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# Power Battery Recycling Model of Closed-Loop Supply Chains Considering Different Power Structures Under Government Subsidies

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**Abstract:** With the rapid growth of the electric vehicle industry, the recycling of power batteries has attracted significant attention. In light of current circumstances, the question of how the government can incentivize relevant stakeholders to actively engage in recycling and improve its efficiency has become increasingly pressing. In this context, this study analyses and develops four closed-loop supply chain recycling models to investigate how different government subsidy recipients under varying power structures influence recycling efficiency, profitability, and the overall supply chain structures. The following conclusions are derived from numerical simulations: (1) Government subsidies serve to elevate recycling prices, expand profit margins, and consequently boost the volume of recycled batteries, thus incentivizing corporate engagement in recycling initiatives. (2) When the processor assumes the role of the leader in the Stackelberg game framework, it can maximize the overall efficiency and profitability of the supply chain. (3) The sensitivity coefficient and the competition coefficient are closely interrelated, exerting opposing impacts on the recycling decision made by enterprises. (4) The supply chain leader plays a crucial role in ensuring orderly supply chain development, with government subsidies of the supply chain being transmitted to its members through the leader. Consequently, this study offers a theoretical foundation for the government to enhance policy-making and for enterprises to make informed decisions. It also holds significant practical relevance in addressing the challenges associated with power battery recycling.

**Keywords:** closed-loop supply chain; power battery recycling; Stackelberg game; government subsidies; power structure



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## 1. Introduction

Waste power batteries, laden with numerous toxic chemicals, pose significant environmental and safety hazards if not disposed of properly. Non-regulated disposal can severely disrupt ecological balance [1]. In 2020, China witnessed the retirement of approximately 200,000 tons of electric vehicle power batteries (equivalent to about 25 GWh). Projections for 2025 anticipate a surge to 780,000 tons (around 116 GWh), a record high [2]. Despite this growing concern, battery recycling in China remains inadequate. In 2018, recycled power batteries constituted a mere 7.4% of the total scrapped volume [3]. This inefficiency is attributed partly to the dominance of small- and medium-sized enterprises in the recycling sector. These entities, frequently hindered by rigid management and disorganized processes, have inadvertently fostered an extensive "underground market". Consequently, a significant portion of waste power batteries escape effective recycling [4].

Moreover, the lack of clarity in defining rights and responsibilities exacerbates the issue. Ideally, the principle of "who produces, who recycles" should apply, placing the responsibility of power battery recycling on producers [5]. However, in practice, consumers, as the end-holders of these batteries, are often left with the responsibility, complicating the recycling process. The urgency for efficient recycling is amplified by the current peak in power battery decommissioning, coupled with the shortage of key raw materials and production shutdown due to epidemics and other external factors [6,7]. Therefore, there is a strong social demand for the recycling and reuse of power battery resources.

Given the current state of recycling, there is an urgent need to improve the efficiency of power battery recycling with government support. Some local governments are already backing this initiative by offering subsidies, favorable policies, and special funds. For instance, the Shanghai municipal government grants subsidies of CNY 1000 for each set of recycled batteries [8], while Hefei bases its recycling incentives on the total number of recycled batteries [9]. Globally, various governments have implemented measures like subsidy systems, deposit returns, and funding policies to encourage companies to engage in battery recycling. However, the effects of these subsidies on the supply chain merit further investigation.

Increasingly, researchers are turning their attention to the area of power battery recycling and utilization. Among them, Jiao and Evans [10] underscored the economic value of power battery recycling, particularly in its role in reducing the production costs of enterprises. Furthermore, Jo and Myung [11] and Abdelbaky et al. [12] highlighted the necessity of recycling used power batteries, emphasizing both resource conservation and environmental benefits. Moreover, promoting the power battery recycling industry boosts consumer environmental awareness and supports environmental protection [13]. It also fosters technological innovation and industrial advancement [14], serving as a crucial pathway for achieving a circular economy and sustainable development [15].

As research advanced, scholars started exploring efficient recycling methods. Fleischman et al. [16] and Savaskan and Van [17] developed a closed-loop supply chain model that incorporates three distinct recycling entities: manufacturers, retailers, and third-party recyclers. Building on this foundation, Song et al. [18] utilized the Stackelberg game method to identify the optimal outcomes for each of these recycling models, analyzing their pros and cons. Ranjbar et al. [19] developed a Stackelberg model involving manufacturers, retailers, and third-party recyclers, finding that a retailer-led decentralized model is often the most effective in closed-loop supply chains and is the closest to a centralized model. Hao et al. [20] compared four recycling models involving automobile manufacturers and other entities through a recycling cost model. However, many studies mentioned above have only focused on single-entity recycling, overlooking the complexities of multi-entity systems, which often involve multiple stakeholders and interactions between different recycling channels. This gap represents a significant limitation in the current research.

Recognizing that most real-world situations involve multiple recycling stakeholders, Liang et al. [21] developed a dual-channel recycling model that includes a battery manufacturer, an automotive alliance, or a third-party recycler. Their findings indicated that a hybrid recycling model typically results in greater efficiency and profitability. Similarly, Alamdar et al. [22] constructed six two-level closed-loop supply chain game models within fuzzy demand environments and conducted a comparative analysis, which demonstrated that a joint recycling approach between manufacturers and third-party recyclers is effective. Additionally, Ma et al. [23] examined the dynamics between new energy vehicle manufacturers and retailers by establishing a dual-channel recycling model, revealing that adopting cost-sharing and responsibility-sharing contracts can enhance profits and improve recycling efficiency. In their examination of multi-entity recycling, Shi et al. [24] focused on the synergistic effects and integration potential among supply chain links, determining the optimal outcomes for the three models. Their study acknowledges the significance of these synergistic effects and integration potential in the context of multi-party recycling.

The collaboration of multiple recycling entities can lead to market competition, and the competitive dynamics of recycling channels significantly influence the design and operation of closed-loop supply chains. To address this issue, Wu and Zhou [25] expanded upon the model proposed by Savaskan et al. [17] to investigate a closed-loop supply chain within a competitive environment, evaluating the impact of competition on model selection. Song et al. [26] developed a Stackelberg game model and found that varying levels of market competition have different effects on participants' profits. Building on this, Feng et al. [27] created a competitive game model involving two manufacturers and two recyclers to analyze optimal profit distribution, demonstrating that this cross-competitive recycling model yields higher profits for all participants compared to a monopoly recycling model. While many studies have focused on developing recycling models, such as single-entity recycling models and multi-entity recycling models, to evaluate their performance in recycling efficiency, cost control, and resource utilization, they often overlook how different power structures can influence decision-making, resource allocation, and profit distribution at each stage. Current research has largely neglected the integration of recycling models with the power structures of closed-loop supply chains.

Recognizing the importance of recycling models with different power structures in designing and operating closed-loop supply chains, researchers have delved into mixed recycling models. Gong et al. [28] and Zhang et al. [29] developed a hybrid recycling model featuring varying power structures and analyzed it to identify the optimal combination. Xie et al. [30] created a closed-loop supply chain recycling model led by a battery manufacturer, designing a multi-level supply chain network for both automobile sales and battery recycling. Wu et al. [31] emphasized that choosing the right recycling decision-making and contractual mechanisms based on the dominant roles of different participants in the closed-loop supply chain is essential for enhancing recycling efficiency. Additionally, Liu et al. [32] further demonstrated that channel power structures significantly influence the functioning of closed-loop supply chains, leading to markedly different decision-making processes among firms depending on the prevailing power dynamics. Therefore, the importance of channel power structures must not be overlooked when designing closed-loop supply chains.

Moreover, due to the significant externalities associated with power batteries, it is crucial to design effective policy mechanisms that guide the behavior of supply chain members to foster sustainable development in the power battery recycling industry. Zhan and Chen [33] focused on government subsidies, analyzing how varying subsidy levels relate to supply chain node variables and their effects on profit distribution. To investigate the government's role in regulating power battery recycling, Li et al. [34] found that a reward and punishment mechanism could significantly enhance recycling rates and overall profits in the closed-loop supply chain. Research conducted by Xiao et al. [35] verified that government subsidies facilitate the integration of a larger volume of retired power batteries into formal recycling channels. Wang et al. [36] conducted an in-depth study of a model where the government implemented a reward and penalty mechanism (RPM) alongside a subsidy mechanism (SM) for manufacturers and recyclers, taking into account input costs and environmental benefits, and explored how government actions impact supply chain efficiency. Gong et al. [37] developed a two-channel closed-loop supply chain model to assess the effects of government involvement on supply chain stability. Shen et al. [38] examined how government subsidies influence the efficiency of supply chains with various power structures. Ding et al. [39] further clarified the effectiveness of these subsidies based on recycling volumes. While most of this research has concentrated on government functions, few studies have effectively integrated government policies with extended producer responsibility (EPR) systems.

As research on power battery recycling continues to advance, EPR has gained significant attention from researchers as an effective management system to enhance the recycling of waste products. Yan et al. [40] demonstrated the effectiveness of producers in fulfilling their recycling responsibilities to support environmental protection. Zheng et al. [41] identified the specific reactions of producers in various EPR system design scenarios, demonstrating that the EPR mechanism was more effective when government incentives were present. He et al. [42] created a closed-loop supply chain evolution game model from the supply side perspective and analyzed the effectiveness of RPMs within the EPR system.

Current research offers a solid theoretical foundation for this study, yet gaps remain, particularly regarding the influence of power structures in closed-loop supply chains on recycling decisions. While much of the focus has been on channel selection and recycling decisions, there is limited exploration of the interactions among government, recycling entities, and consumers in recycling behavior. This paper aims to address these issues by analyzing how different government subsidy targets under varying power structures affect recycling efficiency and profits for all parties involved. It also examines the competitive dynamics between recycling entities and how consumer behavior impacts recycling decisions. Ultimately, this study seeks to identify optimal subsidy strategies to enhance recycling efficiency, profitability, and the overall stability of the supply chain, providing valuable insights for government policy improvements and enterprise decision-making.

## 2. Problem Description and Model Assumptions

### 2.1. Problem Description

This study examines a recycling model involving a government agency, consumers, a processor, and a recycler within the context of power battery recycling.

In the forward supply chain, the processor functions as the battery producer, while the recycler acts as the battery seller. In the reverse supply chain, the recycler is primarily responsible for recycling used batteries, whereas the processor is tasked with dismantling these batteries and also participates in their recycling.

In this context, “processors” typically refer to power battery manufacturers, such as CATL, which has acquired Brunp to establish an integrated industrial park that includes waste battery recycling and material utilization. BYD has partnered with GEM to develop a comprehensive recycling system encompassing battery recycling, material utilization, and new energy vehicle manufacturing. “Recyclers”, on the other hand, often denote vehicle manufacturers or alliances formed with vehicle manufacturers and third-party recyclers. For instance, BMW and Zhejiang Huayou Cycle Technology have collaborated to achieve closed-loop recycling for power batteries, while Volkswagen America has partnered with Redwood for battery recycling in the US. BYD has established power battery recycling outlets in Beijing, Shanghai, Guangdong, and Hunan, acquiring power batteries through its own recycling outlets.

This study centers on the reverse supply chain for used batteries, categorizing power battery manufacturers as “processors” and vehicle manufacturers or alliances formed with vehicle manufacturers and third-party recyclers as “recyclers”.

Specifically, the processor’s role entails manufacturing new batteries and transforming the collected used batteries into remanufactured ones, which can be reintroduced into circulation. On the other hand, the recycler is tasked with both selling and recycling the batteries. The model encompasses both forward and reverse supply chain activities. In the forward supply chain, the processor manufactures new batteries and subsequently wholesales them to the recycler. The recycler then sells these batteries to consumers. Reverse supply chain involves the recycling of power batteries. After a certain usage period, these batteries, no longer meeting usage demands, enter the recycling phase. Consumers return the used batteries to either the recycler or processor. The recycler amasses used batteries and sends them to the processor for dismantling and processing, receiving financial compensation in return. Post-dismantling, these waste batteries are segregated into different materials and resources. The processor then combines these processed materials with other components to produce remanufactured batteries.

Given the government’s influential role in shaping the power battery recycling industry’s future, developing a well-structured and effective subsidy strategy is crucial. Subsidies directed towards different entities in the recycling process exert varying impacts. Therefore, it is essential for the government to identify specific subsidy recipients, whether processors or recyclers. This study focuses on government subsidies to supply chain leaders, aiming to utilize the subsidy amount and the leader's influence to collectively enhance the industry's recycling process. In scenarios involving a single-channel recycling system with only one recycling participant, the analysis concentrates on the game scenario where the supply chain leader undertakes recycling activities. This approach ensures a focused analysis of the results.

### 2.2. Model Assumptions and Parameter Descriptions

The model's parameters are outlined in Table 1.

**Table 1.** Parameters of the model.

| Parameter | Description |
|---|---|
| $w$ | Wholesale price of unit power battery. |
| $p$ | Sales price per unit of power battery. |
| $a$ | Aggregate potential market demand. |
| $b$ | Sales price sensitivity factor. |
| $Q$ | Market demand, here $Q = a - bp$. |
| $c_m$ | Unit cost of battery production using new materials. |
| $c_n$ | The unit cost of producing batteries from recycled materials is the same for all remanufactured batteries; here $c_m > c_n$. |
| $\varphi$ | Cost savings of using recycled materials compared to producing batteries from new materials; it is obvious that $\varphi = c_m - c_n > 0$. |
| $p_r$ | Subsidized price paid by recyclers to consumers. |
| $p_n$ | Purchase price paid by processors to consumers. |
| $p_m$ | Transfer price paid by processors to recyclers, $\varphi - p_m > 0$ which makes sure that the dismantling and remanufacturing process is profitable. |
| $k$ | Initial recycling volume, which is the volume recovered when the unit recycling price is zero. |
| $h$ | Recycling price sensitivity factor (hereinafter referred to as the sensitivity factor), here $h > 1$. |
| $G$ | Recycling volume. |
| $s$ | Unit government subsidy. |

Given the complexity of real-world scenarios, several assumptions are made to streamline the model:

**Assumptions 1.** *Single-cycle scenario: This model assumes the existence of sold existing power cells in the pre-market, thereby enabling the direct recycling of used batteries in the current cycle.*

**Assumptions 2.** *Quality homogeneity of batteries: It is assumed that all recovered used batteries are suitable for dismantling and remanufacturing. Remanufactured batteries are of equivalent quality to new batteries, exhibiting high homogeneity, and are sold at the same price.*

**Assumptions 3.** *Stackelberg game participation: Supply chain members are engaged in a Stackelberg game with complete information. Each entity aims to maximize its own interests. In the M and M*R models, the processor acts as the game leader with the recycler as the follower. Conversely, in the R and MR* models, the recycler is the leader, and the processor is the follower.*

**Assumptions 4.** *Market demand and sales price relationship: Following Panda et al. [43], a linear relationship exists between the market demand Q and the sales price p per unit of power battery, represented as $Q = a - bp$.*

**Assumptions 5.** *Recycling quantity and unit recycling price relationship: Based on Zhu and Li [44], a linear relationship is assumed between the recycling volume G and the unit recycling price $p_\alpha$, which is $G_j^i = k + hp_\alpha - mp_\alpha$. Here, i = M, R, M*R, MR* represents various models: M (government-subsidized processor direct recycling), R (government-subsidized recycler direct recycling), M*R (government-subsidized processor-led recycling), and MR* (government-subsidized recycler-led recycling). Here, $j = m, r, s$, where m denotes the amount of direct recycling by the processor, r represents the amount of direct recycling by the recycler, and s signifies the total amount* *of recycling, respectively. Here, $\alpha = n, r$, where n denotes the processor purchase price and r represents the recycler subsidized price, respectively. The channel competition coefficient (hereafter referred to as the competition coefficient) $m(0 < m < 1)$ indicates the sensitivity of consumers to the change in recycling prices due to competition between channels [45].*

**Assumptions 6.** *Government subsidy policy: The government provides subsidies solely to entities that are leaders in the supply chain. The subsidy amount per unit for recycling used batteries is denoted by s.*

## 3. Single-Channel Recycling Model

### *3.1. Recycling Model with Government Subsidies to Processors for Direct Recycling (M)*

The market features a supply chain where processors handle recycling directly. In this setup, processors are central to battery recycling, leveraging their channels for waste battery recycling and repurposing. A key player in this model is CATL, which founded Brunp, marking its entry into power battery recycling.

In the $M$-model's sales chain, the processor wholesales new and remanufactured batteries at a price $w$ to the recycler, who then sells them to end consumers at price $p$. In this model, the recycler is not engaged in the recycling chain. Instead, the processor directly reclaims the used batteries from consumers at a purchase price $p_n$. As participants in the Stackelberg game, the processor assumes the role of the leader, while the recycler acts as the follower. The government provides direct subsidies to the processor, as depicted in Figure 1.

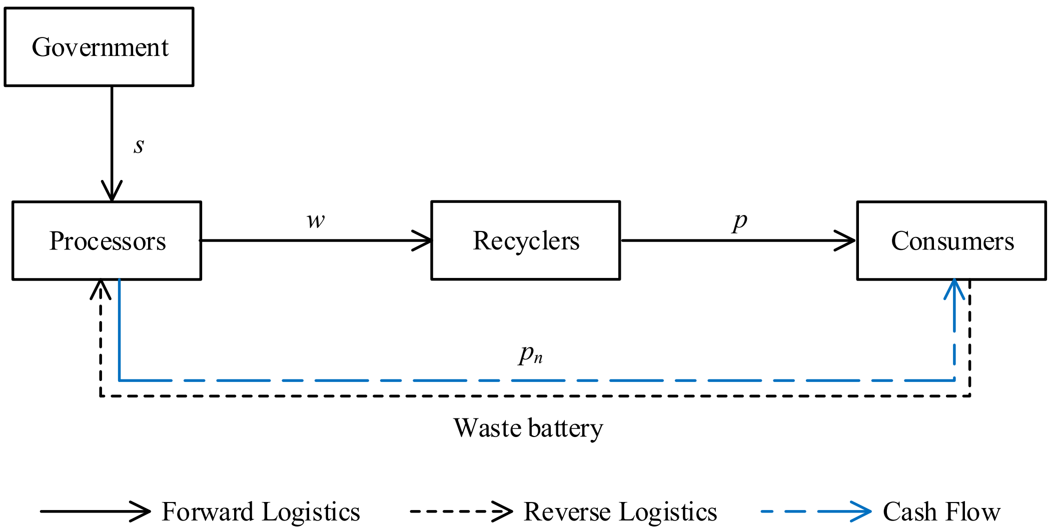



**Figure 1.** Recycling model with government subsidies to processors for direct recycling.

The processor's profit function at this point is expressed as follows:

$$\Pi_m^M = (w - c_m)Q + G_m^M(\varphi - p_n) + sG_m^M \tag{1}$$

The recycler's profit function at this point is expressed as follows:

$$\Pi_r^M = (p - w)Q \tag{2}$$

To solve these equations, we employ backward induction. Setting the first derivative of Equation (2) to zero, the response function for the sales price $p$ is obtained as follows:

$$p(w) = \frac{a + bw}{2b} \tag{3}$$

Given that the second-order derivative $\frac{\partial^2 \Pi_r^M}{\partial p^2} = -2b < 0$, the recycler's profit function $\Pi_r^M$ is a convex function with respect to the sales price $p$, ensuring a unique maximum. Thus, an optimal sales price $p(w)$ exists. Substituting Equation (3) into the processor's profit function (Equation (1)), we derive the Hessian matrix of the processor's profit function $\Pi_m^M$ with respect to the wholesale price w and the purchase price $p_n$ as follows:

$$H = \begin{pmatrix} \frac{\partial^2 \Pi_m^M}{\partial w^2} & \frac{\partial^2 \Pi_m^M}{\partial w \partial p_n} \\ \frac{\partial^2 \Pi_m^M}{\partial p_n \partial w} & \frac{\partial^2 \Pi_m^M}{\partial {p_n}^2} \end{pmatrix} = \begin{pmatrix} -b & 0 \\ 0 & -2h \end{pmatrix}$$

Since $b > 0, h > 0$, it is evident that the Hessian matrix is negatively defined, indicating the presence of an optimal profit. Consequently, there exists a unique optimal solution for the wholesale price $w$ and purchase price $p_n$. The integration of these equations leads to Theorem 1:

**Theorem 1.** *In Model M, the wholesale prices, sales prices, and purchase prices are determined as follows:*

$$w^M = \frac{a + bc_m}{2b}$$
$$p^M = \frac{1}{4}\left(\frac{3a}{b} + c_m\right)$$
$$p_n^M = \frac{-k + h(s + \varphi)}{2h} \tag{4}$$

By inserting the above equation into Equations (1) and (2), we can calculate the processor's profit, the recycler's profit, the total profit of the supply chain, and the recycling volume, respectively.

$$\Pi_m^M = \frac{ah(a - 2bc_m) + b\left(b{c_m}^2 h + 2(k + h(s + \varphi))^2\right)}{8bh} \tag{5}$$

$$\Pi_r^M = \frac{(a - bc_m)^2}{16b} \tag{6}$$

$$\Pi_s^M = \frac{3ah(a - 2bc_m) + b\left(3b{c_m}^2 h + 4(k + h(s + \varphi))^2\right)}{16bh} \tag{7}$$

$$G_m^M = \frac{1}{2}(k + h(s + \varphi)) \tag{8}$$

*3.2. Recycling Model with Government Subsidies to Recyclers for Direct Recycling (R)*

Another supply chain model in the market involves recyclers conducting the recycling process directly. In this approach, recyclers utilize the distribution and service networks of upstream and downstream companies, along with advanced recycling technologies, to enhance efficiency and lower costs. BMW is a key representative in this model, having established a battery traceability system that guarantees that the company will handle the recycling of power batteries once they reach the end of their life cycle.

The sales chain of the *R*-model parallels that of the *M*-model. In this model's recycling chain, recyclers reclaim used batteries from consumers at a subsidized price $p_r$ and subsequently resell them to upstream processors at a transfer price $p_m$ for dismantling and remanufacturing. In this process, the recycler exclusively undertakes recycling activities. The recycler is designated as the leader of the Stackelberg game, receiving direct subsidies from the government, as illustrated in Figure 2. While the order of the game in the *R*-model differs from the *M*-model, the assumptions and parameters remain consistent with those in the $M$-model. Additionally, the recycling and wholesale prices in the $R$-model must satisfy the conditions $p = w + c_1$, $p_r = p_m + c_2$, where $c_1$ and $c_2$ represent the expected returns per unit for the recycler in the sales and recycling channels, respectively.

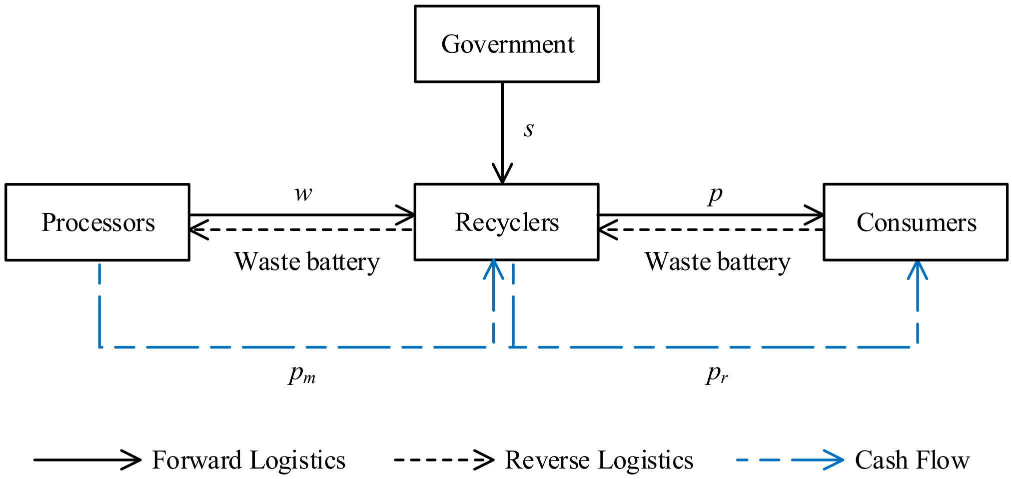



**Figure 2.** Recycling model with government subsidies to recyclers for direct recycling.

The processor's profit function in this model is expressed as follows:

$$\Pi_m^R = (w - c_m)Q + G_r^R(\varphi - p_m) \tag{9}$$

And then the following is obtained:

$$\Pi_m^R = (w - c_m)(a - b(w + c_1)) + (k + h(p_m - c_2))(\varphi - p_m)$$

The following is the recycler's profit function:

$$\Pi_r^R = (p - w)Q + G_r^R(p_m - p_r) + sG_r^R \tag{10}$$

Similarly, the response function is obtained as follows:

$$w(p) = \frac{a + bc_m - bp}{b}$$

$$p_m(p_r) = \frac{-k - hp_r + h\varphi}{h}$$

Associating the above equations yields Theorem 2 as follows:

**Theorem 2.** *In model R, the wholesale prices, sales prices, subsidized prices, and transfer prices are determined as follows:*

$$w^R = \frac{a + 3bcm}{4b}$$

$$p^R = \frac{1}{4}\left(\frac{3a}{b} + c_m\right)$$

$$p_r^R = \frac{-3k + h(s + \varphi)}{4h} \tag{11}$$

$$p_m^R = \frac{-k + h(3\varphi - s)}{4h} \tag{12}$$

Upon substituting the above equation into Equations (9) and (10), the processor's profit, the recycler's profit, the total profit of the supply chain, and the recycling volume can be, respectively, calculated as follows:

$$\Pi_m^R = \frac{ah(a-2bc_m)+b\left(bc_m{}^2h+(k+h(s+\varphi))^2\right)}{16bh} \tag{13}$$

$$\Pi_r^R = \frac{ah(a-2bc_m)+b\left(bc_m{}^2h+(k+h(s+\varphi))^2\right)}{8bh} \tag{14}$$

$$\Pi_s^R = \frac{3\left(ah(a-2bc_m)+b\left(bc_m{}^2h+(k+h(s+\varphi))^2\right)\right)}{16bh} \tag{15}$$

$$G_r^R = \frac{1}{4}(k+h(s+\varphi)) \tag{16}$$

*3.3. Inference and Proof of Single-Channel Recycling Model*

**Proposition 1.** *In distinct recycling models, the benefits generated by the recycling entities vary. The overall supply chain benefits are maximized in a model where the government subsidizes the processor for direct recycling.*

**Proof of Proposition 1.** Given $a > 0$, $b > 0$, $h > 1$, $a - 2bc_m > 0$, a comparison of Equation (4) with Equation (11) and Equation (8) with Equation (16) results in $p_n^M - p_r^R > 0$, $G_m^M - G_r^R > 0$; additionally, contrasting Equation (5) with Equation (13), Equation (6) with Equation (14), and Equation (7) with Equation (15) leads to $\Pi_m^M - \Pi_m^R > 0$, $\Pi_r^M - \Pi_r^R < 0$, $\Pi_s^M - \Pi_s^R > 0$. This completes the proof. □

In the *M*-model, the processor implements a self-constructed reverse supply chain for direct battery recycling to consumers, thereby enhancing recycling efficiency by removing intermediaries such as other principal entities. Coupled with the revenue increase from government subsidies, the processor's benefit is optimized, resulting in greater profits for the *M*-model supply chain compared to the *R*-model. Hence, the *M*-model achieves optimal overall supply chain efficiency in single-channel recycling scenarios.

In contrast, the active participation of recyclers in the closed-loop supply chain directly enhances their revenue streams. Under the *R*-model, recyclers can fully leverage their roles, leading to increased revenue opportunities through active engagement in recycling activities. Consequently, recyclers achieve their highest profit levels in the *R*-model. This phenomenon illustrates the distribution of benefits and the realization of gains among the various participants in the supply chain across different models.

**Proposition 2.** *Government subsidies allocated to the supply chain invigorate the recycling efforts of participating entities and aid in the supply chain's capital asset accumulation.*

**Proof of Proposition 2.** Deriving Equations (4), (8), (11) and (16) with respect to $s$ yields $\frac{\partial p_n^M}{\partial s} > 0$, $\frac{\partial p_r^R}{\partial s} > 0$, $\frac{\partial G_m^M}{\partial s} > 0$, $\frac{\partial G_r^R}{\partial s} > 0$; the further derivation of Equations (5), (7) and (13)–(15) with respect to $s$ results in $\frac{\partial \Pi_m^M}{\partial s} > 0$, $\frac{\partial \Pi_s^M}{\partial s} > 0$, $\frac{\partial \Pi_m^R}{\partial s} > 0$, $\frac{\partial \Pi_r^R}{\partial s} > 0$, $\frac{\partial \Pi_s^R}{\partial s} > 0$, accompanied by second-order derivatives $\frac{\partial^2 \Pi_m^M}{\partial s^2} > 0$, $\frac{\partial^2 \Pi_s^M}{\partial s^2} > 0$, $\frac{\partial^2 \Pi_m^R}{\partial s^2} > 0$, $\frac{\partial^2 \Pi_r^R}{\partial s^2} > 0$, $\frac{\partial^2 \Pi_s^R}{\partial s^2} > 0$ with respect to $s$. □

When either processors or recyclers receive increased government subsidies, they are incentivized to offer consumers higher prices for recyclables. This leads to an increase in recycling volumes, which in turn attracts more subsidies, creating a positive feedback loop. This cycle manifests as increased profits for the supply chain.

This further underscores the significant impact of government subsidy levels on recycling efficiency. As the government increases the subsidy amount, both processors and recyclers benefit from enhanced profit margins due to the additional financial support. This enables them to offer higher recycling prices to consumers. For consumers, the increased recycling price serves as a strong incentive to engage more actively in battery recycling activities, resulting in a substantial rise in the number of recycled products.

**Proposition 3.** *The sensitivity factor plays a crucial role in businesses assessing consumer willingness to participate in recycling. A rise in this factor signals a buoyant recycling market, moderating the growth rate of recycling prices.*

**Proof of Proposition 3.** Deriving Equations (8) and (16) with respect to the sensitivity factor $h$ yields $\frac{\partial G_m^M}{\partial h} > 0$, $\frac{\partial G_r^R}{\partial h} > 0$; similarly, deriving Equations (4) and (11) with respect to $h$ results in $\frac{\partial p_n^M}{\partial h} > 0$, $\frac{\partial p_r^R}{\partial h} > 0$; additionally, there are second-order derivatives $\frac{\partial^2 p_n^M}{\partial h^2} < 0$, $\frac{\partial^2 p_r^R}{\partial h^2} < 0$ with respect to $h$. □

This proposition suggests that enterprises can encourage consumer participation in battery recycling by offering suitable incentives that respond to price sensitivity. Consumers are typically sensitive to price changes. If enterprises can effectively recognize this characteristic, they can offer appropriate incentives to encourage consumer participation in recycling activities. This approach will help increase the volume of recycled batteries, thereby enhancing the overall efficiency of the entire supply chain.

However, the increase in recycling prices influenced by the sensitivity factor is not unlimited. Whether it involves processors or recyclers, businesses will not permit an indefinite increase in recycling prices. This is due to the fact that enterprises face several constraints when setting recycling prices, including cost considerations and market competition. Therefore, they will moderately increase the recycling price within a specific range, eventually reaching a plateau.

**Proposition 4.** *In the R-model, recyclers assume a pivotal role as leaders in the supply chain. They are exploring innovative strategies to promote the whole as an individual and benefit the individual overall. This approach is integral to accelerate the overall momentum of the supply chain, thereby achieving collective success.*

**Proof of Proposition 4.** Deriving Equation (12) with respect to $s$ gives $\frac{\partial p_m^R}{\partial s} < 0$. This completes the proof. □

In the $R$-model, recyclers, as supply chain leaders, stimulate other supply chain members to engage in recycling by distributing government subsidies. This is manifested in recyclers augmenting the processor's revenue by lowering the transfer price, fostering a cooperative win–win situation in the supply chain.

In this context, recyclers assume a crucial role, as government subsidies are directed toward them, providing both resource advantages and motivation. To maximize the positive impact of these subsidies, recyclers often implement strategies to reduce the transfer price charged to processors, thereby increasing the revenue generated during the dismantling and treatment process. Consequently, processors benefit from improved cost control. This dynamic not only effectively encourages processors to engage in recycling but also fosters a win–win cooperation within the supply chain.

**Proposition 5.** *In the single-channel recycling scenario, when* $0 < s < \frac{k+h\varphi}{h}$*, the recycler shares the government subsidy by offering discounts; when* $\frac{k+h\varphi}{h} < s < \frac{-k+3h\varphi}{h}$*, the recycler will distribute the government subsidy via a rebate program.*

**Proof of Proposition 5.** As government subsidies increase, the transfer price is reduced to safeguard the recycler's interests in the used battery transfer process. This requires the condition $p_m - p_r > 0$, implying $p_m - p_r = \frac{k-hs+h\varphi}{2h} > 0$, where $0 < s < \frac{k+h\varphi}{h}$. Moreover, with further increases in government subsidies, the recycler continues to offer concessions to the processor, leading to $p_m - p_r < 0$ and $p_m > 0$, thereby satisfying $p_m - p_r = \frac{k-hs+h\varphi}{2h} < 0$ and $\frac{-k+h(3\varphi-s)}{4h} > 0$. At this point, there are $\frac{k+h\varphi}{h} < s < \frac{-k+3h\varphi}{h}$. This completes the proof. □

In the context of government subsidies per unit meeting the condition $0 < s < \frac{k+h\varphi}{h}$, the recycler strategically lowers the transfer price to pass a portion of the subsidy to the processor, simultaneously ensuring its own revenue. The condition $\frac{k+h\varphi}{h} < s < \frac{-k+3h\varphi}{h}$ is sufficient to compensate for the concessions the recycler makes to the processor in the transfer process. Under these circumstances, the recycler only incurs a financial loss in the transferring link, with the processor's payment for the transferred batteries being lower than the subsidy price the recycler incurs to acquire the batteries from consumers. However, when the subsidy condition reaches $s > \frac{-k+3h\varphi}{h}$, at this time $p_m < 0$, implying that the recycler not only transfers recovered batteries to the processor but might also need to subsidize the processor. Such a scenario is highly unlikely in practical settings.

This analysis highlights that even if the government subsidy is directed towards a single entity within the supply chain, other members can still indirectly benefit from this subsidy. Therefore, a reasonable interval for the government subsidy is established as $0 < s < \frac{-k+3h\varphi}{h}$. This interval ensures that the subsidy mechanism benefits the entire supply chain, promoting more efficient recycling practices and contributing to the sustainable management of resources.

## 4. Dual-Channel Recycling Model

In a dual-channel recycling scenario, both the processor and the recycler function as independent decision-makers and are actively involved in the recycling process, creating a competitive dynamic. The processor reclaims used batteries from consumers at a purchase price $p_n$, while the recycler collects them at a subsidized price $p_r$, with both eventually transferring the used batteries to the processor for dismantling and reuse.

### *4.1. Recycling Model Led by Processors with Government Subsidies to Processors (M*R)*

In the market, supply chain structures are primarily driven by processors in the recycling model. In China, companies like CATL, Guoxuan High-Tech, and BYD are key players in this area. CATL introduced the idea of "upstream and downstream" recycling and, with government support, has developed a novel waste battery recycling supply chain. Meanwhile, Guoxuan High-Tech has initiated commercial activities in data collection, verification, and reporting for waste battery recycling, successfully establishing a comprehensive network from ladder utilization to resource recovery.

In the *M*R* model, the processor is the leader of the Stackelberg game, receiving subsidies from the government, as depicted in Figure 3. The decision-making sequence is as follows: the processor initially sets the wholesale price $w$ of the battery, the purchase price $p_n$ of the waste battery, and the transfer price $p_m$ of the waste battery. Subsequently, the recycler determines the sales price $p$ of the battery and the subsidized price $p_r$ of the waste battery.

The processor's profit function at this point is expressed as follows:

$$\Pi_m^{M^*R} = (w - c_m)Q + G_m^{M^*R}(\varphi - p_n) + G_r^{M^*R}(\varphi - p_m) + sG_m^{M^*R} \quad (17)$$

The recycler's profit function at this point is expressed as follows:

$$\Pi_r^{M^*R} = (p - w)Q + G_r^{M^*R}(p_m - p_r) \quad (18)$$

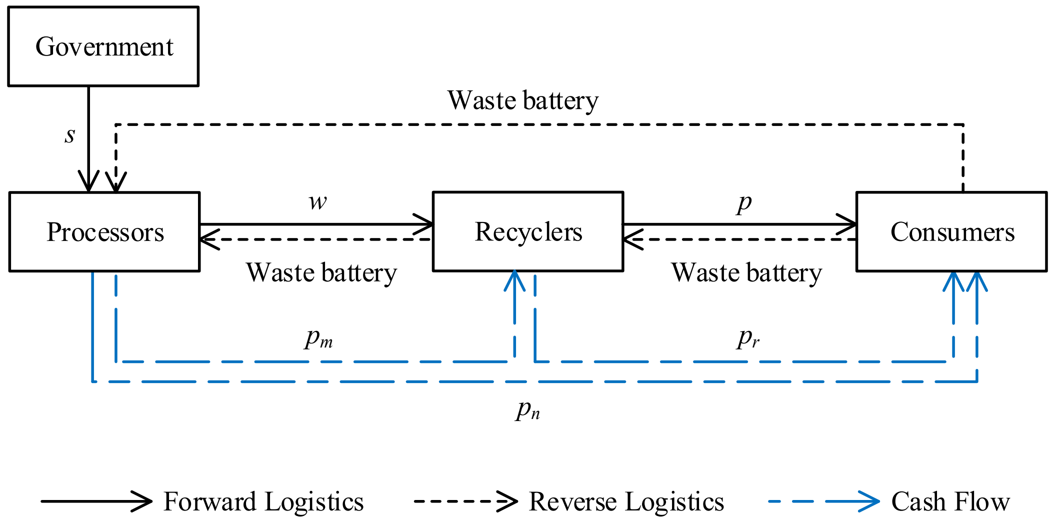



**Figure 3.** Recycling model led by processors with government subsidies to processors.

Similarly, the response function is obtained as follows:

$$p(w) = \frac{a + bw}{2b}$$

$$p_r^* = \frac{-k + hp_m + mp_n}{2h}$$

Associating the above equations yields Theorem 3 as follows:

**Theorem 3.** *Model M*R establishes wholesale prices, sales prices, purchase prices, transfer prices, and subsidized prices as follows:*

$$w^{M^*R} = \frac{a + bc_m}{2b}$$

$$p^{M^*R} = \frac{1}{4}\left(\frac{3a}{b} + c_m\right)$$

$$p_n^{M^*R} = \frac{1}{2}\left(\frac{k}{-h+m} + s + \varphi\right) \quad (19)$$

$$p_m^{M^*R} = \frac{1}{2}\left(\frac{k}{-h+m} + \varphi\right) \quad (20)$$

$$p_r^{M^*R} = \frac{h(-3k + ms) + h^2\varphi + m(k - m(s+\varphi))}{4h(h-m)} \quad (21)$$

Inserting the above equations into Equations (17) and (18), we can calculate the processor's profit and recycling volume, the recycler's profit and recycling volume, and the total profit and recycling volume of the supply chain, respectively.

$$\begin{aligned}\Pi_m^{M^*R} = & \frac{a^2h(h-m) + 2abc_mh(-h+m) + bc_m{}^2h(h-m) + bh(3k+ms-m\varphi)(k-m(s+\varphi))}{8bh(h-m)} \\ & + \frac{b\left(h^2\left(4ks - 2ms^2 + 6k\varphi - 6ms\varphi - 5m\varphi^2\right) + m(k-m(s+\varphi))^2\right) + bh^3\left(2s^2 + 4s\varphi + 3\varphi^2\right)}{8bh(h-m)}\end{aligned} \quad (22)$$

$$\Pi_r^{M^*R} = \frac{ah(a - 2bc_m) + b\left(bc_m{}^2h + (k + h\varphi - m(s+\varphi))^2\right)}{16bh} \quad (23)$$

$$\Pi_s^{M^*R} = \frac{3a^2h(h-m)+6abc_mh(-h+m)+b3bc_m{}^2h(h-m)+bm(k-m(s+\varphi))^2+bh^3\left(4s^2+8s\varphi+7\varphi^2\right)}{16bh(h-m)} + \frac{bh^2\left(8ks-4ms^2+14k\varphi-14ms\varphi-13m\varphi^2\right)+bh(7k+ms-5m\varphi)(k-m(s+\varphi))}{16bh(h-m)} \tag{24}$$

$$G_m^{M^*R} = \frac{2h^2(s+\varphi)+h(2k-m\varphi)+m(k-m(s+\varphi))}{4h} \tag{25}$$

$$G_r^{M^*R} = \frac{1}{4}(k+h\varphi-m(s+\varphi)) \tag{26}$$

$$G_s^{M^*R} = \frac{h^2(2s+3\varphi)+m(k-m(s+\varphi))+h(3k-m(s+2\varphi))}{4h} \tag{27}$$

### *4.2. Recycling Model Led by Recyclers with Government Subsidies to Recyclers (MR*)*

The market also features a supply chain structure where recyclers take the lead in recycling efforts. In China, companies like SAIC, BYD, and GAC are prominent in this area. BYD manages battery recycling through its network of dealers. When a dealer collects a customer's exchanged power battery, it is sent to BYD's Baolong factory for testing and reuse.

In the $MR^*$ model, the recycler assumes the role of the leader in the Stackelberg game and is subsidized by the government, as shown in Figure 4. The decision-making process is structured as follows: the recycler first decides on the sales price $p$ of the battery and the subsidized price $p_r$ of the waste battery. Following this, the processor determines the wholesale price $w$ of the battery, the purchase price $p_n$ of the waste battery, and the transfer price $p_m$ of the waste battery.

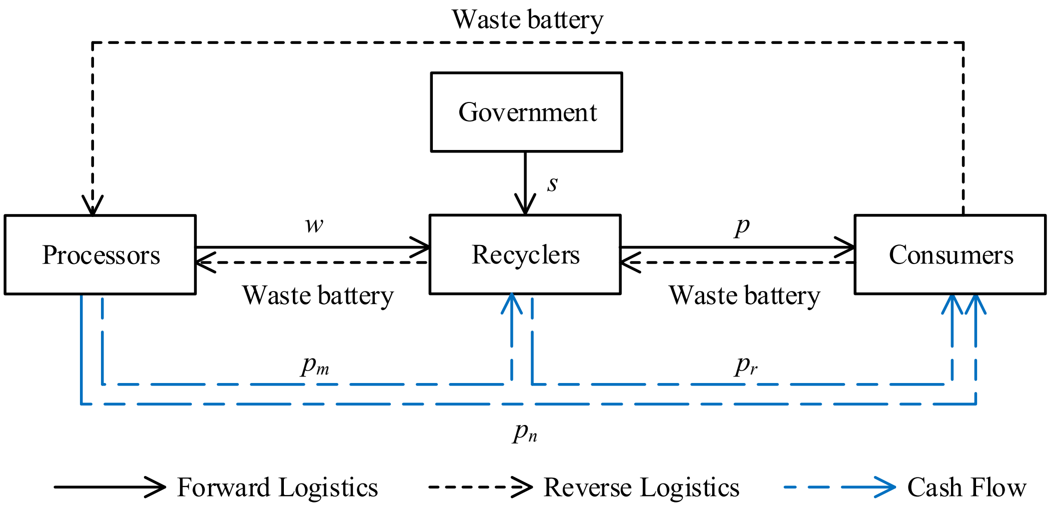



**Figure 4.** Recycling model led by recyclers with government subsidies to recyclers.

The processor's profit function in this model is expressed as follows:

$$\Pi_m^{MR^*} = (w-c_m)Q + G_m^{MR^*}(\varphi - p_n) + G_r^{MR^*}(\varphi - p_m) \tag{28}$$

Recycler's profit function:

$$\Pi_r^{MR^*} = (p-w)Q + G_r^{MR^*}(p_m - p_r) + sG_r^{MR^*} \tag{29}$$

The response function is obtained as follows:

$$w(p) = \frac{a+bc_m-bp}{b}$$

$$p_m^* = \frac{-k + 2mp_n - hp_r + h\varphi - m\varphi}{h}$$

Associating the above equations yields Theorem 4 as follows:

**Theorem 4.** *Model MR* determines wholesale prices, sales prices, purchase prices, transfer prices, and subsidized prices as follows:*

$$w^{MR^*} = \frac{a + 3bc_m}{4b}$$

$$p^{MR^*} = \frac{3a + bc_m}{4b}$$

$$p_n^{MR^*} = \frac{-k + \varphi(h - m)}{2(h - m)} \tag{30}$$

$$p_m^{MR^*} = -\frac{h^2(s - 3\varphi) + m(k - m\varphi) + h(k - ms + 4m\varphi)}{4h(h - m)} \tag{31}$$

$$p_r^{MR^*} = \frac{k(-3h + m) + hs(h - m) + \varphi\left(h^2 - m^2\right)}{4h(h - m)} \tag{32}$$

By substituting the above equation into Equations (28) and (29), we can calculate the processor's profit and recycling volume, the recycler's profit and recycling volume, and the total profit and recycling volume of the supply chain, respectively.

$$\Pi_m^{MR^*} = \frac{a^2h(h-m)+2abc_mh(m-h)+b^2c_m{}^2h(h-m)+3bm(k-m\varphi)^2+bh^2\left(2k(s+5\varphi)-m\left(s^2+4s\varphi+7\varphi^2\right)\right)}{16bh(h-m)} + \frac{+bh(k-m\varphi)(5k+m(\varphi-2s))+bh^3\left(s^2+2s\varphi+5\varphi^2\right)}{16bh(h-m)}$$

$$\Pi_r^{MR^*} = \frac{a^2h - 2abc_mh + b\left(bc_m{}^2h + (k - m\varphi + h(s + \varphi))^2\right)}{8bh}$$

$$\Pi_s^{MR^*} = \frac{6bh^2ks-6bhkms+3bh^3s^2-3bh^2ms^2+b(h-m)^2(7h+m)\varphi^2+2b(h-m)(k(7h+m)+3bh(h-m)s)\varphi}{16bh(h-m)} + \frac{3a^2h(h-m)+6abc_mh(-h+m)+7bhk^2+3b^2c_m{}^2h(h-m)+2b(h-m)(k(7h+m)+3bh(h-m)s)\varphi+bk^2m}{16bh(h-m)}$$

$$G_m^{MR^*} = \frac{2hk + 2h^2\varphi - hm(s + \varphi) + m(k - m\varphi)}{4h} \tag{33}$$

$$G_r^{MR^*} = \frac{1}{4}(k - m\varphi + h(s + \varphi)) \tag{34}$$

$$G_s^{MR^*} = \frac{3hk - hm(s + 2\varphi) + h^2(s + 3\varphi) + m(k - m\varphi)}{4h}$$

*4.3. Inference and Proof of Dual-Channel Recycling Model*

**Proposition 6.** *In a dual-channel recycling framework, the government subsidy policy significantly heightens the beneficiaries' willingness to recycle.*

**Proof of Proposition 6.** Given $0 < m < 1$, $s > 0$, $h > 1$, a comparison of Equation (19) with Equation (30) and Equation (21) with Equation (32) results in $p_n^{M^*R} - p_n^{MR^*} > 0$, $p_r^{M^*R} - p_r^{MR^*} > 0$; further contrasting Equation (25) with Equation (33) and Equation (26) with Equation (34) leads to $G_m^{M^*R} - G_m^{MR^*} > 0$, $G_r^{M^*R} - G_r^{MR^*} < 0$. This completes the proof. □

In the *M*R* model, where the government subsidizes processor-led recycling, processors exhibit higher recycling efficiency. Under this model, the processor, as the leader of the recycling activities, possesses greater resources and incentives to undertake recycling efforts.

Conversely, in the *MR** model with government-subsidized recycler-led recycling, recyclers demonstrate greater efficiency. In this context, recyclers emerge as the central force driving these activities, with government subsidies providing substantial financial support. Recyclers can leverage these subsidies to expand their recycling networks and foster closer partnerships with consumers, thereby enhancing both the volume and efficiency of recycling.

In summary, regardless of the model in place, government subsidies effectively incentivize beneficiary entities to engage in recycling, ultimately extending these benefits throughout the entire supply chain to improve recycling efficiency.

**Proposition 7.** *Government subsidies influence the recycling prices set by the primary recycling entities, ensuring orderly recycling activities.*

**Proof of Proposition 7.** With $0 < m < 1$, $h > 1$ being established, in the *M*R* model, deriving Equations (19) and (21) with respect to $s$ yields $\frac{\partial p_n^{M^*R}}{\partial s} > 0$, $\frac{\partial p_r^{M^*R}}{\partial s} > 0$; a similar proof can be made for the *MR** model, where $\frac{\partial p_n^{MR^*}}{\partial s} = 0$, $\frac{\partial p_r^{MR^*}}{\partial s} > 0$ holds. The proof is complete. □

Whether it is a processor or a recycler, government subsidies boost the profit margins of recycling entities, enabling them to offer higher recycling prices as incentives for consumer participation. Concurrently, rising recycling prices may indicate the presence of inter-channel competition in the market. This is because, in their pursuit of limited resources and market share among channels, they may attract potential customers by, for instance, increasing the recycling price. Notably, in the *MR** model, processor's purchase price remains unaffected by changes in government subsidies. This is in contrast to recyclers who elevate subsidized prices under this model, leading to a diminished direct recycling channel advantage for processors.

In conclusion, government subsidies significantly influence both the recycling entities and market competition within the closed-loop supply chain. In practical applications, it is essential to consider various factors and develop reasonable policy measures that encourage recycling entities to actively participate in recycling activities while promoting fair competition and the sustainable development of the market.

**Proposition 8.** *Supply chain leaders significantly influence the recycling enthusiasm of participating enterprises, enhancing the overall efficiency of the supply chain and fostering a harmonious, orderly power battery recycling system.*

**Proof of Proposition 8.** Deriving Equations (20) and (31) with respect to $s$ yields $\frac{\partial p_m^{M^*R}}{\partial s} > 0$, $\frac{\partial p_m^{MR^*}}{\partial s} < 0$. The proof is complete. □

In the *M*R* model, as government subsidies increase, the transfer price also rises. This indicates that the processor shares the subsidy with the recycler by increasing the transfer price paid to the recycler. This practice not only reflects the processors' willingness to cooperate but also incentivizes recyclers to engage more actively in recycling activities, thereby enhancing the overall recycling efficiency of the supply chain. In the *MR** model, the processor's direct recycling channel advantage diminishes, leading to a sharp decrease in its recycling volume. Consequently, its main revenue in the reverse supply chain arises from processing and reusing used batteries obtained from the recycler. The recycler then shares the subsidy with the processor by lowering the transfer price payable by the processor, which helps reduce the processor's costs and increase its profitability in processing and reuse.

In summary, government subsidies exert varying impacts on transfer prices and the behaviors of different recycling entities in the supply chain depending on the model employed.

**Proposition 9.** *The introduction of government subsidies energizes enterprise participation in recycling, increases the total recycling volume in the supply chain, enhances marginal benefits, and promotes steady supply chain development.*

**Proof of Proposition 9.** With $0 < m < 1$, $h > 1$ being established, in the $M^*R$ model, deriving Equations (25)–(27) with respect to $s$ yields $\frac{\partial G_m^{M^*R}}{\partial s} > 0$, $\frac{\partial G_r^{M^*R}}{\partial s} > 0$, $\frac{\partial G_s^{M^*R}}{\partial s} > 0$; a similar proof for the $MR^*$ model yields $\frac{\partial G_m^{MR^*}}{\partial s} < 0$, $\frac{\partial G_r^{MR^*}}{\partial s} > 0$, $\frac{\partial G_s^{MR^*}}{\partial s} > 0$. The proof is complete. □

This highlights the influence of government subsidy inputs on the recycling volume of used batteries from various recycling entities, as well as the total recycling volume within the supply chain. The increased government subsidies lead to a significant increase in the recycling volume by participants and the overall recycling volume of the supply chain. In the $MR^*$ model, however, the dynamics differ. Processors lose their competitive edge in direct recycling due to price imbalances. However, the increased recycling volume by recyclers, who gain a competitive edge through price advantages, offsets the reduced volume from processors' direct channels. Consequently, although processors face challenges in the direct recycling market, the total recycling volume in the $MR^*$ model still increases with rising government subsidies.

**Proposition 10.** *When the unit government subsidy satisfies* $0 < s < \frac{(2h+m)(k+(h-m)\varphi)}{hm}$*, the dual recycling channels in the* $MR^*$ *model are balanced.*

**Proof of Proposition 10.** To achieve $G_m^{MR^*} > 0$, it is necessary to satisfy $\frac{2hk+2h^2\varphi-hm(s+\varphi)+m(k-m\varphi)}{4h} > 0$, resulting in $0 < s < \frac{(2h+m)(k+(h-m)\varphi)}{hm}$. The proof is complete. □

The implementation of government subsidies somewhat hampers the increase in direct channel recycling by $MR^*$ model processors, reducing the model's recycling efficiency. Several factors contribute to this phenomenon. For instance, government subsidies can alter the price equilibrium in the market, providing recyclers with a competitive advantage and increasing pressure on the direct recycling channels utilized by processors. Consequently, the decline in recycling volumes through the processors' direct channels directly affects the recycling efficiency of the $MR^*$ model. Therefore, to enhance the recycling level of the $MR^*$ model and promote the balanced development of its dual recycling channels, it is vital to ensure that the processors' direct recycling channels function effectively. Hence, the unit government subsidy should meet the condition $0 < s < \frac{(2h+m)(k+(h-m)\varphi)}{hm}$. This scenario could facilitate the balanced development of the dual recycling channels while promoting a higher level of recycling within the $MR^*$ model.

**Proposition 11.** *The efficiency of all participants in the supply chain system will continually increase with government subsidies as the supply chain operates.*

**Proof of Proposition 11.** With $0 < m < 1$, $h > 1$ being established, taking the derivative of Equations (22)–(24) with respect to $s$ yields $\frac{\partial \Pi_m^{M^*R}}{\partial s} > 0$, $\frac{\partial \Pi_r^{M^*R}}{\partial s} > 0$, $\frac{\partial \Pi_s^{M^*R}}{\partial s} > 0$; additionally, there are second-order derivatives $\frac{\partial^2 \Pi_m^{M^*R}}{\partial s^2} > 0$, $\frac{\partial^2 \Pi_r^{M^*R}}{\partial s^2} > 0$, $\frac{\partial^2 \Pi_s^{M^*R}}{\partial s^2} > 0$ with respect to $s$. A similar proof for the $MR^*$ model produces $\frac{\partial \Pi_m^{MR^*}}{\partial s} > 0$, $\frac{\partial \Pi_r^{MR^*}}{\partial s} > 0$, $\frac{\partial \Pi_s^{MR^*}}{\partial s} > 0$ and $\frac{\partial^2 \Pi_m^{MR^*}}{\partial s^2} > 0$, $\frac{\partial^2 \Pi_r^{MR^*}}{\partial s^2} > 0$, $\frac{\partial^2 \Pi_s^{MR^*}}{\partial s^2} > 0$. The proof is complete. □

This underscores the importance of the government subsidy strategy for the benefits of supply chain members and the overall development of the supply chain. The government subsidy strategy substantially increases the benefits for supply chain members. As participants become increasingly sensitive to per-unit government subsidies, the continuous augmentation of government subsidy inputs will allow for the supply chain to accumulate substantial wealth, thus laying a financial foundation for further development and steady expansion of the supply chain.

**Proposition 12.** *In a dual-channel recycling scenario, the recycler shares the government subsidy in the form of a discount when* $0 < s < \frac{k+h\varphi-m\varphi}{h}$ *and as a rebate when* $\frac{k+h\varphi-m\varphi}{h} < s < \frac{-hk-km+3h^2\varphi-4hm\varphi+m^2\varphi}{h(h-m)}$.

**Proof of Proposition 12.** As government subsidies increase, resulting in a decreasing transfer price, the recycler's revenue protection in the battery transfer process necessitates the condition $p_m - p_r > 0$, i.e., $p_m - p_r = \frac{k-hs+h\varphi-m\varphi}{2h} > 0$, leading to $0 < s < \frac{k+h\varphi-m\varphi}{h}$. Further, if the recycler continues to offer concessions to the processor, as denoted by $p_m - p_r < 0$ and $p_m > 0$, then $\frac{k+h\varphi-m\varphi}{h} < s < \frac{-hk-km+3h^2\varphi-4hm\varphi+m^2\varphi}{h(h-m)}$ holds. The proof is complete. □

When the unit government subsidy is within the range $0 < s < \frac{k+h\varphi-m\varphi}{h}$, the recycler, after securing revenue from the transfer, may pass part of this subsidy to the processor by lowering the transfer price. If the subsidy is substantial enough to fall within $\frac{k+h\varphi-m\varphi}{h} < s < \frac{-hk-km+3h^2\varphi-4hm\varphi+m^2\varphi}{h(h-m)}$, it can adequately cover the discounts provided by the recycler to the processor during the transfer phase. In such a scenario, the recycler might incur losses at this stage, meaning that the processor's transfer price could be less than the subsidy the recycler offers consumers for battery collection. However, if $s > \frac{-hk-km+3h^2\varphi-4hm\varphi+m^2\varphi}{h(h-m)}$, indicated by $p_m < 0$, the recycler ends up not only providing the used batteries to the processor for free but also subsidizing them. Nonetheless, this situation is highly unlikely in reality.

Consequently, a reasonable value for $s$ is established as $0 < s < \frac{-hk-km+3h^2\varphi-4hm\varphi+m^2\varphi}{h(h-m)}$. This reasonable range of values is determined through a comprehensive assessment of the interests of each participant in the supply chain, the market mechanisms, and the prevailing conditions.

## 5. Analysis

MATLAB 2017a software was used to explore the impact of unit government subsidy $s$, sensitivity coefficient $h$, and competition coefficient $m$ on recycling activities. Based on the defined parameters in the model and the assumptions regarding their relationships, we assume the following parameter values, drawing inspiration from the research conducted by Wu et al. [31]: $a = 250$, $b = 0.3$, $c_m = 80$, $\varphi = 60$, $k = 6$.

### *5.1. Analysis of Single-Channel Recycling Model*

As illustrated in Figure 5, two key observations are noted in the single-channel recycling model: Firstly, in the $M$-model, the recycling price is consistently higher than in the $R$-model. Secondly, the recycling price is positively correlated with the sensitivity coefficient. Initially, as the sensitivity coefficient increases, the recycling price rises, but this growth rate gradually decelerates and eventually stabilizes.

The consumers' sensitivity to changes in recycling prices indicates that enterprises can adjust these prices to align with consumer expectations, thereby enhancing the volume of recycling in the market and increasing the recycling numbers. However, such adjustments are typically more prevalent in the early stages of industrial development when consumer awareness of active recycling is weak, and market mechanisms are needed to encourage participation.

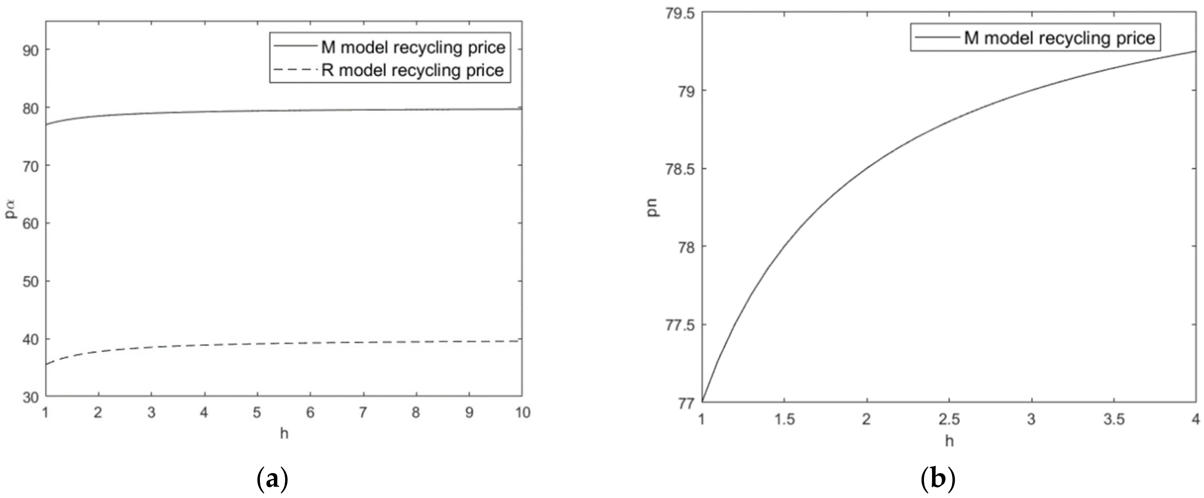



**Figure 5.** Impact of sensitivity coefficients on recycling prices: (**a**) two single-channel recycling models; (**b**) *M*-model recycling price ($1 < h < 4$).

However, this scenario cannot become the standard practice because profit-seeking enterprises will set their own upper limit on the recycling price they offer. Over time, as consumers develop a habit of independent recycling and the recycling market achieves stability, the recycling prices offered by enterprises will return to a stable level. This reinforces the conclusion drawn from previous reasoning that the sensitivity coefficients have the most pronounced impact on recycling prices within the range $1 < h < 4$.

Figure 6 presents the variation in profits for government-subsidized processors across different recycling models in relation to the unit government subsidy. It is found that with no government subsidy, the processor in the *M*-model, as the supply chain leader, exhibits significantly higher benefits than when it plays a follower role in the *R*-model. The *M*-model processor, being the direct recipient of the government subsidy, consistently shows better performance in earnings and greater sensitivity to the subsidy compared to the processor in the *R*-model.

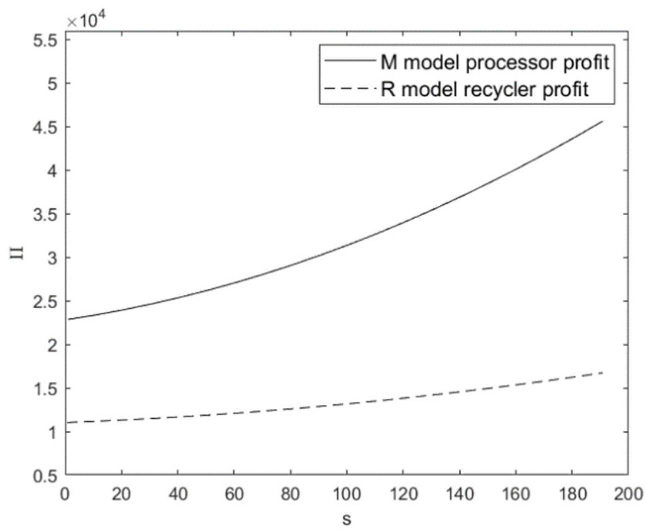



**Figure 6.** Impact of unit government subsidy on processors' profits.

In conclusion, *M*-model processors exhibit significant advantages as supply chain leaders by effectively identifying changes in government subsidy policies and promptly adjusting their business strategies to fully leverage the benefits provided by these subsidies.

In Figure 7, several trends emerge under the combined effects of unit government subsidy and sensitivity coefficients: Firstly, *M*-model processors consistently achieve the highest profits, followed by *R*-model recyclers, with *R*-model processors having the lowest profits. As the *M*-model recycler is not engaged in reverse recycling and derives profit solely from forward sales, it remains unaffected by unit government subsidy and sensitivity coefficients and is thus excluded from this analysis. Secondly, profits for all participating entities exhibit varying degrees of upward trends with increased unit government subsidy and sensitivity coefficients. The impact of unit government subsidy on profits is more pronounced compared to the impact of sensitivity coefficients. Thirdly, processors in the *R*-model, despite not being direct subsidy recipients, also show profits positively correlated with unit government subsidy. This is attributed to the fact that batteries recovered by recyclers under the EPR system are still processed by the processors for dismantling, the extraction of reusable parts, remanufacturing, and sales. Thus, government subsidies indirectly bolster processor profits through increased recycling activities. In summary, processors in the *R*-model indirectly benefit from government subsidies through the secondary recycling of used batteries from recyclers.

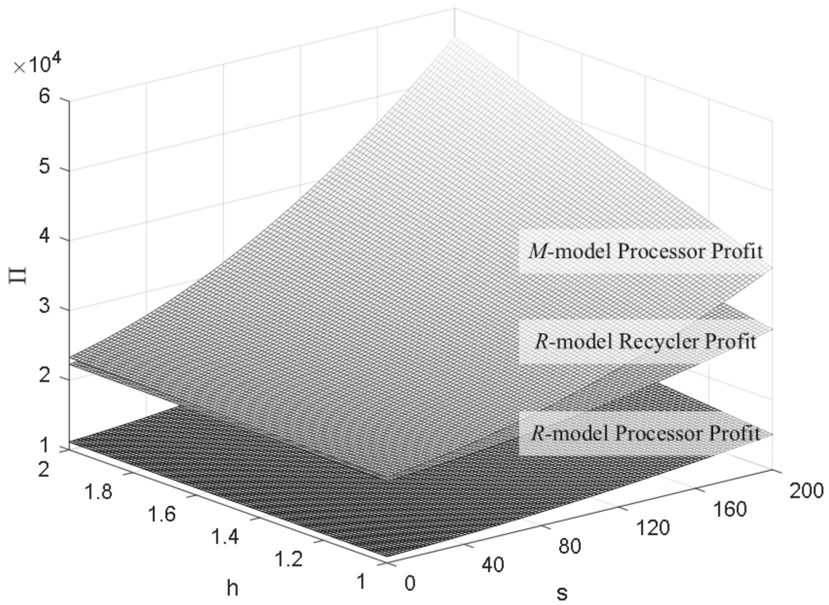



**Figure 7.** Relationship between unit government subsidy, sensitivity coefficients, and profits.

Figure 8 illustrates that government subsidies to processors for direct recycling significantly benefit the entire supply chain. The rationale is that subsidies to processors aid in reducing recycling costs and expanding profit margins, thereby enhancing the efficiency of both recyclers and the supply chain collectively. Notably, the total profit growth rate of the *M*-model exhibits an accelerating trend with the increase in both the sensitivity factor and unit government subsidy. Consequently, in a single-channel recycling scenario, government subsidies for processors' direct recycling can optimize the supply chain to achieve maximum benefits. Therefore, when formulating relevant policies, the government should take into account the advantages of this model to promote the sustainable development of the supply chain.

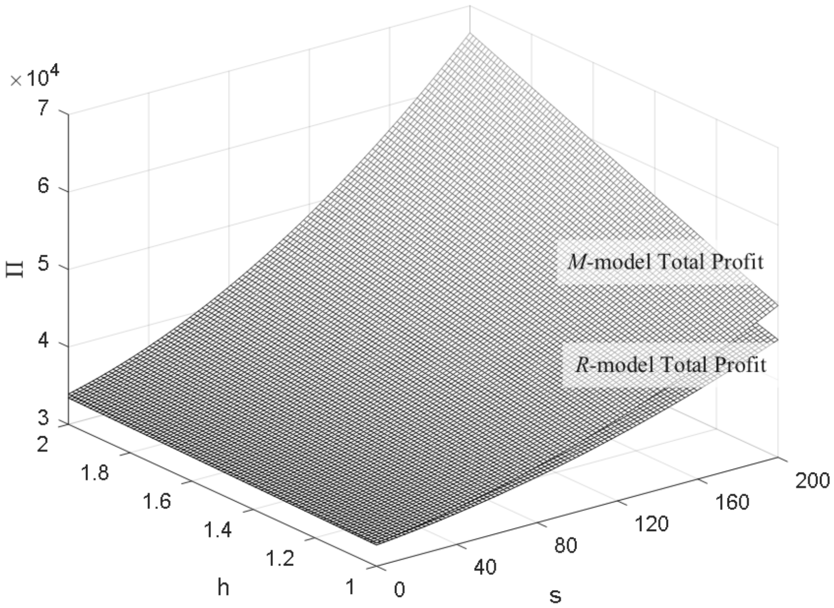



**Figure 8.** Relationship between unit government subsidy, sensitivity coefficients, and total profits in the case of single-channel recycling model.

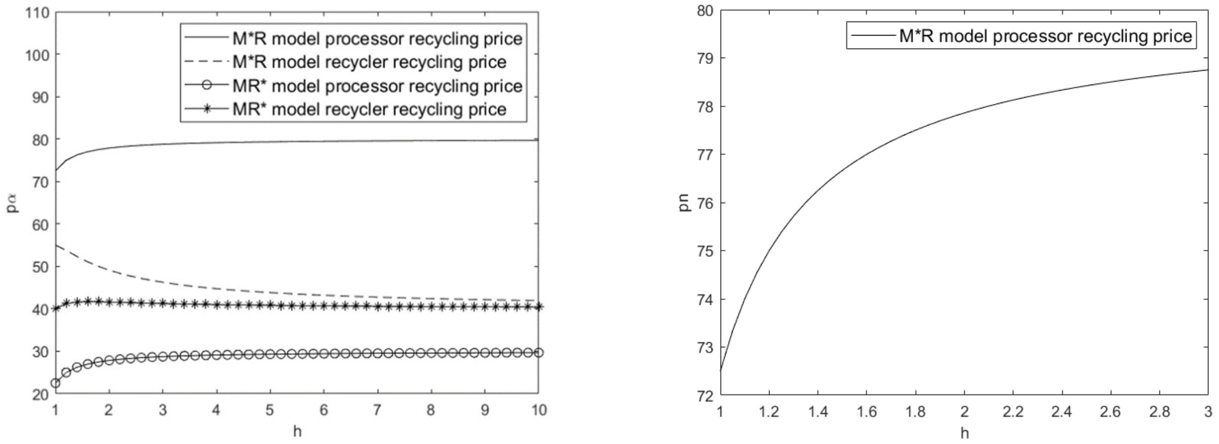
### *5.2. Analysis of Dual-Channel Recycling Model*

In Figure 9, within the dual-channel recycling framework, the following trends are observed:

- Recycling price hierarchy: The *M*R* model processor has the highest recycling price, followed by the *M*R* model recycler. The *MR** model recycler offers slightly lower recycling prices, with the *MR** model processor presenting the lowest prices.
- Impact of sensitivity coefficients: As sensitivity coefficients rise, all recycling prices exhibit a gradual increase, except for the *MR** model recycler, whose recycling price shows a slight decrease before stabilizing. A higher sensitivity coefficient implies that recyclers need to offer more competitive prices to attract consumer participation, guiding them to join the battery recycling effort. After a period of market competition, the recycling market stabilizes, and the recycling prices reach a plateau.
- Dynamics in the *M*R* model: In the *M*R* model, the processor, as the supply chain leader, wields significant influence over product circulation. This dominance results in a squeezed profit margin for the recycler from the outset. Consequently, in the reverse recycling link, the recycler, unable to compete effectively with the processor, offers standard or even lower recycling prices to maintain basic recycling income. It is determined that the sensitivity factor impacts the recycling price most significantly within the range $1 < h < 3$.

Figure 10 indicates that the recycling prices of different entities react differently to the increase in the competition coefficient in both *M*R* and *MR** models. The processor's recycling price demonstrates a gradual decline regardless of the model. This trend suggests that processors adopt a conservative approach to avoid engaging in price wars, which could lead to significant losses. Conversely, the recycler's recycling price exhibits an upward trajectory. This is indicative of recyclers attempting to challenge processors by raising their recycling prices, aiming to capture a larger market share.

Therefore, analyzing the trends in recycling prices among different participants and the competitive strategies of processors and recyclers enhances the understanding of competitive dynamics within the closed-loop supply chain. This analysis provides robust support for enterprises in formulating reasonable competitive strategies and assists the government in developing effective regulatory policies.




(**a**) (**b**)

**Figure 9.** Impact of sensitivity coefficients on recycling prices: (**a**) four dual-channel recycling models; (**b**) *M*R* model processor recycling price ($1 < h < 3$).

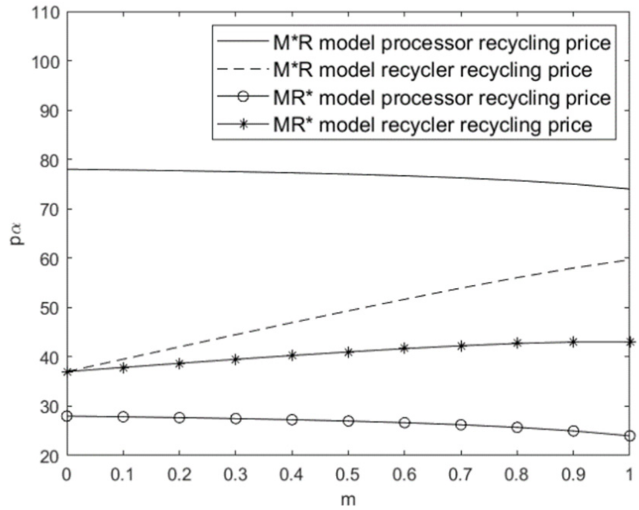



**Figure 10.** Impact of the competition factor on recycling prices.

From Figure 11, two observations are made:

- Total recycling volume in M*R vs. MR* models: The total recycling volume in the *M*R* model consistently surpasses that in the *MR** model. The introduction of government subsidies in the *MR** model leads to fluctuations in recycling prices and a notable decrease in the recycling volume through processors' direct channels, resulting in a lower total recycling volume compared to the *M*R* model. This observation completes the inferences made in Propositions 6 and 9. Therefore, to promote efficient waste battery recycling, government subsidies should favor recycling programs led by processors, as this approach intensifies recycling efforts and ensures a steady increase in the total recycling volume of the supply chain.
- Government subsidies vs. competition factors: Government subsidies and competition factors exert opposing effects on recycling activities. Theoretically, a combination of high government subsidies and a low competition coefficient is most advantageous for the overall supply chain. However, due to the dynamic nature of government subsidies and competition coefficients, government agencies and market entities should strive to find an equilibrium state that optimally satisfies all parties involved.

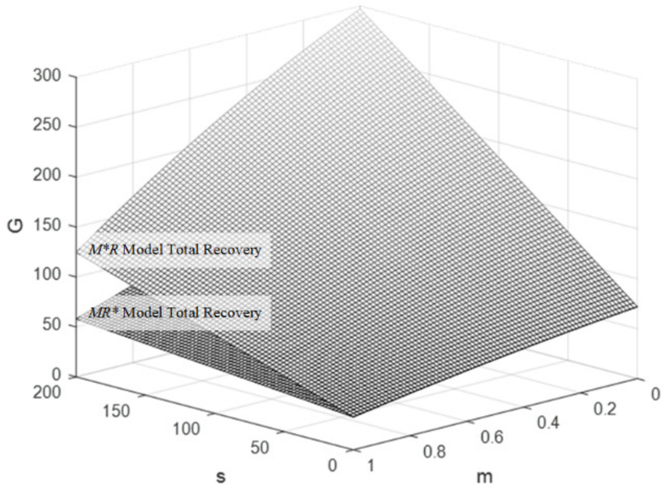



**Figure 11.** Relationship between unit government subsidy, competition coefficients, and recycling volumes.

Figure 12 illustrates the benefits of the same recycling entities under different recycling models. When $s = 0$, where the government provides no subsidies, entities acting as supply chain leaders significantly outperform those in follower roles within the same mode. This is because supply chain leaders typically possess more resources, a stronger market presence, and more efficient decision-making capabilities. This underscores the advantage of being a supply chain leader in terms of profitability. As government investment increases, other members of the supply chain begin to share in the government subsidies, indicating a more equitable distribution of benefits among all participants. This positively contributes to the overall development and efficiency of the supply chain.

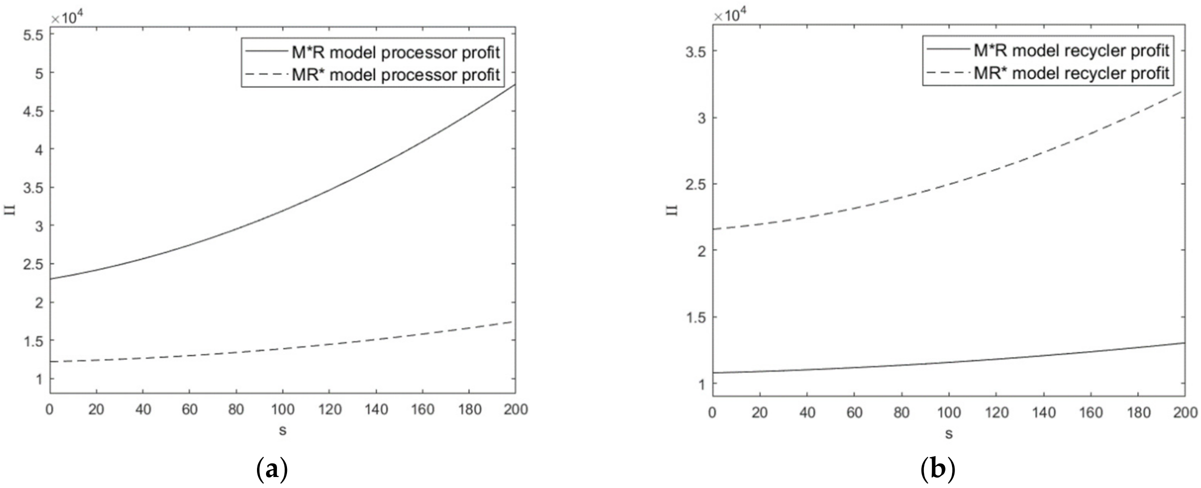



**Figure 12.** Impact of unit government subsidy on profits: (**a**) two processor profit models; (**b**) two recycler profit models.

In conclusion, analyzing the differences in benefits among enterprises under various recycling models and the impact of government subsidies on supply chain members enhances the understanding of the benefit distribution mechanism in closed-loop supply chains, the role of government subsidies, and the cooperative relationships among enterprises. This analysis provides robust support for achieving efficient management and sustainable development within supply chains.

Insights from Figures 13 and 14 reveal the following trends: Firstly, the total profit in the *M*R* model consistently exceeds that of the *MR** model. Secondly, the total profit increases with the rising sensitivity coefficient. A higher sensitivity coefficient implies that the recycling price becomes a crucial factor for consumers when deciding to join the recycling system. Enterprises can leverage government subsidies to adjust recycling prices, thereby encouraging consumer participation in the recycling process and boosting revenue in the recycling segment. Thirdly, the total profit tends to decrease as the competition coefficient increases. In a competitive market, enterprises often offer attractive recycling prices to draw consumer attention. Increased sensitivity to recycling price differences due to channel competition suggests a larger competition coefficient. However, intense market competition can lead to disorder, with potential outcomes like high operational costs, indiscriminate investment expansion, and severe resource wastage. These consequences are detrimental to the sustainable development of the supply chain.

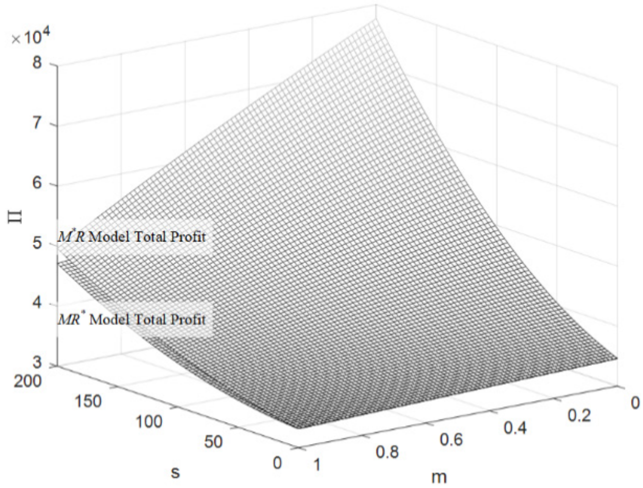



**Figure 13.** Relationship between unit government subsidy, competition coefficients, and total profits in the case of dual-channel recycling model.

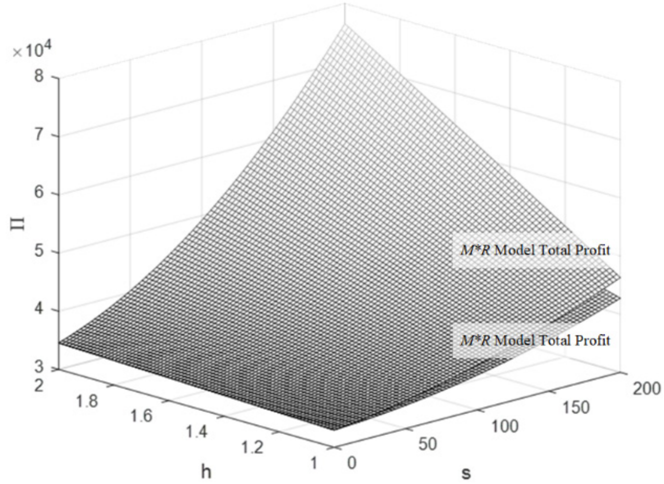



**Figure 14.** Relationship between unit government subsidy, sensitivity coefficients, and total profits in the case of dual-channel recycling model.

In conclusion, analyzing the changes in total profits across different models, as well as the effects of sensitivity and competition coefficients on total profits, enhances our understanding of the economic principles governing supply chain operations.

## 6. Conclusions and Discussion

This study, grounded in the EPR system and utilizing game theory, investigates power battery recycling models under the influence of government subsidies considering the power structure differences. The key conclusions drawn are as follows:

- Government subsidies positively influence the supply chain by increasing the recycling price and the volume of used batteries recycled. Particularly in the early stages of the waste battery recycling industry, government support is instrumental in facilitating the industry's transformation and upgrade. Furthermore, the role of the leader in the supply chain is crucial for orderly development, as government macro-regulation can be transmitted through the leader to other members. In the long term, a leader considering the overall interests of the supply chain can drive sustainable growth.
- In single-channel recycling scenarios, processor-led direct recycling models, backed by government subsidies, outperform recycler-led models in enhancing supply chain efficiency and stimulating consumer recycling. Recyclers, with relatively simple profit structures, should actively engage in the recycling system to diversify their revenue streams and increase market share. In dual-channel recycling models, government subsidies favoring processor-led recycling are more effective in augmenting the recycling volume collected and boosting the efficiency and profitability of supply chain members.
- The sensitivity coefficient and the competition factor have contrasting effects on recycling decisions. As the sensitivity coefficient increases, indicating greater consumer emphasis on recycling prices, enterprises can adjust their pricing strategies to attract consumer attention, potentially initiating market competition. However, heightened competition can diminish both the recycling volume and the overall efficiency of individual enterprises or the supply chain. Prolonged intense competition poses a threat to the stability and development of the supply chain, warranting caution against the adverse effects of market rivalry.

This study's findings lead to the following management suggestions:

1. While government subsidies can boost the power battery recycling industry, they should not be the sole driving force for the industry's innovation and growth. Businesses must avoid over-reliance on these subsidies, particularly in the industry's mature stages, and should actively seek collaborative mechanisms to strengthen ties with other enterprises in the supply chain. Additionally, the government must recognize the strategic importance of subsidy policies and create a targeted, forward-looking, and scientific strategy to enhance the power battery recycling sector.
2. Companies should be cautious of falling into a "price war" trap. To gain critical resources for establishing recycling networks, companies often focus too much on setting recycling prices, leading to frequent "price wars". In response, government agencies should adopt a "two-pronged approach" in collaboration with the market. This approach involves expediting the development of the primary network led by responsible producers, relying on downstream enterprises to establish a robust recycling network infrastructure. It is essential to fully leverage the primary market's role in guiding enterprises to foster cooperation and elevate the level of collaboration. Simultaneously, the government should implement detailed policies and control measures to strengthen industry regulations, enhance their binding nature, enforce them rigorously, and act as a deterrent to any irregularities within the industry. Furthermore, the government must continually fine-tune policy controls, reinforcing the binding and enforcement capabilities of industry norms to discourage disorderly competition and ensure the stable operation of the supply chain system.
3. Supply chain leaders often wield significant market influence and possess extensive social reach, enabling them to access more favorable resources easily. Consequently, it is imperative for supply chain leaders to actively foster a comprehensive, forward-looking, and overarching approach. They should fully harness their role in coordinating the overall structure, harmonizing the strengths of all stakeholders, and consolidating and integrating resources based on their unique capabilities. The ultimate goal is to maximize overall benefits and establish effective connections throughout the entire industrial chain, ensuring the stable functioning of the supply

chain system. It is crucial to establish effective linkages across the entire industry chain and strive to create an all-win scenario within the supply chain industry.

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