

Article

Research on Recycling Strategies for New Energy Vehicle Waste Power Batteries Based on Consumer Responsibility Awareness

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Abstract: Due to the limited service life of new energy vehicle power batteries, a large number of waste power batteries are facing “retirement”, so it will soon be important to effectively improve the recycling and reprocessing of waste power batteries. Consumer environmental protection responsibility awareness affects the recycling of waste power batteries directly. Therefore, under the two recycling modes of new energy vehicle manufacturers and third-party recycling enterprises, this study analyzes the impact of consumer environmental protection responsibility awareness on the recycling price of waste power batteries and profit in the supply chain. The influence of factors such as recycling income, recycling input cost, and black-market recycling prices on consumer awareness of responsibility is also analyzed. Through theoretical research, it was found that: Under the model that third-party recycling enterprises are responsible for recycling, it can obtain better overall supply chain benefits; consumer environmental protection responsibility awareness and recycling benefits are positively correlated with supply chain benefits overall; and recycling benefits have a certain role in promoting consumer awareness of responsibility, while the increase in informal recycling prices inhibits consumer awareness of responsibility.

Keywords: NEV; waste power batteries; consumer environmental protection responsibility awareness; recycling strategy; reverse supply chain



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1. Introduction

With growing environmental problems, all countries have focused on the new energy vehicle industry and expect to alleviate the global energy crisis and environmental problems through the promotion of new energy vehicles (NEV). In China, the NEV industry is developing rapidly and it has been the largest producer and seller of NEVs in the world for more than 6 years, since 2015. While the production and sales of NEVs are booming, the new energy vehicle power batteries of the first batch are facing “retirement”. It is estimated that, by 2025, the “retired” power batteries in China will be up to 780,000 tons [1]. Owing to the high technical requirements and high cost of power battery recycling, the Ministry of Industry and Information Technology of China has announced a “whitelist” of 26 enterprises that have agreed to the *Industry Specifications for Comprehensive Utilization of Waste Power Batteries for New Energy Vehicles* to improve recycling efficiency. Meanwhile, by the end of September 2021, 171 new energy vehicle manufacturers and comprehensive utilization enterprises have set up 9985 recycling service networks across the country to ensure the effective recycling of power batteries. However, under such circumstances, only about 20% of the power batteries on the market are recycled by “whitelisted” enterprises in formal channels, which means that most of the waste power batteries are recycled in informal channels. This results in a greatly reduced recycling rate of waste power batteries

and is likely to cause a series of environmental problems and safety hazards. Therefore, it is necessary to effectively improve consumer environmental protection responsibility awareness and improve the recycling rate of waste power batteries in a formal channel.

According to the “*Resource Continuation: Research Report on the Circular Economy Potential of New Energy Vehicle Batteries in 2030*”, released by the international environmental protection organization Greenpeace and the China Environmental Protection Federation on 29 October 2020, the total amount of decommissioned power batteries for passenger electric vehicles worldwide will reach 12.85 million tons in 2021–2030, and the market scale of recycling and reuse will exceed 100 billion yuan [2]. The decommissioning of new energy vehicle batteries is a global phenomenon. The European Union, the United States, Japan, and other countries started earlier in the recycling of lead–acid batteries and lithium batteries, and the established recycling system has achieved good results [3]. For example, US power battery recycling laws involve federal, state, and local governments at all levels, and laws at all levels complement and regulate each other. It guides retailers and consumers (referring to new energy vehicle owners, the same below) through the power battery recycling price mechanism. In 2016, the European Union mandated that member states must recycle at least 45% of waste batteries, and the processing and utilization rate of lead, nickel, and isolators should not be less than 50% [4]; German law stipulates that producers, consumers, and recyclers should take corresponding responsibilities and obligations in the power battery recycling industry chain and emphasizes the extended producer responsibility system; Japan has promulgated laws and regulations in basic law, comprehensive law, and special law [5], and it has established a battery recycling system of “battery production-sales-recycling-renewable processing” [6]. Judging from the fact that most developed countries have formulated different levels of laws and regulations for power battery recycling and particularly emphasize the obligations and roles of consumers, we can see that consumers are extremely important in the process of power battery recycling. In China, the State Council promulgated the *Implementation Plan for the Extended Producer Responsibility System (EPR system)* (General Office of the State Council. Implementation plan of extended producer responsibility system (EB/OL). (25 December 2016). http://www.gov.cn/zhengce/content/2017-01/03/content_5156043.htm e.g., (accessed on 6 April 2022)) in 2017 [7] to ensure the effective recycling of power batteries, which stipulates that new energy vehicle manufacturers and battery production enterprises are responsible for the recycling of power batteries. Since 2017, the Ministry of Industry and Information Technology has issued eight policies for power battery recycling management to promote the construction of a new energy vehicle power battery recycling system [8]. In July 2021, the National Development and Reform Commission and other ministries of China jointly issued the *Circular on Issuing the 14th Five-Year Plan for the Development of Circular Economy* (National Development and Reform Commission. Development plan of circular economy in the 14th five year plan (EB/OL). (1 July 2021). https://www.ndrc.gov.cn/xxgk/zcfb/ghwb/202107/t20210707_1285527.html?code=&state=123 e.g., (accessed on 6 April 2022)) [9], which proposed action: strengthening the construction of traceability management platform and improving the traceability management system of new energy vehicle power batteries. Although the framework of the power battery recycling system in China is becoming more and more mature [10], the law still mainly focuses on new energy vehicle manufacturers and battery manufacturers, and it ignores the other stakeholders in the power battery recycling process, especially consumers, who are the source of power battery recycling.

In research on power battery recycling strategies, the recycling rate is one of the most important parameters. Many researchers regard the recycling rate as a fixed parameter [11–14] or take the recycling rate (or recycling amount) as the linear/nonlinear function of the recycling price. For example, Li and Mu [15], based on the research results of Heydari [16], took the recovery rate as a linear function of the recovery price to analyze the pricing strategy and its impact on the recycling rate with or without government regulation; Lu [17], considering the dual risks of market demand and quality in power

battery recycling, took the recycling price as a function of the recycling rate to analyze the optimal recycling price under decentralized and centralized decisions. In addition, many researchers have focused on analyzing other factors affecting the recycling rate of power batteries, such as government supervision and subsidy policy [18,19], socio-ecological environment, economic conditions and recycling technology [20], supply chain cooperation degree and recycling technology [14], government subsidies and channel selection [21], etc. Obviously, the current research ignores the influence of consumer environmental protection responsibility awareness on the recycling rate. Consumer environmental protection responsibility awareness means that consumers should not affect the living environment of others with their own consumption, which has an important impact on the selection of recycling channels, recycling rates, and recycling prices [22], but only increasing the recycling price is not effective in increasing consumers' environmental protection responsibility awareness of recycling [15,23]. Therefore, in research on power battery recycling strategies, it is necessary to take the consumer environmental protection responsibility awareness as one of the main factors affecting the recycling rate of power batteries in formal channels.

The recycling entities of the waste power batteries of new energy vehicles generally include new energy vehicle manufacturers, retailers, third-party recycling enterprises, battery manufacturers, etc. Savaskan et al. first studied the selection of the optimal recycling channel in a closed-loop supply chain and concluded that, under this assumption, retailer recycling is better than manufacturer recycling or third-party recycling [24]. Then, Savaskan et al. concluded that the degree of competition between retailers will have an impact on the manufacturer's recycling channel selection decision to a certain extent [25]. Sun et al. analyzed the impact of recycling price and sales volume on channel selection [26]. Hong et al. considered the significant impact of advertising on consumers and studied the impact of advertising on the selection of recycling channels and recycling pricing decisions [27]. Li et al. (2016) investigated the impact of different recycling channels on the profits of each supply chain member under a decentralized structure and identified the conditions and equilibrium characteristics of each recycling channel selection [28]. Chen and Tian found that the recycling price and sales price have an important impact on the choice of recycling mode for manufacturers and retailers [29]. Zhou considered the impact of collection efforts and the quality of recycled products, and the result showed that recycling by manufacturers or retailers depends on the cost-saving level of remanufacturing [30]. Zhang et al. analyzed the impact of environmental benefits, economic benefits, and social welfare on recycling channels [31]. Chen et al. studied the optimal selection of recycling channels based on mutual win-win situations in the supply chain [32]. Gong studied government funding policies with respect to ecological design levels, the recycling of power batteries as a government funding policy of reward factors, and the choice of power battery closed-loop supply chain recycling channels [33]. Although researchers have considered the many influencing factors of recycling channels, there is little research on the impact of consumer environmental protection responsibility awareness on channel selection.

In summary, consumers are the source of waste power battery recycling and play a crucial role in the recycling rate in formal channels. However, previous researchers did not take consumer factors into account. Therefore, this paper aims at the reverse supply chain formed by consumers, new energy vehicle manufacturers, and third-party recycling enterprises. It determines the pricing strategy and recycling channel strategy of the reverse supply chain based on consumer environmental protection responsibility awareness and explores the impact of different factors on consumers' sense of responsibility.

2. The Pricing Model of the Reverse Supply Chain of Waste Power Batteries

2.1. Problem Description

According to the *EPR*, new energy vehicle manufacturers and battery manufacturers are mainly responsible for power battery recycling. Ding [34] comprehensively considered factors, such as economic profits, recycling costs, and resource utilization, and believed that it is more appropriate to adopt the manufacturer alliance mode to recycle power

batteries. Yao and Jiang [35] proposed a battery recycling mode based on new energy vehicle enterprises, which is conducive to recycling power batteries from consumers and solving the problem of the irregular battery recycling market. This paper establishes a three-level reverse supply chain composed of consumers, new energy vehicle manufacturers, and third-party recycling enterprises, as shown in Figure 1. New energy vehicle manufacturers and third-party recycling enterprises can participate in power battery recycling, and the latter is responsible for the disposal of waste power batteries. Consumers, as the source of power battery recycling, can recycle waste power batteries in formal or informal channels, but both channels will be regulated by the government.

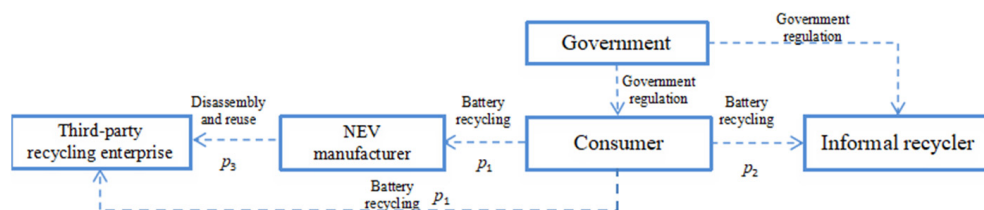


Figure 1. Reverse supply chain of power battery recycling.

2.2. Model Assumptions

(1) There are two recycling paths in the reverse supply chain. One is that the manufacturer is responsible for recycling waste power batteries from consumers at the price of p_1 and then sells them to a third-party recycling enterprise at the price of p_3 , which is responsible for processing; second, the third-party recycling enterprises directly obtain waste power batteries from consumers at the price of p_1 .

(2) Whether consumers will recycle waste power batteries through formal channels is mainly affected by two factors, namely, consumer environmental protection responsibility awareness and recycling price. Assuming that consumer environmental protection responsibility awareness is β , $\beta \in (0, 1]$. If $\beta = 1$, consumers are willing to recycle waste power batteries in formal channels no matter what the recycling price is. The waste power batteries can be sold to NEV manufacturers or third-party recycling enterprises at the price of p_1 , and they can also be sold to an informal recycler at the price of p_2 . The closer p_1 is to p_2 , the more the formal channels are preferred by consumers. When $p_1 \geq p_2$, regardless of consumer environmental protection responsibility awareness, they will always choose the formal channels. Therefore, this paper believes that the recycling rate (r) at which consumers choose in formal channels to recycle waste power batteries is $1 - (1 - \beta)\left(1 - \frac{p_1}{p_2}\right)$. When the sales volume of NEV is Q , assuming that its formal recycling volume is $Q\left[1 - (1 - \beta)\left(1 - \frac{p_1}{p_2}\right)\right]$, then the informal recycling volume will be $Q(1 - \beta)\left(1 - \frac{p_1}{p_2}\right)$.

(3) The government has a certain supervision role over consumers. If consumers are found to recycle waste power batteries illegally, they will be punished and fined. The probability of punishment is set as t , and the fine is set as δ .

(4) Recycling channels could be offered by NEV manufacturers or third-party recycling enterprises, both of which are not limited in terms of recycling capacity, while their recycling investment is related to the recycling rate, r . Drawing on the research results of [36], we set recycling investment as $\frac{1}{2}d_m\left(1 - (1 - \beta)\left(1 - \frac{p_1}{p_2}\right)\right)^2$ or $\frac{1}{2}d_r\left(1 - (1 - \beta)\left(1 - \frac{p_1}{p_2}\right)\right)^2$, where d_m represents the manufacturer's cost coefficient for recycling waste power batteries and d_r represents the third-party recycling enterprises' cost coefficient for recycling waste power batteries.

(5) The ability of third-party recycling enterprises is not limited. The treatment and reuse of waste batteries can obtain recycling income, ω . Meanwhile, because power batteries are recycled and reused, the cost of new energy vehicle manufacturers can be reduced, a factor which is set as $\Delta\epsilon$.

2.3. Single-Channel Recycling Decision Model for New Energy Manufacturers

2.3.1. Decentralized Decision Model

Under decentralized decision-making, the profits of manufacturers, third-party recycling enterprises, and consumers are as follows:

$$\pi_m^{md} = Q \left(1 - (1 - \beta) \left(1 - \frac{p_1}{p_2} \right) \right) (p_3 - p_1 + \Delta\epsilon) - \frac{1}{2} d_m \left(1 - (1 - \beta) \left(1 - \frac{p_1}{p_2} \right) \right)^2 \quad (1)$$

$$\pi_r^{md} = Q \left(1 - (1 - \beta) \left(1 - \frac{p_1}{p_2} \right) \right) (\omega - p_3) \quad (2)$$

$$\pi_k^{md} = \left(1 - (1 - \beta) \left(1 - \frac{p_1}{p_2} \right) \right) p_1 + \left((1 - \beta) \left(1 - \frac{p_1}{p_2} \right) \right) (p_2 - t\delta) \quad (3)$$

The first item in Formula (1) is the income from the recycling of waste power batteries by NEV manufacturers, and the second item is the investment required to carry out the recycling of waste power batteries; Formula (2) represents the income from the recycling of waste power batteries by third-party recycling enterprises; and Formula (3) represents the consumer's income.

NEV manufacturers determine the recycling prices with the goal of maximizing their own profits, it can be obtained:

$$p_1^{md*} = \frac{p_2[Qk_1 + \beta Qp_2 - 2\beta k_2]}{2(1 - \beta)k_2}, \quad p_3^{md*} = \frac{(1 - \beta)(\omega - \Delta\epsilon) - p_2\beta}{2(1 - \beta)}.$$

where: $k_1 = (1 - \beta)(\omega + \Delta\epsilon)$; $k_2 = 2Qp_2 + (1 - \beta)d_m$.

According to (p_1^{md*}, p_3^{md*}) , the optimal profits of NEV manufacturers, third-party recycling enterprises, and consumers can be obtained, respectively, as:

$$\begin{aligned} \pi_m^{md*} &= \frac{Q^2(k_1 + \beta p_2)^2}{8k_2(1 - \beta)}, \quad \pi_r^{md*} = \frac{Q^2(k_1 + \beta p_2)^2}{4k_2(1 - \beta)}, \text{ and} \\ \pi_k^{md*} &= \frac{Q^2 p_2 (k_1 + \beta p_2) (Qk_1 - 2\beta k_2 + Q\beta p_2)}{4(1 - \beta)k_2^2} + \frac{Q(2k_2 - Qk_1 - 4Q\beta p_2)}{2k_2} (p_2 - t\delta). \end{aligned}$$

2.3.2. Centralized Decision-Making Model

Under centralized decision-making, the reverse supply chain profits are as follows:

$$\pi_{sc}^{mc} = Q \left(1 - (1 - \beta) \left(1 - \frac{p_1}{p_2} \right) \right) (\omega - p_1 + \Delta\epsilon) - \frac{1}{2} d_m \left(1 - (1 - \beta) \left(1 - \frac{p_1}{p_2} \right) \right)^2 \quad (4)$$

According to the maximization of the reverse supply chain profits, the following can be obtained: $p_1^{mc*} = \frac{p_2[Qk_1 + \beta Qp_2 - \beta k_2]}{(1 - \beta)k_2}$, $\pi_{sc}^{mc*} = \frac{Q^2(k_1 + \beta p_2)^2}{2k_2(1 - \beta)}$.

Proposition 1. Under the NEV manufacturer recycling mode, the optimal value of the recycling price will be (p_1^{md*}, p_3^{md*}) . Under decentralized decision-making, the profits of manufacturers and third-party recycling enterprises will be $(\pi_m^{md*}, \pi_r^{md*})$, and the supply chain profits will be $\frac{3Q^2(k_1 + \beta p_2)^2}{8k_2(1 - \beta)}$. In the case of a centralized decision, the optimal value of the recycling price is p_1^{mc*} , and the reverse supply chain profits will be $\frac{Q^2(k_1 + \beta p_2)^2}{2k_2(1 - \beta)}$. It is obvious that centralized decisions can achieve higher profits than decentralized decisions, and the consumer profits under centralized decisions are also higher than those under decentralized decisions.

2.4. Single-Channel Recycling Model for Third-Party Recycling Enterprises

2.4.1. Decentralized Decision-Making Model

When the third-party recycling enterprises are responsible for recycling waste power batteries, the profits of NEV new energy vehicle manufacturing will be:

$$\pi_m^{rd} = Q \left(1 - (1 - \beta) \left(1 - \frac{p_1}{p_2} \right) \right) \Delta \varepsilon \quad (5)$$

The profits of third-party recycling enterprises are as follows:

$$\pi_r^{rd} = Q \left(1 - (1 - \beta) \left(1 - \frac{p_1}{p_2} \right) \right) (\omega - p_1) - \frac{1}{2} d_r \left(1 - (1 - \beta) \left(1 - \frac{p_1}{p_2} \right) \right)^2 \quad (6)$$

Under decentralized decision-making, $p_1^{rd*} = \frac{p_2[Qk_3 - \beta(k_4 - Qp_2)]}{(1 - \beta)k_4}$; $\pi_m^{rd*} = Q^2 \Delta \varepsilon \frac{(k_3 + p_2\beta)}{k_4}$; $\pi_r^{rd*} = \frac{Q^2(k_3 + \beta p_2)^2}{2k_4(1 - \beta)}$, where $k_3 = (1 - \beta)\omega$ and $k_4 = 2Qp_2 + (1 - \beta)d_r$.

2.4.2. Centralized Decision Model

Under centralized decision-making, the reverse supply chain profits are as follows:

$$\pi_{sc}^{rc} = Q \left(1 - (1 - \beta) \left(1 - \frac{p_1}{p_2} \right) \right) (\omega - p_1 + \Delta \varepsilon) - \frac{1}{2} d_r \left(1 - (1 - \beta) \left(1 - \frac{p_1}{p_2} \right) \right)^2 \quad (7)$$

We can thus obtain the following: $p_1^{rc*} = \frac{p_2[Qk_1 - \beta k_4 + \beta Qp_2]}{(1 - \beta)k_4}$ and $\pi_{sc}^{rc*} = \frac{Q^2(k_1 + \beta p_2)^2}{2k_4(1 - \beta)}$.

Proposition 2. In the single-channel recycling of third-party recycling enterprises, the optimal value of the recycling price obtained under decentralized decision-making is p_1^{rd*} , the profits of manufacturers and third-party enterprises will be $(\pi_m^{rd*}, \pi_r^{rd*})$, and the supply chain profits will be $\frac{Q^2(k_3 + \beta p_2)(k_1 + \beta p_2 + (1 - \beta)\Delta \varepsilon)}{2k_4(1 - \beta)}$. The optimal value of the recycling price obtained under centralized decision-making is p_1^{rc*} , and the total supply chain profits will be $\pi_{sc}^{rc*} = \frac{Q^2(k_1 + \beta p_2)^2}{2k_4(1 - \beta)}$. Higher profits will be obtained under centralized decisions than under decentralized decisions, and as will the profits for consumers.

3. Model Analysis

Based on the assumed parameters used to analyze the impact of different parameters on the recycling price, p_1 , recycling rate, r , and the profits of consumers and supply chain, the hypothesis is as follows:

$$p_2 = 500, \omega = 1200, \Delta \varepsilon = 200, \delta = 100, d_r = 5000, d_m = 5000, Q = 1000, t = 0.5.$$

3.1. Analysis of Recycling Pricing, p_1

According to Figure 2, the recycling price, p_1 , decreases when consumer environmental protection responsibility awareness, β , gradually increases. At the same time, when β reaches a certain value, the value of p_1 will be 0, which means consumers are still willing to recycle waste power batteries through formal channels even if they are not paid. According to Figure 2a, the value of p_1 will also gradually increase when the value of the recycling income, ω , increases. The main reason is that when the recycling income, ω , increases, third-party recycling enterprises are willing to feed more profits back to consumers, that is, by raising the recycling price, p_1 , so as to improve the recycling rate and form a virtuous circle. According to Figure 2b,c, the recycling cost coefficient, d_m , and the sales volume, Q , have little effect on the recycling price, p_1 . According to Figure 2d, it can be seen that the value of p_1 will decrease as the value of p_2 increases. This is mainly due to the fact

that, when informal recycling prices, p_2 , continue to rise, fewer and fewer consumers are willing to recycle waste power batteries through formal channels, resulting in a decline in the profits of recyclers, which, in turn, leads to the value of p_1 decreasing.

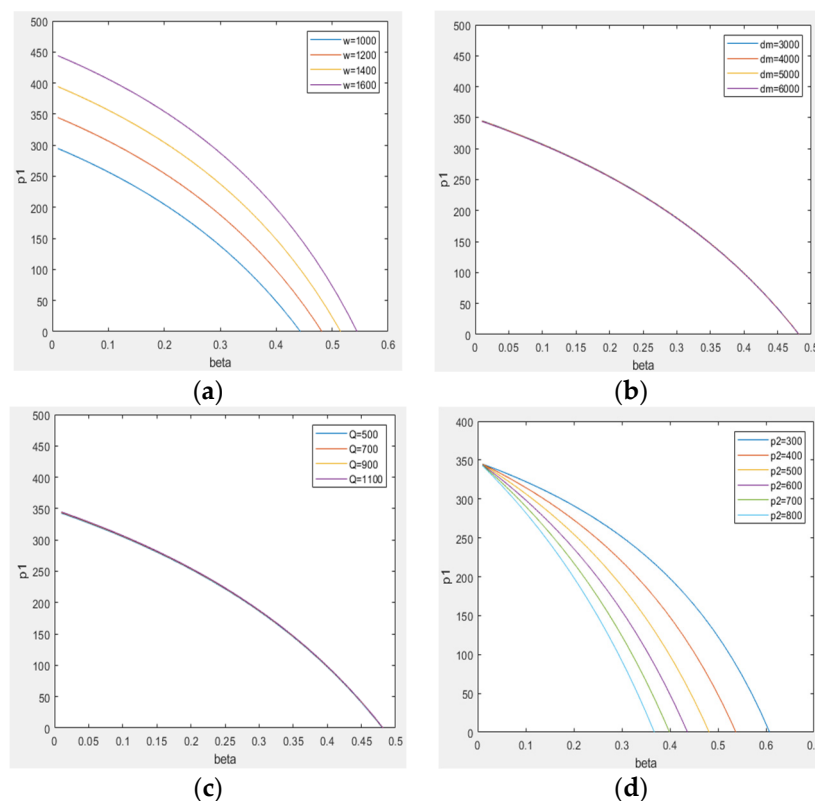


Figure 2. Influence of parameter β , ω , d_m , Q , p_2 on the recycling price, p_1 . (a) Influence of parameter β and ω on the recycling price, p_1 . (b) Influence of parameter β and d_m on the recycling price, p_1 . (c) Influence of parameter β and Q on the recycling price, p_1 . (d) Influence of parameter β and p_2 on the recycling price, p_1 .

It can be seen from Figure 3 that, when β and ω are determined and $d_m = d_r$, then $p_1^{md*} < p_1^{rd*} < p_1^{mc*} = p_1^{rc*}$, which means that the optimal recycling price under the decentralized decision-making of manufacturer recycling is the lowest, the optimal recycling price of centralized decision-making is significantly higher than that of decentralized decision-making (consistent with the conclusion of Proposition 1 and Proposition 2), and the difference of p_1^{mc*} and p_1^{rc*} is determined by d_m and d_r .

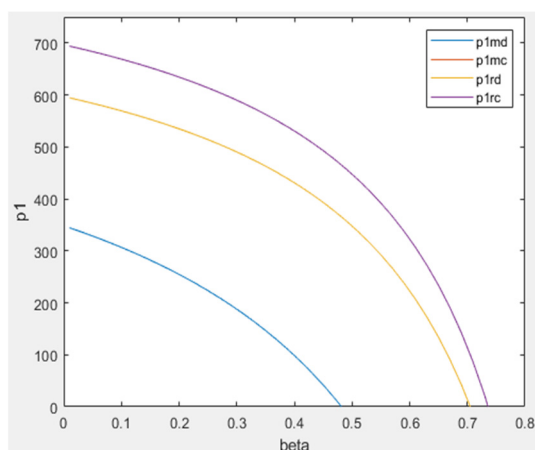


Figure 3. Comparison of recycling price changes under different recycling modes.

3.2. Analysis of the Recycling Rate, r

It can be seen from Figure 4 that, when the consumer environmental protection responsibility awareness, β , gradually increases, the recycling rate, r , initially decreases, and after β reaches the lowest point, the recycling rate, r , gradually rises. This is mainly because the recycling rate is $r = 1 - (1 - \beta)\left(1 - \frac{p_1}{p_2}\right)$; when the value of β is lower, the increase in β leads to a decrease in the recycling price, p_1 , and a decrease in $(1 - \beta)$ is greater than the increase in $\left(1 - \frac{p_1}{p_2}\right)$, which leads to a decrease in the recycling rate, r . However, when the value of β is larger, consumers are willing to recycle waste power batteries through formal channels even though the recycling price is very low, even if it tends toward 0. When $\left(1 - \frac{p_1}{p_2}\right) = 1$, then $r = \beta$, which means the recycling rate, r , increases linearly with the value of β . According to Figure 2a, when the value of the recycling income, ω , increases, the recycling rate, r , increases gradually. This is mainly because when the value of recycling income, ω , increases, the recycling price, p_1 , can be appropriately increased, thereby increasing the recycling rate, r . However, when the recycling rate reaches the lowest point, no matter how ω changes, the recycling rate is $r = \beta$; this is because after β increases to a certain value, the recycling price becomes $p_1 = 0$. From Figure 2b,c, it can be seen that the recycling cost coefficient, d_m , and the sales volume, Q , have little effect on the recycling rate, r . According to Figure 2d, the recycling rate, r , is negatively correlated with p_2 ; thus, it is easy to understand why, when the value of p_2 increases, more consumers will naturally tend to sell waste power batteries through informal channels for a greater profit.

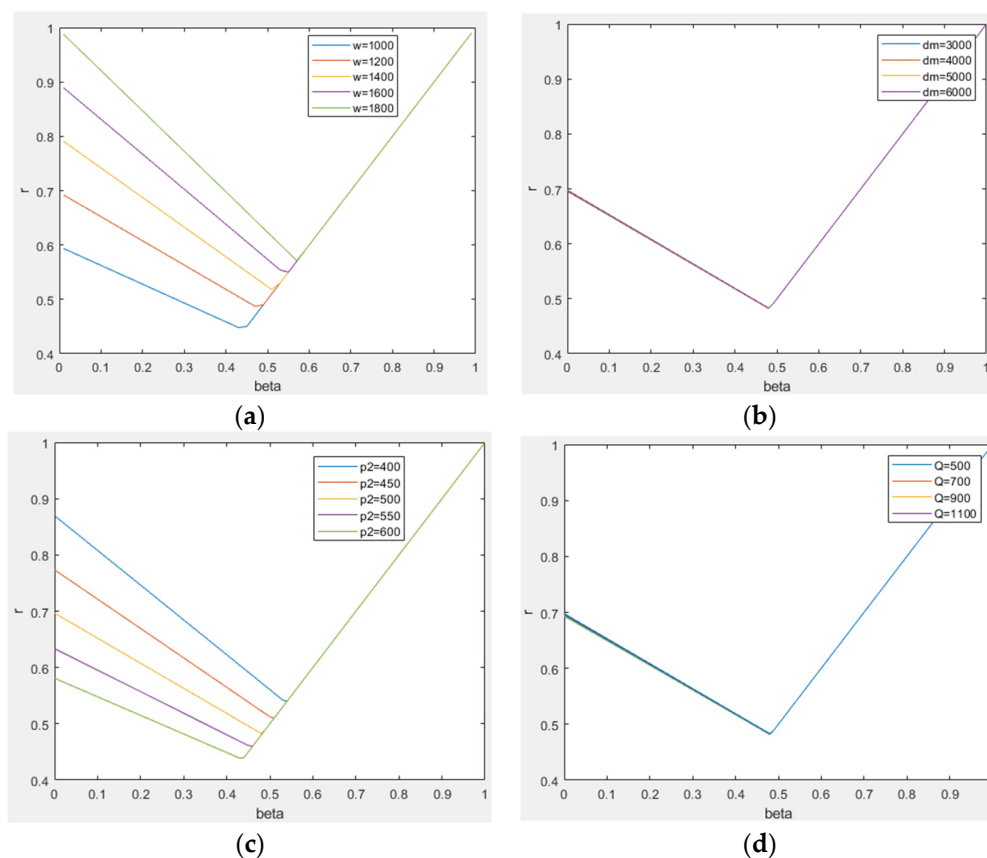


Figure 4. Influence of parameter β , ω , d_m , Q , p_2 on the recycling rate, r . (a) Influence of parameter β and ω on the recycling rate, r . (b) Influence of parameter β and d_m on the recycling rate, r . (c) Influence of parameter β and p_2 on the recycling rate, r . (d) Influence of parameter β and Q on the recycling rate, r .

3.3. Analysis of Consumer Profits

Comparing Figures 2 and 5, it can be seen that the changing trend in consumer expected profit, π_k , is basically the same as that of recycling price, p_1 . As the consumer environmental protection responsibility awareness, β , gradually increases, the recycling price, p_1 , gradually decreases, and π_k also gradually decreases. It can be seen from Figure 5a that recycling income, ω , is positively correlated with π_k . When the value of recycling income, ω , continues to increase, the value of p_1 will also gradually increase, and so does the value of π_k . It can be seen from Figure 2b,c that the cost coefficient, d_m , and the sales volume, Q , have little effect on π_k . According to Figure 5d,e, at first, π_k decreases with the increase in p_2 and then increases with the increase in p_2 , which is mainly due to $\pi_k = rp_1 + (1-r)(p_2 - t\delta)$, and p_2 with p_1 and r are both negatively correlated. When p_2 increases, rp_1 decreases and $(1-r)(p_2 - t\delta)$ increases. When the value of p_2 is small, rp_1 decreases more than $(1-r)(p_2 - t\delta)$, so π_k decreases with the increase in p_2 . When p_2 increases to a certain value, rp_1 decreases less than $(1-r)(p_2 - t\delta)$, so π_k increases as p_2 increases.

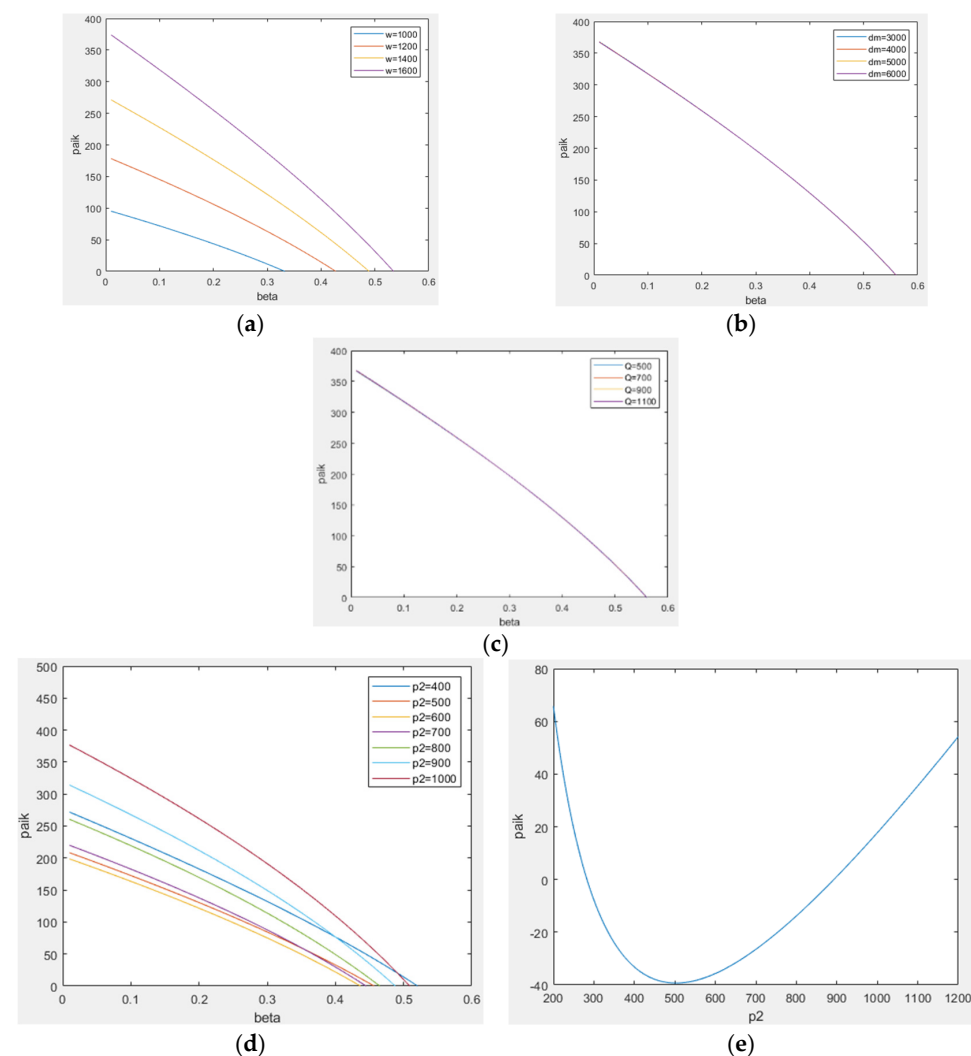


Figure 5. The effect of parameter β , d_m , Q , p_2 on the consumer expected profit, π_k . (a) The effect of parameter β and ω on the consumer expected profit, π_k . (b) The effect of parameter β and d_m on the consumer expected profit, π_k . (c) The effect of parameter β and Q on the consumer expected profit, π_k . (d) The effect of parameter β and p_2 on the consumer expected profit, π_k . (e) The effect of parameter p_2 on the consumer expected profit, π_k .

Meanwhile, it can be seen from Figure 6 that, when β and ω are determined and $d_m = d_r$, then $\pi_k^{md*} < \pi_k^{rd*} < \pi_k^{mc*} = \pi_k^{rc*}$. That means the expected profits of consumers, π_k , in centralized decision-making are higher than those of decentralized decision-making under the two recycling modes. In the recycling mode of third-party recycling enterprises, the expected profit of consumers, π_k , is higher than that of the manufacturer recycling mode (consistent with the conclusion of Proposition 1 and Proposition 2). In centralized decision-making, the expected profit of consumers π_k under the two modes is basically the same, the difference is mainly caused by the recycling cost coefficients d_m and d_r .

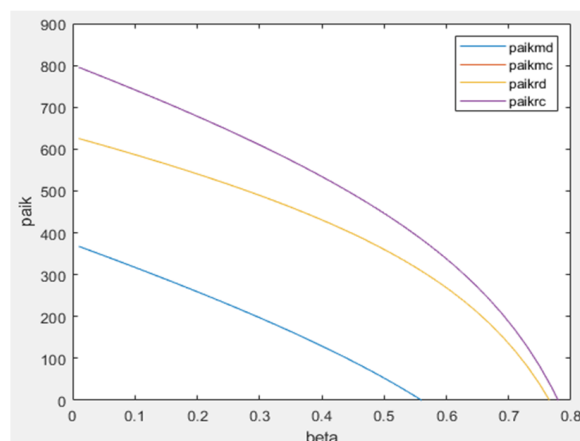


Figure 6. Comparison of consumer profits under different recycling modes.

3.4. Analysis of Profit of the Supply Chain

According to Figure 7a, the profits of the supply chain, π_{sc} , increase with an increase in recycling income ω , which is mainly due to the fact that $\pi_{sc} = G\omega^2$ (according to Table 1, it can be seen that, when other parameters are determined, G is a constant). When the value of β is less than a certain value, the change in the profits of the supply chain, π_{sc} , is not very large, but when β is greater than this value, the change in the profits of the supply chain π_{sc} increases significantly. The main reason is $\pi_{sc} = A \frac{Q^2((1-\beta)(\omega+\Delta\epsilon)+\beta p_2)^2}{(2Qp_2+(1-\beta)d_m)(1-\beta)}$ (according to Table 1, A is a constant value under different recycling modes); when the value of β is too large, the value of $(2Qp_2+(1-\beta)d_m)(1-\beta)$ tends toward 0, which leads to a significant increase in the value of π_{sc} . At the same time, when ω is small, the profits of the supply chain, π_{sc} , increase with the increase in β , but the increase is gentle at first and then rises sharply. When the value of ω increases to a certain value, the profit of the reverse supply chain π_{sc} decreases with the increase in β , and after β reaches a minimum value, π_{sc} increases as an increase in β . It can be seen from Figure 7b that the cost coefficient d_m has little effect on π_{sc} . From Figure 7c, it can be seen that π_{sc} increases with the increase in sales volume, Q , and its curve shape is similar to ω . According to Figure 7d,e, at first, π_{sc} decreases with the increase in p_2 ; when $p_2 = \frac{(1-\beta)[Q(\omega+\Delta\epsilon)-\beta d_m]}{\beta Q}$, π_{sc} reaches the lowest value, and then it increases with the increase in p_2 .

It can be seen from Figure 8 that, when β and ω are determined and $d_m = d_r$, then $\pi_{sc}^{md*} < \pi_{sc}^{rd*} \approx \pi_{sc}^{mc*} = \pi_{sc}^{rc*}$, and the profit of the supply chain, π_{sc} , obtained though decentralized decision-making under the manufacturer recycling mode is the smallest (consistent with the conclusion of Proposition 1 and Proposition 2), while the profits of the other three modes are not significantly different, which shows that this system can obtain greater profits under the third-party recycling enterprise recycling mode.

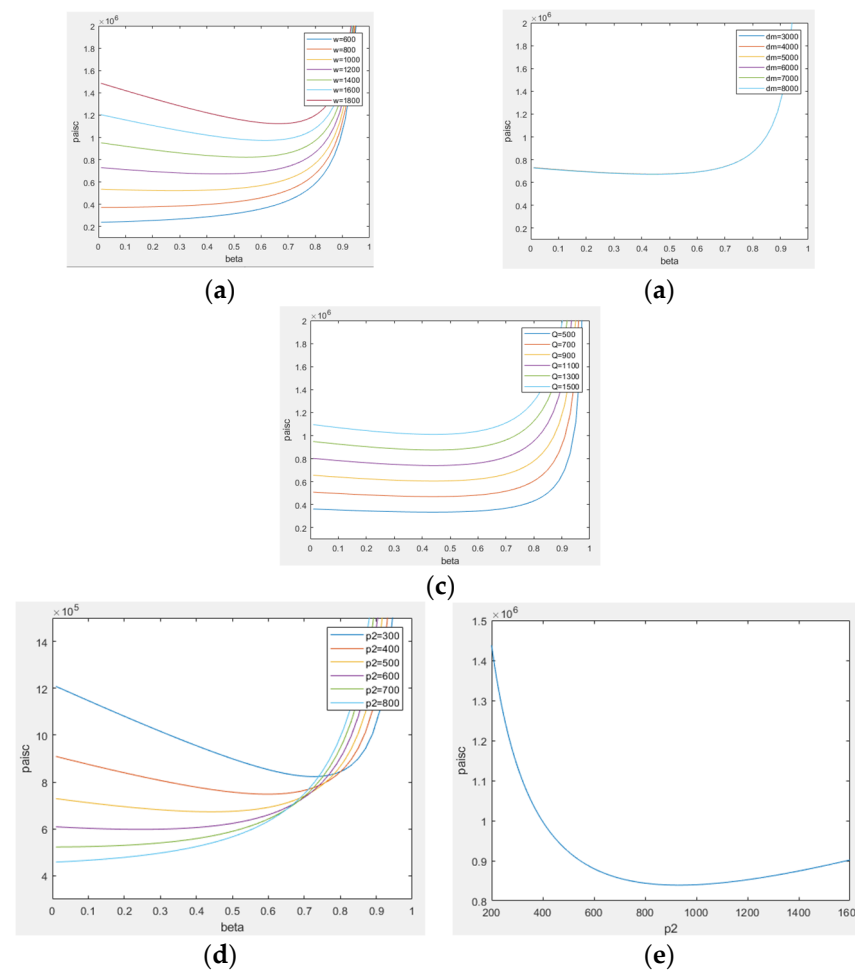


Figure 7. Impact of parameter β , ω , d_m , Q , p_2 on the π_{sc} of the reverse supply chain. (a) Impact of parameter β and ω on the π_{sc} of the reverse supply chain. (b) Impact of parameter β and d_m on the π_{sc} of the reverse supply chain. (c) Impact of parameter β and Q on the π_{sc} of the reverse supply chain. (d) Impact of parameter β and p_2 on the π_{sc} of the reverse supply chain. (e) Impact of parameter p_2 on the π_{sc} of the reverse supply chain.

Table 1. Recycling prices and profits of the supply chain under different recycling modes.

Modes	p_1	π_m	π_r	π_{sc}	π_k
Manufacturer recycling (decentralized decision-making)	$\frac{p_2 [Qk_1 + \beta Qp_2 - 2\beta k_2]}{2(1-\beta)k_2}$	$\frac{Q^2 (k_1 + \beta p_2)^2}{8k_2(1-\beta)}$	$\frac{Q^2 (k_1 + \beta p_2)^2}{4k_2(1-\beta)}$	$\frac{3Q^2 (k_1 + \beta p_2)^2}{8k_2(1-\beta)}$	$\frac{Qp_2 (k_1 + \beta p_2) (Qk_1 - 2\beta k_2 + Q\beta p_2)}{4(1-\beta)k_2^2} + \frac{(2k_2 - Qk_1 - 4Q\beta p_2)}{2k_2} (p_2 - t\delta)$
Manufacturer recycling (centralized decision-making)	$\frac{p_2 [Qk_1 + \beta Qp_2 - \beta k_2]}{(1-\beta)k_2}$			$\frac{Q^2 (k_1 + \beta p_2)^2}{2k_2(1-\beta)}$	$\frac{Qp_2 (k_1 + \beta p_2) (Qk_1 + Q\beta p_2 - \beta k_2)}{(1-\beta)k_2^2} + \frac{(k_2 - Qk_1 - Q\beta p_2)}{k_2} (p_2 - t\delta)$
Third-party recycling (decentralized decision-making)	$\frac{p_2 [Qk_3 - \beta (k_4 - Qp_2)]}{(1-\beta)k_4}$	$Q^2 \Delta \epsilon \frac{(k_3 + \beta p_2)}{k_4}$	$\frac{Q^2 (k_3 + \beta p_2)^2}{2k_4(1-\beta)}$	$\frac{Q^2 (k_3 + \beta p_2) (k_1 + (1-\beta)\Delta \epsilon + \beta p_2)}{2k_4(1-\beta)}$	$\frac{Qp_2 (k_3 + \beta p_2) (Qk_3 + Q\beta p_2 - \beta k_4)}{(1-\beta)k_4^2} + \frac{(k_4 - Qk_3 - Q\beta p_2)}{k_4} (p_2 - t\delta)$
Third-party recycling (centralized decision-making)	$\frac{p_2 [Qk_1 - \beta k_4 + \beta Qp_2]}{(1-\beta)k_4}$			$\frac{Q^2 (k_1 + \beta p_2)^2}{2k_4(1-\beta)}$	

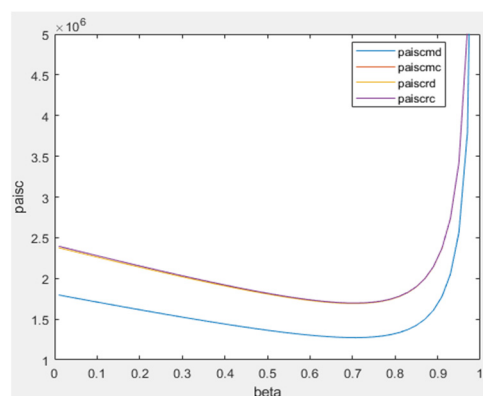


Figure 8. Comparison of profits under two recycling modes.

3.5. Analysis of the Influencing Factors of Consumer Environmental Protection Responsibility Awareness, β

Sections 3.1–3.4 mainly analyze the influence of different parameters on the recycling price (p_1), recycling rate (r), and the profits of supply chain (π_{sc}), but at the same time, consumer environmental protection responsibility awareness, β , is also related to ω , p_2 , and cost coefficients d_m or d_r . Under the two recycling modes, the value of consumer environmental protection responsibility awareness, β , can be seen in Table 2 based on the maximization of profit in the reverse supply chain.

Table 2. Values of consumer environmental protection responsibility awareness.

Recycling Mode	β
Manufacturer recycling (decentralized/centralized decision-making)	$\frac{[-2Q(\omega+\Delta\epsilon)^2+4Qp_2(\omega+\Delta\epsilon)-2Qp_2^2+2(\omega+\Delta\epsilon)d_m-d_m p_2]}{2[-Q(\omega+\Delta\epsilon)^2+2Qp_2(\omega+\Delta\epsilon)-Qp_2^2+(\omega+\Delta\epsilon)d_m-d_m p_2]} + \frac{\sqrt{4Q^2p_2^4+d_m^2p_2^2+8Q^2p_2^3+4Q^2p_2^2(\omega+\Delta\epsilon)^2-4Qp_2^2d_m(\omega+\Delta\epsilon)+4Qd_m p_2^3}}{2[-Q(\omega+\Delta\epsilon)^2+2Qp_2(\omega+\Delta\epsilon)-Qp_2^2+(\omega+\Delta\epsilon)d_m-d_m p_2]}$
Third-party recycling (decentralized decision-making)	$\frac{[-4Q(\omega+\Delta\epsilon)\omega-4Q\omega\Delta\epsilon+4Qp_2\omega+4Q(\omega+\Delta\epsilon)-4Qp_2^2+2d_r p_2+3\omega d_r+4\Delta\epsilon d_r]}{2[-2Q(\omega+\Delta\epsilon)\omega-2Q\omega\Delta\epsilon+4Qp_2\omega+2Q(\omega+\Delta\epsilon)+6Qp_2^2+2d_r p_2+3\omega d_r+2\Delta\epsilon d_r]} + \frac{\sqrt{16Q^2p_2^4+4d_r^2p_2^2+9\omega^2d_r^2+32Q^2p_2^3\omega+40Qp_2^2\omega d_r+24\omega^2Qp_2d_r+16Qp_2^3d_r+12p_2\omega d_r^2+32Q^2\omega p_2^2(\omega+\Delta\epsilon)-16Q^2p_2^2(\omega+\Delta\epsilon)-16Qp_2^2\Delta\epsilon d_r}}{2[-2Q(\omega+\Delta\epsilon)\omega-2Q\omega\Delta\epsilon+4Qp_2\omega+2Q(\omega+\Delta\epsilon)+6Qp_2^2+2d_r p_2+3\omega d_r+2\Delta\epsilon d_r]}$
Third-party recycling (centralized decision-making)	$\frac{[-2Q(\omega+\Delta\epsilon)^2+4Qp_2(\omega+\Delta\epsilon)-2Qp_2^2+2(\omega+\Delta\epsilon)d_r-d_r p_2]}{2[-Q(\omega+\Delta\epsilon)^2+2Qp_2(\omega+\Delta\epsilon)-Qp_2^2+(\omega+\Delta\epsilon)d_r-d_r p_2]} + \frac{\sqrt{4Q^2p_2^4+d_r^2p_2^2+8Q^2p_2^3+4Q^2p_2^2(\omega+\Delta\epsilon)^2-4Qp_2^2d_r(\omega+\Delta\epsilon)+4Qd_r p_2^3}}{2[-Q(\omega+\Delta\epsilon)^2+2Qp_2(\omega+\Delta\epsilon)-Qp_2^2+(\omega+\Delta\epsilon)d_r-d_r p_2]}$

According to Figure 9a, consumer environmental protection responsibility awareness, β , is positively correlated with recycling income, ω ; that is, when the value of ω increases, the β will also increase. When third-party recycling enterprises obtain more profits from recycling waste power batteries, this will inevitably increase the publicity of recycling or feedback on some of the recycling profits to consumers, thereby increasing consumer environmental protection responsibility awareness. It is obvious that when the value of ω is small, the marginal effect brought by ω is better, and the increase in β is large; however, as the value of ω increases, the marginal effect gradually decreases, and the increase in β gradually decreases. It can be seen from Figure 9b that, when the sales volume, Q , of NEV increases, the value of β also increases. When the Q increases from 500 to 2000, β increases from 0.4382 to 0.4427, only by 0.0045, which means that Q has little effect on β . It can also be seen from Figure 9c that when d_m increases, β will decrease, but the overall effect is not large. Under normal circumstances, when d_m is larger, it indicates that the recycler has invested more cost into recycling channels and recycling efforts, which should increase the value of β , but as the cost of recycling investment is too large, the recycling profits fed back to consumers will decline, which will affect the decrease in β . Therefore, under the action of this positive–negative mechanism, the change in d_m has little effect on β . From Figure 9d, it can be seen that β and p_2 are negatively correlated. When the value of p_2 increases, the value of β is declining, which is consistent with the way of thinking of rational individuals;

that is, when higher prices can be obtained under informal channels, there will be more shakeups in environmental protection awareness.

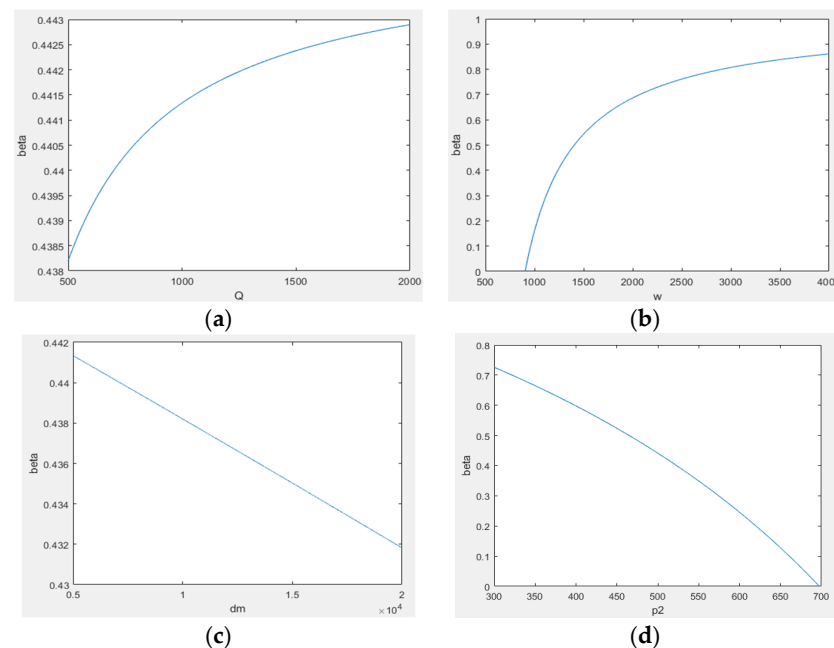


Figure 9. The relationship between β and some parameters. (a) The relationship between β and Q . (b) The relationship between β and w . (c) The relationship between β and d_m . (d) The relationship between β and p_2 .

4. Conclusions

The recycling of waste power batteries for NEV has always attracted the attention of the business community and academia. This paper studies the reverse supply chain of waste power battery recycling, which is composed of consumers, NEV manufacturers, and third-party recycling enterprises, and analyzes how different parameters affect the recycling price, recycling rate, consumer expected profit, and supply chain profit under the two recycling modes of NEV manufacturers and third-party recycling enterprises. It comes to the following conclusions: (1) According to the Proposition 1 and Proposition 2, under the two recycling modes, the supply chain profits obtained under decentralized decision-making are lesser than those under centralized decision-making. (2) Under the recycling mode of third-party recycling enterprises, the profits of the supply chain are higher than those under the NEV manufacturer mode. (3) Consumer environmental protection responsibility awareness, β , is negatively correlated with recycling price, p_1 , and consumer expected profit, π_k . At the same time, when $p_1 > 0$, β is negatively correlated with the recycling rate, r , and when $p_1 = 0$, β is linearly and positively correlated with recycling rate, r . β is basically positively correlated with supply chain profit, π_{sc} . (4) Recycling income, ω , is positively correlated with recycling price, p_1 ; recycling rate, r ; consumer expected profit, π_k ; and supply chain profit, π_{sc} . (5) The recycling price, p_2 , through informal recycling channels is negatively correlated with the recycling price, p_1 , and the recycling rate, r , while the impact on the expected profit of consumers, π_k , and the supply chain profit, π_{sc} , decreases first and then rises. (6) NEV sale volume, Q , and recycling cost coefficient, d_m , have little effect on recycling price, p_1 ; recycling rate, r ; consumer expected profit, π_k ; and supply chain profit, π_{sc} . (7) Recycling income, ω , has a positive effect on β , while an increase in recycling price, p_2 , through informal recycling channels inhibits β .

According to the above conclusions, although different parameters have certain influences on recycling prices, recycling rates, consumer profits, and supply chain profits, the main influences are consumer environmental protection responsibility awareness, β ; recycling income, ω ; and recycling price, p_2 , through informal recycling channels. Therefore,

the following suggestions may improve the recycling rate of waste power batteries through formal channels:

(1) Continuously improving consumer environmental protection responsibility awareness through positive publicity and regulatory constraints. The government, new energy manufacturers, and 4S stores can publicize the method and role of power battery recycling and disposal, as well as the harm caused by improper disposal to the environment through advertising and other means, and they can encourage consumers to recycle the waste power batteries of NEVs in a formal way. Government departments can strengthen the supervision and management of consumers according to the gradually improved national monitoring system of NEVs and the comprehensive management platform for the recycling and traceability of power batteries. If consumers are found to dispose of waste power batteries in violation of regulations, they can be fined or dismissed from public office, etc.

(2) By strengthening investment in scientific research, the recycling and processing income of waste power batteries can be continuously improved. The government can provide subsidies originally given to NEV sale enterprises to the waste power battery recycling industry, which can help recycling enterprises increase investment in scientific research. Meanwhile, third-party recycling enterprises can cooperate with universities and research institutes to carry out technical research on effectively designing a closed-loop supply chain for the gradient utilization of NEV power battery recycling, strengthening the selective separation and purification technology of various metals, etc., thus improving the economic value of waste power battery recycling and enhancing consumer environmental protection responsibility awareness and the recycling rate.

(3) The government should strictly prohibit waste lithium-ion batteries from entering the informal market and crack down on informal workshops so as to encourage the healthy development of the waste power battery recycling industry to gradually get on the right track and enter into a new era.

In addition, there are some shortcomings in this paper. This paper concludes that the unified recycling and processing of waste power batteries by third-party recycling enterprises can form economies of scale and improve recycling income. However, third-party recycling companies can recycle waste power batteries from different brands of NEV, so it is necessary to adopt a responsibility-sharing contract to better divide the responsibilities between different entities and establish a closed-loop supply chain coordination mechanism for NEV waste power batteries to promote the effective recycling of waste power batteries, which is also one of the directions of follow-up research.

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