must be collected and reused rather than being discarded.

Research on the collection of EV batteries has attracted increasing attention, including the application of EV battery echelon utilization in backup power and energy storage systems as well as EV battery applications as backup power for communications base stations. An EV battery can be applied in energy storage systems to enhance power supply-demand management (Heymans et al., 2014). Gu et al. (2018) propose an optimum pricing strategy to maximize the overall profit of a closed-loop supply chain consisting of battery manufacturers and re-manufacturers and maximize profits by optimizing the manufacturing and re-manufacturing quantity of EV batteries as well as the purchase price of the collected EV battery.

The government reward and punishment mechanism plays an important role in the operation of a closed-loop supply chain. Governments worldwide have effectively promoted and stimulated relevant companies to engage in reverse logistics for collecting used EV batteries, according to Xie and Ma (2016). Simic and Dimitrijevic (2012) consider the influence of legislation on end-of-life car collections and environmental ecology. Incentives in the form of government subsidies for re-manufacturing activities have been proposed (Wang, K. Z. et al., 2014). Esenduran et al. (2015) analyze the influence of government collection policies on manufacturers and recyclers involved in a reverse supply chain. Wang and Chen (2013) study the positive effects of the government's policies and regulations on EV collection before putting forward a proposal for improving the government's policies and regulations on EV collection. Liu et al. (2015) analyze the impact of a government-subsidized recycler on collection prices and show that governmental reward and punishment measures affect closed-loop supply chain collections. Consequently, it is necessary to study the influence of government reward and punishment mechanisms on end-of-life EV battery collections. Normally, when the battery of electric vehicles drops to 70%~80%, for performance and safety reasons, the EVB has to be replaced. But the removed battery can still be used for energy storage and other purposes (Gu, X. Y. et al., 2021; Saxena et al., 2015). Furthermore, the government encourages EVB recycling for environmental protection and sustainable development considerations. Therefore, the EVB dual recycling channel CLSC should be built based on the recycling channels proposed by Zheng et al. (2021) and Zheng et al. (2022), thereby discussing the optimal decision.

Particularly, the paper considers the following research questions:

1. Optimum collection price decisions with and without the government reward and punishment model.
2. The influence of government rewards and punishments on the collection price, collection capacity, and the profit obtained by participants in the closed-loop supply chain.
3. The influence of echelon utilization and recycler's EV battery collection costs on the collection price, collection capacity, and profit obtained by participants in the closed-loop supply chain both with and without the government reward and punishment model.

A dual-channel closed loop supply chain composed of an EV battery manufacturer, an EV manufacturer, and an online EV battery recycler was developed in this study to address these issues. The EV battery manufacturer manufactures and sells the EV battery to the EV manufacturer, while the EV manufacturer sells to consumers the EV, with the EV battery as its part. Since both the EV manufacturer and the online EV battery recycler collect scrapped batteries, there is a collection competition between the two. The EV battery manufacturer makes profits from collecting EV batteries through echelon utilization. The government implements a reward and punishment mechanism for enterprises collecting end-of-life EV batteries in accordance with the government's target for collection capacity.

The main contributions of this paper are a) to present the influence of the reward and punishment mechanism set by the government for recyclers upon the collection capacity, collection price, and recycler profits in the EV battery closed-loop supply chain and, b) to analyze the degree of influence of government reward and punishment mechanisms, echelon utilization, and EV battery collection costs on the collection price, collection capacity, and profit obtained by participants in a closed-loop supply chain. At the same time, the authors develop online to offline (O2O) closed-loop supply chain pricing models both with and without a government reward and punishment mechanism so as to illustrate the influence of the government mechanism on the closed-loop EV battery supply chain.

The remainder of the paper is organized as follows. The next section is a brief literature review on relevant studies. The model assumptions are covered in the next section. The following section explores the model formulation and solution. In the next section, numerical examples are illustrated and sensitivity analyses are performed on the basis of the established model. Finally, the authors conclude the paper in the final section.

LITERATURE REVIEW

This section covers the literature concerning a) price decisions in a closed-loop supply chain, b) collection channels, and c) the influence of government intervention, subsidies, rewards, and punishment mechanisms on a closed-loop supply chain.

Price Decisions

Recently, research on closed-loop supply chains and collections has been attracting attention. Govindan and Soleimani (2017) and Govindan et al. (2015) present full-scale literature reviews on reverse logistics and closed-loop supply chains. This paper focuses on the pricing strategy of a closed-loop supply chain and the influence of the government on this supply chain.

Fleischmann (1997) proposes that the price of collecting a product is related to the final profit of each member of the reverse supply chain and the reverse supply chain system while appropriate pricing can encourage enterprises to select Pareto optimality. Savaskan et al. (2004) study the pricing problem in the re-manufacturing closed-loop supply chain formed by one manufacturer and one retailer. Savaskan and Van Wassenhove (2006) consider pricing strategies with direct and indirect collecting models under retailer competition. Wei et al. (2015) discuss optimum strategies for manufacturers and retailers' pricing and collection rate based on the game theory with symmetric and asymmetric data.

The Stackelberg game has been studied by a large number of scholars to describe the autonomy of supply-chain participants, to increase supply chain profits, and to formulate optimum price strategies. Yenipazarli (2016) analyzes the social, economic, and environmental benefits of collected products from the perspective of collection rate and the re-manufacturing of scrap products using the Stackelberg game model. Taleizadeh and Sadeghi (2018) apply a manufacturer-led Stackelberg model in the pricing of the closed-loop supply chain. Wang et al. (2017) consider the relationship between supply chain companies and the government. The government's carbon tariff policy is studied with the centralized and decentralized Stackelberg game model. Zhao et al. (2017) derive an optimum pricing strategy by proposing a Stackelberg model between two manufacturers and studying the pricing of complementary products in a supply chain that comprises two manufacturers and one retailer. Wang et al. (2018) study the optimum pricing strategy of a closed-loop supply chain in a competitive collection market and product market using the Stackelberg game model. Li and Chen (2018) establish the Stackelberg game theory model to study the retailer supply chain and explore the price, quality competition, and supply chain performance between the "two brands".

Collection Channels

A closed-loop supply chain with dual collection channels has been widely used in optimizing collection pricing strategy. Giovanni and Zaccour (2014) study the conditions under which manufacturers can outsource the collection business to retailers and third parties under a multi-channel collection model. Modak et al. (2018) discuss the influence of collection and product quality on the price decision by constructing a two-echelon closed-loop supply chain with dual channels. Jafari et al. (2017) study a dual-channel supply chain consisting of recyclers and manufacturers in addition to discussing the influence of the sustainability of waste collection on the economy and environment. Taleizadeh et al. (2018) study price, quality level, sales, and optimum collection strategies based on the established Stackelberg game model with dual-channel collection structures. Huang et al. (2013) and Gao et al. (2016) compare pricing strategies of single-channel and dual-channel collections in a closed-loop supply chain. Ding et al. (2016), Xiang and Li (2016), as well as Shang and Yang (2015) study the influence of dual-channel competition in reverse logistics on collection.

With respect to pricing strategies for online-offline collection channels, Di et al. (2018) analyze the pricing mechanisms and strategies for online and offline collection channels. Xie et al. (2018) study the contract coordination mechanism of the closed-loop supply chain to raise the profits of online and offline channels for supply chain members based on a Stackelberg game of the online-offline closed-loop supply chain. Kong et al. (2017) develop an online-offline closed-loop supply chain and observe that product pricing and service strategies are optimized by channel contradictions between the manufacturer and the retailer.

Government Intervention

The government intervenes in collections in the closed-loop supply chain through legislation and taxation. Yang and Chen (2018) discuss the optimum level of the government to launch carbon taxation in a supply chain consisting of manufacturers and retailers. Focusing on the O2O retail supply chain in a low-carbon environment, Ji et al. (2017) establish a transaction control decision-making model to discuss the government's optimum decision. According to an analysis by Heydari et al. (2017), the effect of the supply chain can be improved when the government offers tax exemptions and subsidies to the members of a closed-loop supply chain formed by manufacturers and retailers. Focusing on the government's legislation on the management of end-of-life products, Hammond and Beullens (2007) point out the influence of legislation on the reverse logistics of closed-loop supply chains.

Also, the government usually intervenes in collections within a closed-loop supply chain by providing rewards and punishments, such as subsidies. Li et al. (2018) establish a game model involving manufacturers, traditional retailers, and online retailers and also study the influence of the government's consumption subsidy policy on consumers. Based on game theory, Cao et al. (2017) study the interaction between the government and green supply chains and discuss the government's optimum decision-making by studying the influence of carbon caps and trading policies as well as a low-carbon subsidy policy on manufacturers. Wang, Y. X. et al. (2014) point out the characteristics of the government subsidy for automotive engine re-manufacturing by studying the influence of government-subsidized automotive engine re-manufacturing.

To sum up, the existing literature is very enlightening in understanding the closed-loop supply chain pricing, recycling channels, government intervention, subsidies, and reward and punishment mechanisms. It provides an important basis and reference for this research. However, worth further discussion is the role of government rewards and punishments in increasing EVB recovery for environmental protection and sustainable development purposes. On top of the above expandable research status, with the characteristics of echelon utilization in the closed-loop supply chain of EVB taken into consideration, the optimal pricing strategy for participants of the EVB dual recycling channel CLSC is explored in the context of the impact of government rewards and punishments.

To further clarify the contributions of the authors' research and highlight its differences from related works, they have sorted and briefly summarized these studies in Table 1. Firstly, past studies on Closed-Loop Supply Chains (CLSCs) have not adequately reflected the characteristics of Lithium-ion battery recycling, while the authors' study constructs a CLSC model for cascade utilization and material recovery of spent lithium-ion batteries. Secondly, past studies focused on comparing single-channel and dual-channel recycling models (Tang et al., 2019) while overlooking online recycling channels. Thirdly, previous works mainly explored the impacts of government policy-making on CLSCs of

Table 1. A brief review of the related literature

Author (year)	Used products collectors	Online-Offline	Government subsidy	Recycling approach			Demand pattern	
				Echelon utilization	Material extraction	Remanufacture	Certain	Uncertain
De Giovanni (2018)	R	-	-	-	✓	✓	-	✓
Chen et al. (2019)	R	-	-	-	-	✓	✓	-
Yang et al. (2020)	M; R; T	-	-	-	✓	-	✓	-
Gu, X. et al. (2021)	Rm	-	✓	✓	✓	✓	-	✓
Konstantaras et al. (2021)	Rm	-	-	-	-	✓	-	✓
Gorji et al. (2021)	T	-	✓	-	-	✓	-	✓
Luo et al. (2022)	M					✓	✓	
Zhou et al. (2023)	R; T	-	-	-	✓	✓	✓	-
Zhang et al. (2023)	R	-	-	✓	✓	-	✓	-
This paper	M; O	✓	✓	✓	✓	-	-	✓

Note: M: manufacturer; Rm: remanufacturer; R: retailer; T: third-party collector; O: online.

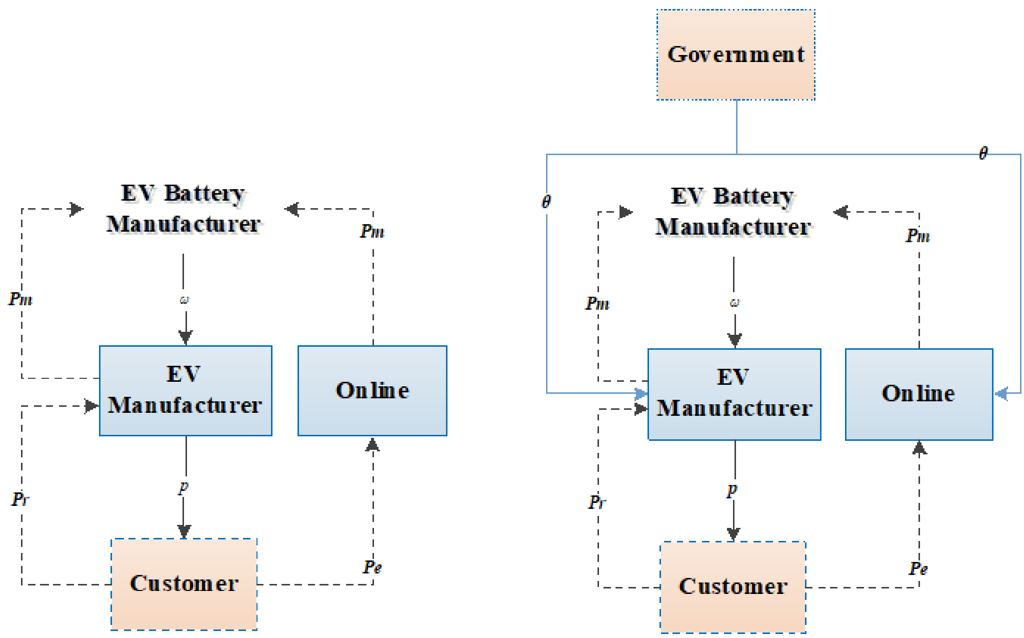
lithium-ion batteries (Xu et al., 2023), but the effects of government subsidies for recycling channels on such CLSCs deserve further investigation. Furthermore, the authors' study also considers customer preferences for online recycling channels, which is an aspect that has been relatively overlooked in previous research on Lithium-ion batteries.

PROBLEM DESCRIPTION

A closed-loop supply chain that is composed of an EV battery manufacturer, an EV manufacturer, and an online EV battery recycler has been developed in this study, as shown in Figure 1. The EV battery manufacturer produces and sells EV batteries to the EV manufacturer, while the EV manufacturer sells the EV with the EV battery to consumers. Since both the EV manufacturer and the online EV battery recycler collect end-of-life batteries, there is a collection competition between the two. The EV battery manufacturer can profit from collecting EV batteries through echelon utilization. The government implements a reward and punishment mechanism to influence enterprises collecting end-of-life EV batteries in accordance with its target. As the online collecting channel removes an intermediate stage in the transaction, operational costs can be lower, and thus, the online channel's collection cost is lower than that of the traditional collection channel. Based on this, the online collection channel is considered to be involved in the closed-loop EV battery supply chain.

Recycling channels are the basis for recycling. EVB enters subsequent echelon utilization, remanufacturing, and other reverse supply chain processes through the recycling channels. With the development of online e-commerce platforms, Aihuishou, alahb.com, and other online recycling channels have found their way into the commercial practice of recycling, providing consumers with convenient one-stop recycling services. Seeing the convenience of online recycling methods, recycling has also shifted from traditional recycler channels to online recycling channels. Furthermore,

Figure 1. Online to offline closed-loop supply chain of EV battery



considering the extended producer responsibility (EPR) system, introducing an online recycling platform built by EVB manufacturers here will better meet practical needs.

Baseline Hypothesis

Information among the EV battery manufacturer, EV manufacturer, and online EV battery recycler is symmetric in the closed-loop supply chain.

The cost of new raw materials for the EV battery manufacturer is c_m; and the cost of using collected materials for production is c_r, $\Delta = c_m - c_r$, $c_m > c_r$, indicating that it is cost-saving to use collected materials. No difference is found in the quality of products made from new raw materials or collected materials (Savaskan et al., 2004).

The EV battery manufacturer produces and sells an EV battery to the EV manufacturer at the wholesale price ω, and the EV manufacturer sells the EV with the EV battery as a part to consumers at the price p. The EV manufacturer collects used products from consumers at the price p_r, while the online EV battery recycler collects the used EV battery from consumers at the price p_e. The EV battery manufacturer collects all used products from the EV manufacturer and the online EV battery recycler at the price p_m. The profits obtained by each participant in the closed-loop supply chain are presented as $p_m > p_e$, $p_m > p_e$, $\omega > p$.

Demand function $d = \left(\alpha - \beta * p\right)$; $\alpha > \beta$ *p, where α and β represent the market demand and price sensitivity coefficient, respectively.

Total collection capacity $R = r_r + r_e$; where, r_r is the collection capacity of the EV manufacturer, and r_e is the collection capacity of the online EV battery recycler. $R < d$.

$r_r = m_1 p_r - m_2 p_e$, $r_e = m_1 p_e - m_2 p_r$; m_1 is the coefficient of consumer sensitivity to the collected price of the EV battery; m_2 is the collection competition coefficients of the EV manufacturer and the online EV battery recycler. $m_1 > m_2 > 0$

I_r and I_e are the collection costs of the EV manufacturer and the online EV battery recycler, respectively.

All EV batteries can be collected and reused. k is the ratio that can be used for echelon utilization; $k-1$ is the ratio of EV batteries that can be re-manufactured; v is the profitability $v > cm - cr$ of echelon utilization.

θ is the reward and punishment provided by the government for EV battery collection units. r_0 is the targeted collection capacity set by the government in order to raise the collection level of the closed-loop supply chain $r_r > r_0 > 0$, $r_e > r_0 > 0$. With objectives set for resource conservation, environmental protection, and sustainable development in the automotive industry (Zhou et al., 2023), the government aims to increase the quantity of recycling by providing subsidies for recycling lithium-ion batteries from electric vehicles (Wang et al., 2021; Yu et al., 2019). This is the primary purpose of these subsidies (Commerce, 2021), without any preference for specific recycling channels. Therefore, in this study, both EV manufacturers and online recyclers are eligible to receive equal amounts of subsidies. Gorji et al. (2021) have pointed out that the subsidies paid by the government to recycling channels have the effect of increasing recycling quantities.

Parameters

In order to formulate the problems, the following notations are utilized throughout the paper:

- d Market demand
- α Maximum market demand
- β Price sensitivity coefficient for consumers
- r_r Function of the EV manufacturer's collection capacity
- m_1 Sensitivity coefficient of the collection price for consumers
- m_2 Competition coefficient of collection channels
- r_e Function of the online EV battery recycler's collection capacity
- I_r EV manufacturer's collection cost
- I_e Online EV battery recycler collection cost
- θ Government rewards and punishments $\theta > 0$
- r_0 Target collection capacity $r_0 > 0$
- k Echelon utilization $0 < k < 1$
- v Profitability of echelon utilization
- c_m The cost of using new raw materials for production
- c_r The cost of using collected materials for production
- Π_m EV battery manufacturer profit
- Π_r EV manufacturer profit
- Π_e Online EV battery recycler profit
- ω The price at which the EV battery manufacturer sells the EV battery to the EV manufacturer
- p The price at which the EV manufacturer sells the EV battery as a separate component to a consumer

Decision Variables

p_r : The EV manufacturer's collection price
p_e : The collection price of the online EV battery recycler
p_m : The EV battery manufacturer's collection price

MODEL FORMULATION AND SOLUTION

Pricing Strategy of the Closed-Loop Supply Chain Without the Government Reward and Punishment Mechanism

Participants in the EV battery closed loop supply chain composed of an EV battery manufacturer, an EV manufacturer, and an online EV battery recycler are rational decision makers keen on maximizing their own profits. A two-stage game is formed by the EV battery manufacturer, the EV manufacturer, and the online EV battery recycler. The EV battery manufacturer is a Stackelberg leader, while the EV manufacturer and the online EV battery recycler are followers. The EV battery manufacturer determines the selling price ω and the collection price p_m. On this basis, the EV manufacturer and online EV battery recycler respond and set the selling price p as well as the collecting prices p_r and p_e, so as to maximize their own profits.

The EV battery manufacturer gains profits from manufacturing and selling the EV battery, from dismantling the EV battery for reuse, and from echelon utilization. Its decision function is:

$$\Pi_m^d = \left(\omega - c_m\right)d + \left(1-k\right)\left(c_m - c_r\right)\left(r_r + r_e\right) + vk\left(r_r + r_e\right) - p_m\left(r_r + r_e\right) \tag{1}$$

The EV manufacturer gains profits generated by the EV battery from selling the EV battery as a part of the EV and from collecting the EV battery. Its decision function is:

$$\Pi_r^d = \left(p - \omega\right)d + \left(p_m - p_r\right)r_r - I_r r_r \tag{2}$$

The online EV battery recycler gains profits from collecting the EV battery. Its decision function is:

$$\Pi_e^d = \left(p_m - p_e\right)r_e - I_e r_e \tag{3}$$

Π_m^d is the concave function with respect to ω and p_m; Π_r^d is the concave function with respect to p and p_r; and Π_e^d is the concave function with respect to p_e. Proof procedures are as shown in Appendix. With the existence of a unique optimum solution, the backward induction method can be used for solving the decision function, so as to derive the optimum decision of the closed-loop supply chain:

$$\frac{\partial \Pi_r^d}{\partial p} = \alpha - p\beta - \beta\left(p - \omega\right)$$

$$\frac{\partial \Pi_r^d}{\partial p_r} = -I_r m_1 + m_2 p_e + m_1\left(p_m - p_r\right) - m_1 p_r$$

$$\frac{\partial \Pi_e^{\,d}}{\partial p_e} = -I_e m_1 - m_1 p_e + m_1 \left(p_m - p_e\right) + m_2 p_r \tag{4}$$

The simultaneous solution for $\frac{\partial \Pi_r^{\,d}}{\partial p} = 0$, $\frac{\partial \Pi_r^{\,d}}{\partial p_r} = 0$, $\frac{\partial \Pi_e^{\,d}}{\partial p_e} = 0$ are:

$$p^d = \frac{\alpha + \beta\omega}{2\beta}$$

$$p_r^{\,d} = -\frac{2I_r m_1^{\,2} + I_e m_1 m_2 - 2m_1^{\,2} p_m - m_1 m_2 p_m}{4m_1^{\,2} - m_2^{\,2}}$$

$$p_e^{\,d} = -\frac{-2I_e m_1^{\,2} - I_r m_1 m_2 + 2m_1^{\,2} p_m + m_1 m_2 p_m}{4m_1^{\,2} - m_2^{\,2}} \tag{5}$$

Substitute p^d , $p_r^{\,d}$, and $p_e^{\,d}$ into equation (4) to solve $\frac{\partial \Pi_m^{\,d}}{\partial p_m}$ and $\frac{\partial \Pi_m^{\,d}}{\partial \omega}$. When $\frac{\partial \Pi_m^{\,d}}{\partial p_m} = 0$, $\frac{\partial \Pi_m^{\,d}}{\partial \omega} = 0$, it can be obtained:

$$p_m^{\,d*} = \frac{I_e + I_r + 2c_m\left(1-k\right) - 2c_r\left(1-k\right) + 2kv}{4}$$

$$\omega^{d*} = \frac{\alpha + c_m\beta}{2\beta} \tag{6}$$

By substituting $p_m^{\,d*}$ and ω^{d*} into p^d , $p_r^{\,d}$, and $p_e^{\,d}$, the authors obtain:

$$p^{d*} = \frac{3\alpha + c_m\beta}{4\beta}$$

$$p_r^{\,d*} = \frac{m_1\left(m_1\left(2I_e - 6I_r\right) - m_2\left(3I_e - I_r\right) + \left(2m_1 + m_2\right)\left(1-k\right)\left(2c_m - 2c_r\right) + 4m_1 kv + 2m_2 kv\right)}{16m_1^{\,2} - 4m_2^{\,2}}$$

$$p_e^{\,d*} = \frac{m_1\left(m_1\left(2I_r - 6I_e\right) + m_2\left(I_e - 3I_r\right) + \left(2m_1 + m_2\right)\left(1-k\right)\left(2c_m - 2c_r\right) + 4m_1 kv + 2m_2 kv\right)}{16m_1^{\,2} - 4m_2^{\,2}} \tag{7}$$

$\Pi_m^{\,d*}$, $\Pi_r^{\,d*}$ and $\Pi_e^{\,d*}$ can be obtained by substituting the optimum solution p^{d*} , $p_r^{\,d*}$, $p_e^{\,d*}$, $p_m^{\,d*}$, and ω^{d*} into the decision functions of the EV battery manufacturer, the EV manufacturer, and the online EV battery recycler.

Pricing Strategy of the Closed-Loop Supply Chain With the Government Reward and Punishment Mechanism

The EV battery manufacturer is a Stackelberg leader in the closed loop supply chain that is composed of an EV battery manufacturer, an EV manufacturer, and an online EV battery recycler. The government sets a reward and punishment mechanism for the EV manufacturer and the online EV battery recycler in order to enhance the collection of the EV battery and protect the environment. θ is the reward and punishment degree, while r_0 is the targeted collection capacity.

The decision functions of the EV battery manufacturer, the EV manufacturer, and the online EV battery recycler are:

$$\begin{aligned}
&\Pi_m^{\ \theta} = \left(\omega - c_m\right)d + \left(1-k\right)\left(c_m - c_r\right)\left(r_r + r_e\right) + vk\left(r_r + r_e\right) - p_m\left(r_r + r_e\right)\\
&\Pi_r^{\ \theta} = \left(p - \omega\right)d + \left(p_m - p_r\right)r_r - I_r r_r + \theta * \left(r_r - r_0\right)\\
&\Pi_e^{\ \theta} = \left(p_m - p_e\right)r_e - I_e r_e + \theta * \left(r_r - r_0\right)
\end{aligned} \tag{8}$$

The backward induction method can be used for solving the optimum decision of the closed-loop supply chain for the decision function:

$$\begin{aligned}
&\frac{\partial \Pi_r^{\ \theta}}{\partial p} = \alpha - p\beta - \beta\left(p - \omega\right)\\
&\frac{\partial \Pi_r^{\ \theta}}{\partial p_r} = -I_r m_1 + m_2 p_e + m_1\left(p_m - p_r\right) - m_1 p_r + m_1\theta\\
&\frac{\partial \Pi_e^{\ \theta}}{\partial p_e} = -I_e m_1 - m_1 p_e + m_1\left(p_m - p_e\right) + m_2 p_r + m_1\theta
\end{aligned} \tag{9}$$

When $\frac{\partial \Pi_r^{\ \theta}}{\partial p} = 0$, $\frac{\partial \Pi_r^{\ \theta}}{\partial p_r} = 0$ and $\frac{\partial \Pi_e^{\ \theta}}{\partial p_e} = 0$ the simultaneous solution can be obtained:

$$\begin{aligned}
&p^{\theta} = \frac{\alpha + \beta\omega}{2\beta}\\
&p_r^{\ \theta} = -\frac{2I_r m_1^{\ 2} + I_e m_1 m_2 - 2m_1^{\ 2} p_m - m_1 m_2 p_m - 2m_1^{\ 2}\theta - m_1 m_2\theta}{4m_1^{\ 2} - m_2^{\ 2}}\\
&p_e^{\ \theta} = -\frac{-2I_e m_1^{\ 2} - I_r m_1 m_2 + 2m_1^{\ 2} p_m + m_1 m_2 p_m + 2m_1^{\ 2}\theta + m_1 m_2\theta}{4m_1^{\ 2} - m_2^{\ 2}}
\end{aligned} \tag{10}$$

Substitute p^{θ}, $p_r^{\ \theta}$, and $p_e^{\ \theta}$ into equation (9) to solve $\frac{\partial \Pi_m^{\ \theta}}{\partial p_m}$ and $\frac{\partial \Pi_m^{\ \theta}}{\partial \omega}$. When $\frac{\partial \Pi_m^{\ \theta}}{\partial p_m} = 0$ $\frac{\partial \Pi_m^{\ \theta}}{\partial \omega} = 0$:

$$p_m^{\theta*} = \frac{I_e + I_r - 2\theta + 2c_m\left(1-k\right) - 2c_r\left(1-k\right) + 2kv}{4}$$

$$\omega^{\theta*} = \frac{\alpha + c_m\beta}{2\beta} \tag{11}$$

Substitute $p_m^{\theta*}$ and $\omega^{\theta*}$ into p^{θ}, p_r^{θ}, and p_e^{θ} to obtain:

$$p^{\theta*} = \frac{3\alpha + c_m\beta}{4\beta}$$

$$p_r^{\theta*} = \frac{m_1(m_1\left(2I_e - 6I_r\right) - m_2\left(3I_e - I_r\right) + \left(2m_1 + m_2\right)\left(1-k\right)\left(2c_m - 2c_r\right)}{16m_1^2 - 4m_2^2} + \frac{2\theta\left(2m_1 + m_2\right) + 4m_1kv + 2m_2kv)}{16m_1^2 - 4m_2^2}$$

$$p_e^{\theta*} = \frac{m_1(m_1\left(2I_r - 6I_e\right) + m_2\left(I_e - 3I_r\right) + \left(2m_1 + m_2\right)\left(1-k\right)\left(2c_m - 2c_r\right)}{16m_1^2 - 4m_2^2} + \frac{2\theta\left(2m_1 + m_2\right) + 4m_1kv + 2m_2kv)}{16m_1^2 - 4m_2^2} \tag{12}$$

$\Pi_m^{\theta*}$, $\Pi_r^{\theta*}$, and $\Pi_e^{\theta*}$ can be obtained by substituting the optimum solution $p^{\theta*}$, $p_r^{\theta*}$, $p_e^{\theta*}$, $p_m^{\theta*}$, and $\omega^{\theta*}$ into the decision functions of the EV battery manufacturer, the EV manufacturer, and the online EV battery recycler.

Proposition 1: When the government sets a reward and punishment mechanism for the EV manufacturer and the online EV battery recycler, the collection prices of the EV manufacturer and the online EV battery recycler are greater than when there is no reward and punishment mechanism. As for detailed proofing process, see Appendix.

When the government sets a reward and punishment mechanism for the EV manufacturer and the online EV battery recycler, consumers who can benefit from the increase of the collection price of end-of-life EV batteries tend to collect the end-of-life EV battery.

Proposition 2: When the government sets a reward and punishment mechanism for the EV manufacturer and the online EV battery recycler, the collection prices of the EV manufacturer and the online EV battery recycler rise with the increase of the reward and punishment θ. As for detailed proofing process, see Appendix.

When the government has a reward and punishment mechanism for the EV manufacturer and the online EV battery recycler, consumers' willingness to collect the EV battery will rise with the increase of reward and punishment θ.

Proposition 3: When the government sets a reward and punishment mechanism for the EV manufacturer and the online EV battery recycler, the collection prices of the EV battery manufacturer, the EV manufacturer, and the online EV battery recycler increase with the rise of echelon utilization. As for detailed proofing process, see Appendix.

When the government has a reward and punishment mechanism for the EV manufacturer and the online EV battery recycler, the increased collection prices brought about by the rise of echelon utilization k can increase the willingness of consumers, the EV manufacturer, and the online EV battery recycler to collect the end-of-life EV battery.

Proposition 4: When the government sets a reward and punishment mechanism for the EV manufacturer and the online EV battery recycler, the collection price of the EV battery manufacturer collecting the EV battery is lower than when there is no reward and punishment mechanism. As for detailed proofing process, see Appendix.

When the government sets a reward and punishment mechanism for the EV manufacturer and the online EV battery recycler, the recycler will assign $-\frac{\theta}{2}$ profits. The lowered price of the EV battery manufacturer collecting the EV battery can increase the profit obtained by the EV battery manufacturer.

Proposition 5: When the government sets a reward and punishment mechanism for the EV manufacturer and the online EV battery recycler, the collection capacities of the EV manufacturer and the online EV battery recycler are greater than when there is no reward and punishment mechanism. As for detailed proofing process, see Appendix.

When the government has a reward and punishment mechanism for the EV manufacturer and the online EV battery recycler, the government can adapt its purpose of reward and punishment with the increased capacity of the end-of-life EV battery.

Proposition 6: When the government sets a reward and punishment mechanism for the EV manufacturer and the online EV battery recycler, the EV battery manufacturer sells the EV battery to the EV manufacturer at an invariable price; the EV manufacturer sells the EV battery to consumers at an invariable price. That is to say, the government reward and punishment mechanism has no influence on the selling price of the EV battery. As for detailed proofing process, see Appendix.

NUMERICAL EXPERIMENTS AND SENSITIVITY ANALYSIS

Numerical Experiments

In this section, the authors use the same parameters as those applied previously to make further comparisons. Here, parameters related to market demand (i.e., α , β) shall refer to Ferrer and Swaminathan (2006); functions related to recycling costs (i.e., I_r , I_e , c_m , c_r , k , v) shall refer to Savaskan et al. (2004), Savaskan and Van Wassenhove (2006), Lambert (2019), and International Energy Agency (2019). In addition, the authors assume that the optimal recycling volume is the full recycling volume (i.e., r_0), and the magnitude of government rewards and punishments θ is 1; m_1 and m_2 are the coefficients of consumer sensitivity to the recycling price and the coefficient of competitiveness of the recycling channel, respectively; $m_1 > m_2 > 0$ therefore, the authors have $m_1 = 20$, $m_2 = 10$. The relevant parameters are selected, as shown in Table 2.

The optimum profits of the EV battery manufacturer, the EV manufacturer, and the online EV battery recycler both with and without the government reward and punishment mechanism are shown in Table 3.

The optimum collection prices and collection capacities of the EV battery manufacturer, the EV manufacturer, and the online EV battery recycler with and without the government reward and punishment mechanism are shown in Table 4.

As can be observed from Table 3 and Table 4, $\Pi_m^{\theta*} > \Pi_m^{d*}, \Pi_r^{\theta*} > \Pi_r^{d*}, \Pi_e^{\theta*} > \Pi_e^{d*}$, $\omega^{d*} = \omega^{\theta*}$, $p^{d*} = p^{\theta*}$, $p_m^{\theta*} < p_m^{d*}$, $p_r^{\theta*} > p_r^{d*}$, $p_e^{\theta*} > p_e^{d*}$, $r_r^{\theta} > r_r^{d}$, $r_e^{\theta} > r_e^{d}$.

When the government sets a reward and punishment mechanism for the EV manufacturer and the online EV battery recycler:

- The optimum profits of the EV battery manufacturer, the EV manufacturer, and the online EV battery recycler are greater than when there is no reward and punishment mechanism.
- The government reward and punishment mechanism has no influence on the selling price of the EV battery.
- The price of the EV battery manufacturer collecting the EV battery under a reward and punishment mechanism is lower than when there is no reward and punishment mechanism.
- The collection prices of the EV manufacturer and the online EV battery recycler are greater than when there is no reward and punishment mechanism.
- The collection capacities of the EV manufacturer and the online EV battery recycler are greater than when there is no reward and punishment mechanism.

Table 2. Value of the parameters in the numerical study

Parameters	α	β	m_1	m_2	I_r	I_e	r_0	k	v	c_m	c_r	θ
Value	100	3	20	10	1	0.5	1	0.5	4	6	4	1

Table 3. Value of the optimum profits

	Π_m	Π_r	Π_e	Π
Without reward & punishment	297.042	141.096	5.5125	443.65
With reward & punishment	315.375	142.151	8.56806	466.094

Table 4. Value of the optimum recycling prices and recycling capacities

	p	ω	p_m	p_r	p_e	r_r	r_e
Without reward & punishment	26.5	19.67	1.875	0.65	0.85	4.5	10.5
With reward & punishment	26.5	19.67	1.375	0.983	1.183	7.833	13.8333

Sensitivity Analysis

To examine the capability of the model under different values of the parameters, the authors carry out a sensitivity analysis regarding the key parameters of the model.

Influence of Government Reward and Punishment θ on the Collection Prices p_r^{θ}, p_e^{θ}, the Collection Capacities r_r^{θ}, r_e^{θ} as Well as the Profits Π_m^{θ}, Π_r^{θ}, and Π_e^{θ}

When the government sets a reward and punishment mechanism for the EV manufacturer and the online EV battery recycler, the collection prices p_r^{θ} and p_e^{θ} for the EV manufacturer and the online EV battery recycler rise with the increase of reward and punishment, as shown in Figure 2. In this way, consumers seeking profits tend to collect the end-of-life EV battery. With the enhancement of the reward and punishment, the collection capacities r_r^{θ} and r_e^{θ} of the EV manufacturer and the online EV battery recycler increase, as shown in Figure 3. In this way, the government achieves the purpose of the reward and punishment with a large volume of end-of-life EV batteries collected. With the enhancement of the reward and punishment, the profits Π_m^{θ}, Π_r^{θ}, and Π_e^{θ} of the EV battery manufacturer, the EV manufacturer, and the online EV battery recycler increase, as shown in Figure 4. In this way, profits obtained can stimulate participants in the closed-loop supply chain to actively participate in collecting suitable batteries.

Influence of Echelon Utilization k on the Collection Capacities r_r^{θ}, r_r^{d}, r_e^{θ}, and r_e^{d} With and Without the Reward and Punishment Mechanism

When the government sets a reward and punishment mechanism for the EV manufacturer and the online EV battery recycler, the collection capacities r_r^{θ} and r_e^{θ} of the EV manufacturer and the online EV battery recycler are larger than the collection capacities r_r^{d} and r_e^{d} without reward and punishment. Meanwhile, the collection capacity increases with the rise of echelon utilization k, as shown in Figure 5 and Figure 6. The collection capacity is positively affected by echelon utilization k, while the collection capacity under the reward and punishment mechanism is larger than without it.

Figure 2. Influence of the reward and punishment degree θ on the collection prices p_r^{θ} and p_e^{θ}

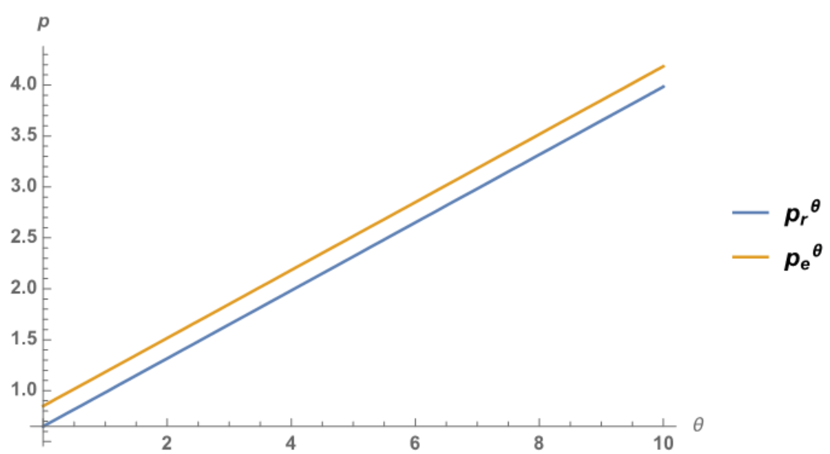


Figure 3. Influence of the reward and punishment degree θ on the collection capacity r_r^{θ} and r_e^{θ}

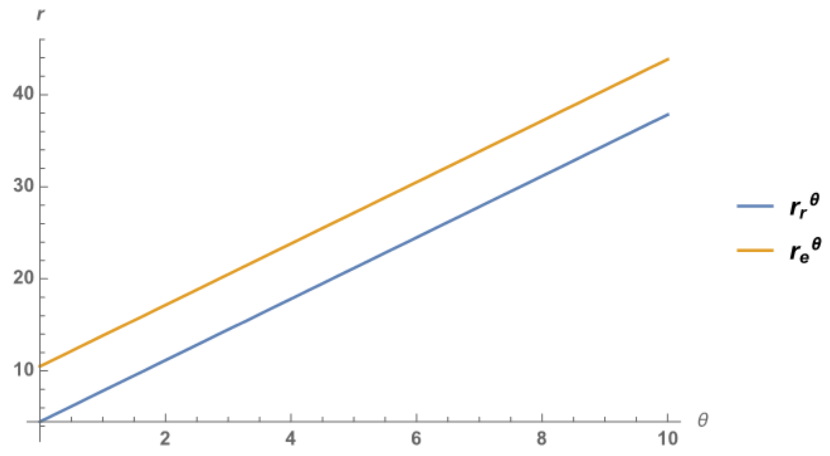
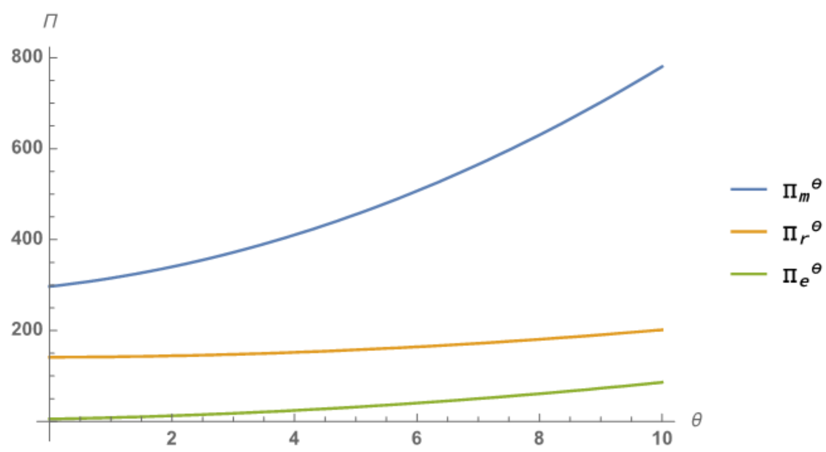


Figure 4. Influence of the reward and punishment degree θ on the profit Π_m^{θ}, Π_r^{θ}, and Π_e^{θ}



Influence of the Echelon Utilization k on the Collection Prices p_r^{θ}, p_r^{d}, p_e^{θ}, and p_e^{d} With and Without the Reward and Punishment Mechanism

When the government sets a reward and punishment mechanism for the EV battery manufacturer and the online EV battery recycler, the collection prices p_r^{θ} and p_e^{θ} of the EV manufacturer and the online EV battery recycler are larger than the collection prices p_r^{d} and p_e^{d} without the reward and punishment. Meanwhile, the collection price increases with the rise of echelon utilization k, as shown in Figure 7 and Figure 8. The collection price is positively affected by the echelon utilization k, while the collection price with the reward and punishment mechanism is larger than without it.

Figure 5. Influence of the echelon utilization k on the collection capacity r_r^{θ}, r_r^{d}

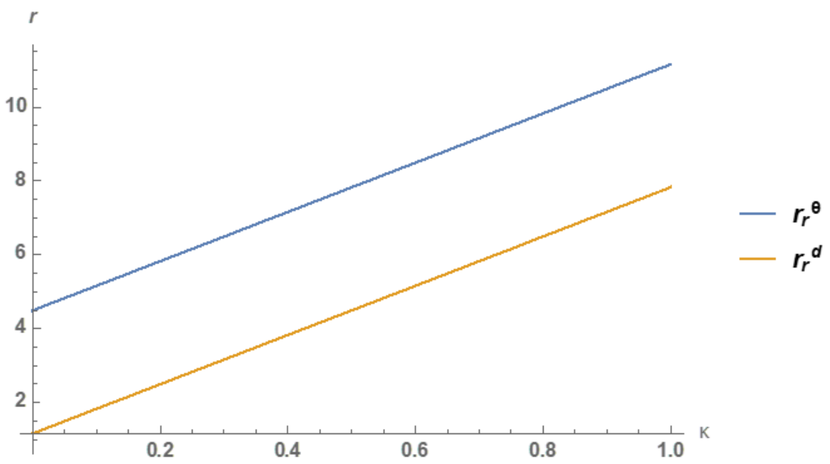
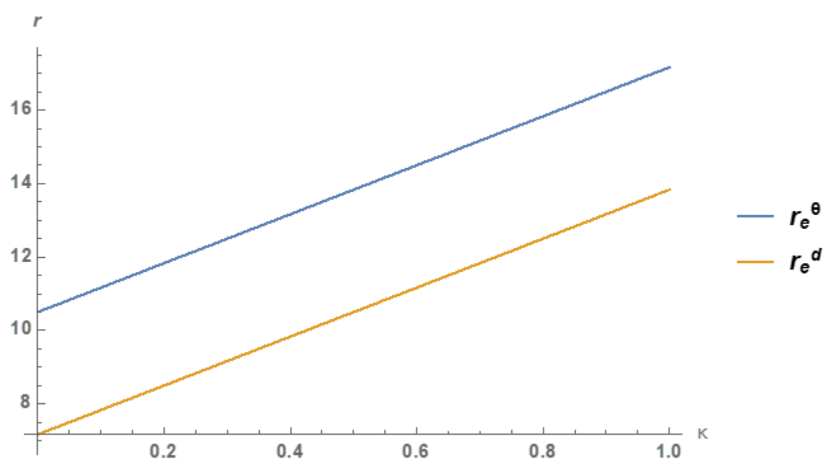


Figure 6. Influence of the echelon utilization k on the collection capacity r_e^{θ}, r_e^{d}



Influence of Echelon Utilization k on Respective Profits Π_m^{θ}, Π_r^{θ}, Π_e^{θ} and Π_m^{d}, Π_r^{d}, Π_e^{d} With and Without the Reward and Punishment Mechanism

Irrespective of whether the government sets a reward and punishment mechanism for the EV manufacturer and the online EV battery recycler, the profits Π_m^{θ} and Π_r^{θ} of the EV battery manufacturer and the EV manufacturer participating in the closed-loop supply chain as well as the profit of online EV battery recycler Π_e^{θ} increase with the increment of echelon utilization. Moreover, the increased range of profits Π_m^{θ}, Π_r^{θ}, and Π_e^{θ} of the participants in the closed-loop supply chain with echelon utilization k should be less than the increased range of profits Π_m^{d}, Π_r^{d}, and Π_e^{d} of the participants in the closed-loop supply chain with echelon utilization k when the government

Figure 7. Influence of echelon utilization k on collection price p_r^{θ}, p_r^{d}

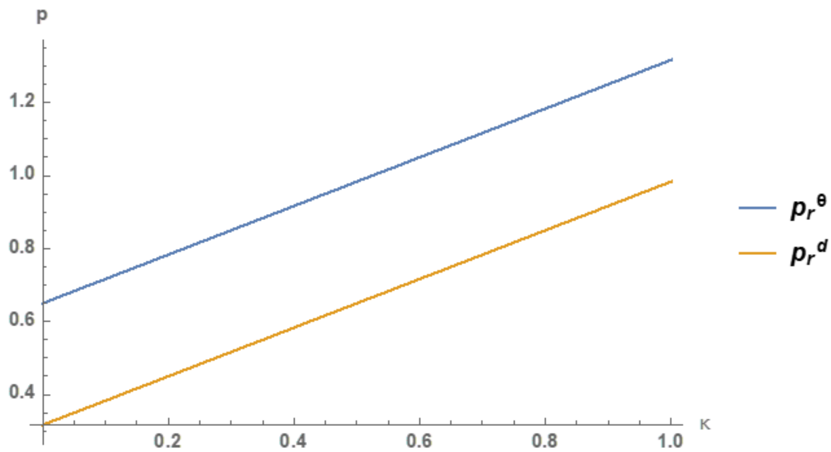
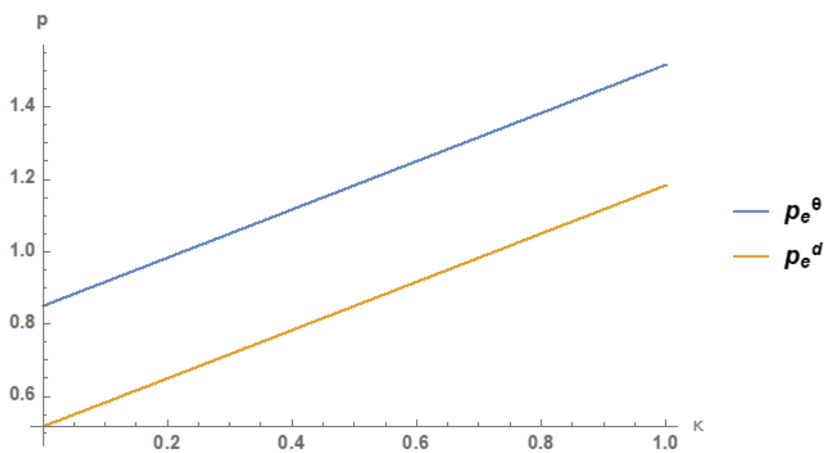


Figure 8. Influence of echelon utilization k on collection price p_e^{θ}, p_e^{d}



does not set the reward and punishment mechanism, as shown in Figure 9, Figure 10, and Figure 11. Echelon utilization has a positive impact on the profits obtained by the participants in the closed-loop supply chain.

Influence of Collection Costs I_r and I_e on Profits Π_m^{θ}, Π_r^{θ}, and Π_e^{θ}

As collection costs I_r and I_e of the EV manufacturer and the online EV battery recycler, respectively, increase, the collection costs of the EV manufacturer and the online EV battery recycler will be transferred to the EV battery manufacturer, resulting in increased collection costs and decreased profits of EV battery manufacturer Π_m^{θ}, as shown in Figure 12.

Figure 9. Influence of echelon utilization k on profits Π_m^θ and Π_m^d

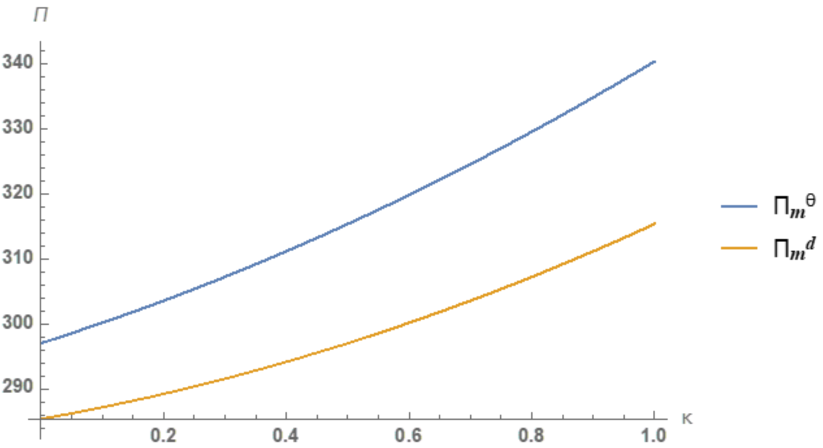
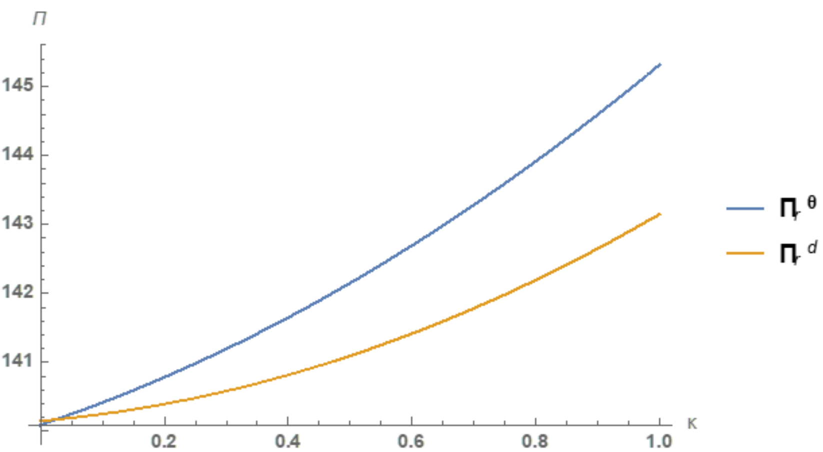


Figure 10. Influence of echelon utilization k on profits Π_r^θ, Π_r^d



As the collection cost I_r of the EV manufacturer increases, the profit Π_r^θ of the EV manufacturer decreases due to increased collection costs. Nevertheless, profit Π_r^θ of the EV manufacturer increases with the increased collection cost I_e of the online EV battery recycler, as shown in Figure 13.

As the collection cost I_e of the online EV battery recycler increases, the profit Π_e^θ of the online EV battery recycler decreases due to its increased collection cost. Nevertheless, the profit Π_e^θ of the online EV battery recycler increases with the increased collection cost I_r of the EV manufacturer, as shown in Figure 14.

Figure 11. Influence of echelon utilization k on profits $\Pi_e^{\theta}, \Pi_e^{d}$

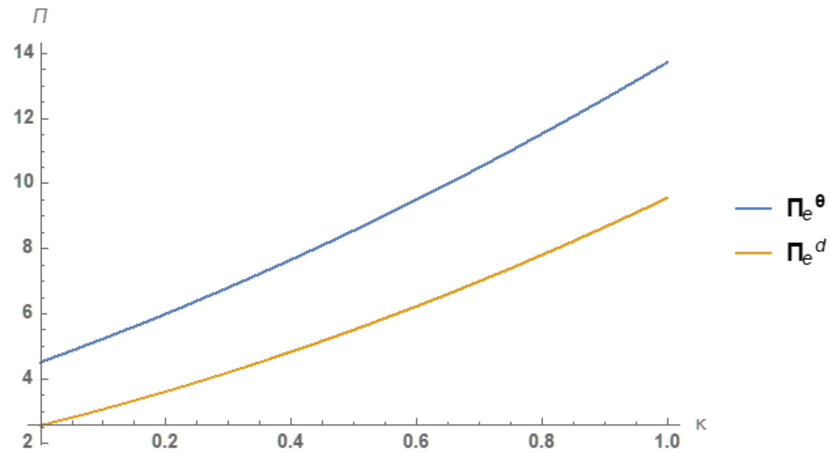
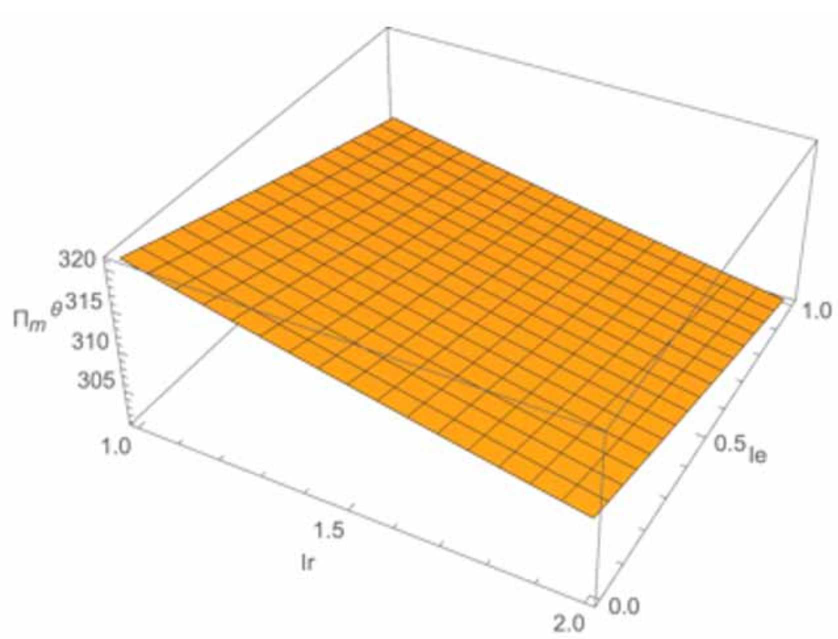


Figure 12. Influence of collection costs I_r and I_e on profits Π_m^{θ}



Influence of Collection Costs I_r I_e on Profits Π^{θ} and Π^{d}

The gross profits of the closed-loop supply chain without the reward and punishment mechanism as well as with the mechanism are $\Pi^{d} = \Pi_m^{d} + \Pi_r^{d} + \Pi_e^{d}$ and $\Pi^{\theta} = \Pi_m^{\theta} + \Pi_r^{\theta} + \Pi_e^{\theta}$, respectively. The profits of the closed-loop supply chain decrease as the collection cost I_r of the EV manufacturer

Figure 13. Influence of collection costs I_r and I_e on profits Π_r^{θ}

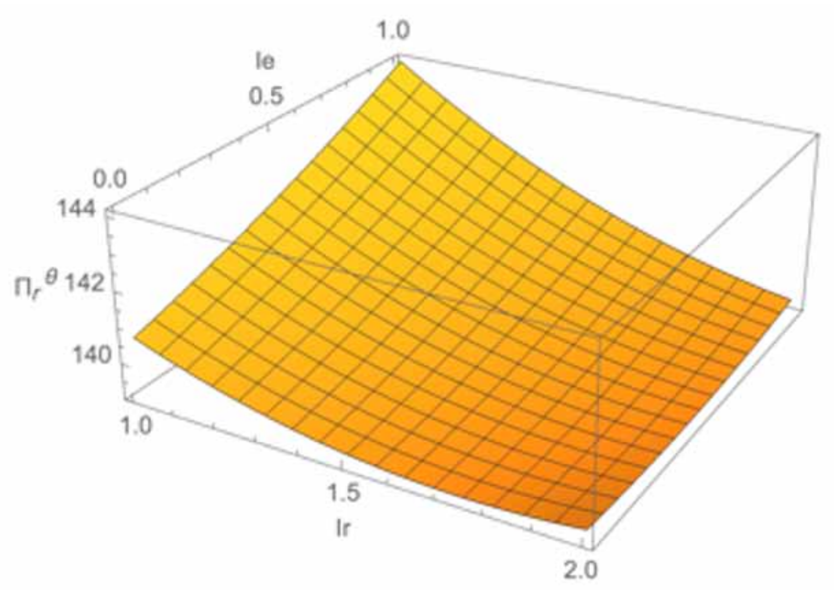
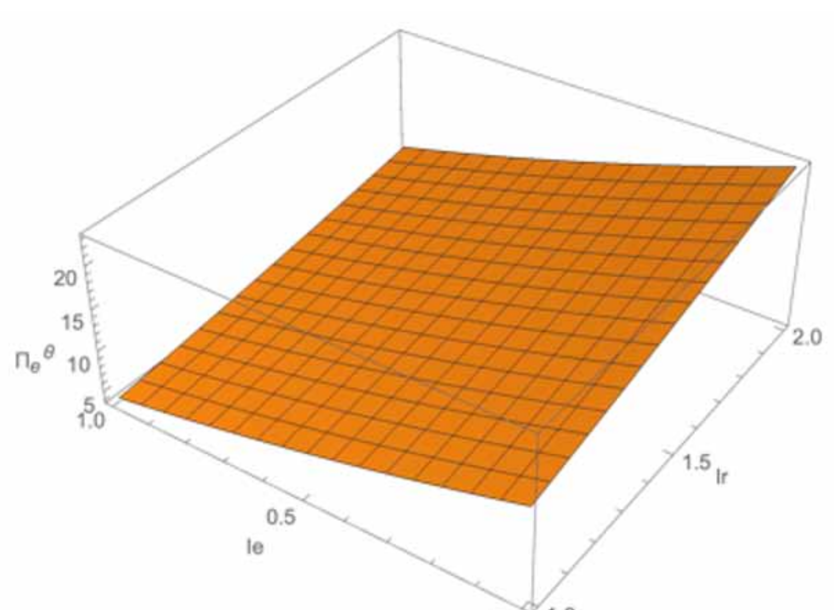


Figure 14. Influence of collection costs I_r and I_e on profit Π_e^{θ}



and the collection cost I_e of the online EV battery recycler increase. The profit Π^θ affected by the reward and punishment mechanism is higher than the profit Π^d, as shown in Figure 15.

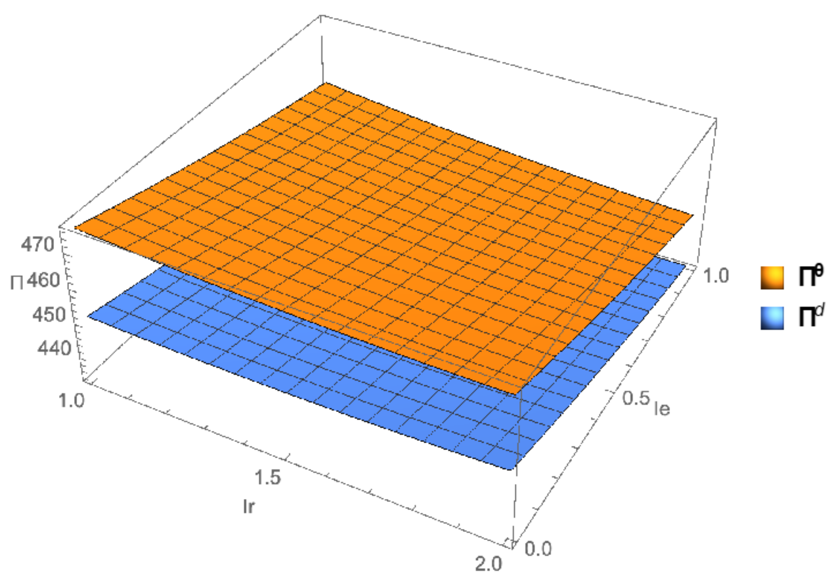
CONCLUSION

A closed-loop supply chain with online to offline collection channels consisting of an EV battery manufacturer, an EV manufacturer, and an online EV battery recycler was developed to ensure that the closed-loop supply chain can reach a certain collection capacity. Furthermore, the government has considered the influence of echelon utilization and collection costs on the closed-loop supply chain by designing a reward and punishment mechanism optimized for the targeted collection capacity. The collection capacity, collection price, and profit obtained by participants in the closed-loop supply chain have been studied both with and without the government reward and punishment mechanism for the EV manufacturer and the online EV battery recycler, respectively.

The main findings of the study include:

1. **Government rewards and punishments:** The recycling prices and volume of EV manufacturers and online EVB recyclers are higher with corresponding government rewards and punishments. In addition, as the magnitude of such rewards and punishments increases, EVB manufacturers, EV manufacturers, and online battery recyclers see greater profits. As the recycling prices rise, consumers benefit more, and therefore prefer to recycle end-of-life batteries; as the recycling profits increase, participants of the CLSC benefit more, and therefore actively participate in the recycling of end-of-life batteries. Overall, the increase in recycling volume achieves the goal of the government design of rewards and punishment.
2. **Consumer preferences:** Consumer preference for online recycling has a positive effect on EVB recycling volume and profits, which effect is captured in the government reward and punishment models. The government should prioritize productivity generated by technological advances when providing subsidies and incentives. In the discussion of this paper, Internet technology-based

Figure 15 Influence of collection costs I_r and I_e on profits Π^θ and Π^d



online recycling platforms provide convenient one-stop recycling service for consumers who need to dispose of EVB. Consumer preference for online recycling has brought online recycling platforms into recycling practice.

3. **Encouraging echelon utilization:** The prices and volume of batteries recycled by EVB manufacturers, EV manufacturers, and online battery recyclers increase as the rate of echelon utilization increases. Furthermore, compared with the situation without government rewards and punishments, the profits for CLSC participants increase to a larger extent with government rewards and punishments as the rate of echelon utilization increases. Therefore, it is necessary to encourage EVB echelon utilization (Ahmadi et al., 2017) and the development of more application scenarios for ex-service EVB.

This paper mainly discussed the influence of the government setting a reward and punishment mechanism for the EV manufacturer and online EV battery recycler on the collection capacity, collection price, and profits obtained by participants in the closed-loop supply chain. Possible directions for further research consist of: (1) considering the pricing strategy of the closed-loop supply chain with multi-cycle and random demands; and (2) considering the influence of consumer behavior on the pricing strategy of the closed-loop supply chain. Moreover, it is not uncommon for manufacturers and third-party recyclers to form alliances to make pricing decisions in certain industries (Choi et al., 2013; Savaskan et al., 2004). The authors are considering discussing the mechanism of alliance pricing in EVB CLSC.

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COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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APPENDIX

Proof 1: To prove the concavity of $\Pi_r{}^d$ with respect to p, p_r, the following Hessian matrix of $\Pi_r{}^d$ must be negative definite.

$$H\left(\Pi_r{}^d\right) = \begin{bmatrix} \dfrac{\partial^2 \Pi_r{}^d}{\partial p^2} & \dfrac{\partial^2 \Pi_r{}^d}{\partial p \partial p_r} \\ \dfrac{\partial^2 \Pi_r{}^d}{\partial p_r \partial p} & \dfrac{\partial^2 \Pi_r{}^d}{\partial p_r{}^2} \end{bmatrix} = \begin{bmatrix} -2\beta & 0 \\ 0 & -2m_1 \end{bmatrix} \tag{A1}$$

The Hessian matrix must be negative definite if conditions $-2\beta < 0$ and $4m_1\beta > 0$ are established.

Proof 2: To prove the concavity of $\Pi_e{}^d$ with respect to p_e.

$$\frac{\partial^2 \Pi_e{}^d}{\partial p_e{}^2} = -2m_1 \tag{A2}$$

The concavity of $\Pi_e{}^d$ with respect to p_e if conditions $-2m_1 < 0$.

Proof 3: To prove the concavity of $\Pi_m{}^d$ with respect to ω, p_m, the following Hessian matrix of $\Pi_m{}^d$ must be negative definite.

$$H\left(\Pi_m{}^d\right) = \begin{bmatrix} \dfrac{\partial^2 \Pi_m{}^d}{\partial \omega^2} & \dfrac{\partial^2 \Pi_m{}^d}{\partial \omega \partial p_m} \\ \dfrac{\partial^2 \Pi_m{}^d}{\partial p_m \partial \omega} & \dfrac{\partial^2 \Pi_m{}^d}{\partial p_m{}^2} \end{bmatrix} = \begin{bmatrix} \dfrac{4m_1\left(-m_1 + m_2\right)}{2m_1 - m_2} & 0 \\ 0 & -\beta \end{bmatrix} \tag{A3}$$

The Hessian matrix must be negative definite if conditions $\dfrac{4m_1\left(-m_1 + m_2\right)}{2m_1 - m_2} < 0$ and $\dfrac{4m_1\left(m_1 - m_2\right)\beta}{2m_1 - m_2} > 0$ are established.

Proof 4: Proof of Proposition 1

Proof

$$p_r{}^{\theta*} - p_r{}^{d*} = \frac{m_1\theta}{4m_1 - 2m_2} > 0$$

$$p_e{}^{\theta*} - p_e{}^{d*} = \frac{m_1\theta}{4m_1 - 2m_2} > 0 \tag{A4}$$

Proof 5: Proof of Proposition 2

Proof

$$\frac{\partial p_r^{\theta*}}{\partial \theta} = \frac{m_1\left(4m_1 + 2m_2\right)}{16m_1 - 4m_2} > 0$$

$$\frac{\partial p_e^{\theta*}}{\partial \theta} = \frac{m_1\left(4m_1 + 2m_2\right)}{16m_1 - 4m_2} > 0 \tag{A5}$$

Proof 6: Proof of Proposition 3

Proof

$$\frac{\partial p_m^{\theta*}}{\partial k} = \frac{-2c_m + 2c_r + 2v}{4} > 0$$

$$\frac{\partial p_r^{\theta*}}{\partial k} = \frac{m_1(-2c_m\left(2m_1 + m_2\right) + 2c_r\left(2m_1 + m_2\right) + 2v\left(2m_1 + m_2\right)}{16m_1 - 4m_2} > 0$$

$$\frac{\partial p_e^{\theta*}}{\partial k} = \frac{m_1(-2c_m\left(2m_1 + m_2\right) + 2c_r\left(2m_1 + m_2\right) + 2v\left(2m_1 + m_2\right)}{16m_1 - 4m_2} > 0 \tag{A6}$$

Proof 7: Proof of Proposition 4

Proof

$$p_m^{\theta*} - p_m^{d*} = -\frac{\theta}{2} < 0 \tag{A7}$$

Proof 8: Proof of Proposition 5

Proof

Without the reward and punishment mechanism, the collection capacities of the EV manufacturer and the online EV battery recycler are:

$$r_r^d = m_1 p_r^{d*} - m_2 p_e^{d*}$$

$$r_e^d = m_1 p_e^{d*} - m_2 p_r^{d*} \tag{A8}$$

With the reward and punishment mechanism, the collection capacities of the EV manufacturer and the online EV battery recycler are:

$$r_r^{\theta} = m_1 p_r^{\theta*} - m_2 p_e^{\theta*}$$

$$r_e^{\theta} = m_1 p_e^{\theta*} - m_2 p_r^{\theta*}$$

$$r_r^{\theta} - r_r^{d} = \frac{m_1(m_1 - m_2)\theta}{4m_1 - 2m_2} > 0$$

$$r_e^{\theta} - r_e^{d} = \frac{m_1(m_1 - m_2)\theta}{4m_1 - 2m_2} > 0 \tag{A9}$$

Proof 9: Proof of Proposition 6

Proof

$$\omega^{d*} = \omega^{\theta*} = \frac{\alpha + c_m\beta}{2\beta}$$

$$p^{d*} = p^{\theta*} = \frac{3\alpha + c_m\beta}{4\beta} \tag{A10}$$

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