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Research on Pricing Decisions for Battery Swapping Mode Based on Different Power Structures in Staged Utilization of Power Batteries

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Abstract: To address challenges in power battery recycling, the integrated application of battery swapping and secondary utilisation technology enhances both economic efficiency and environmental performance, providing crucial support for the sustainable development of new energy vehicles. Accordingly, this paper constructs separate Stackelberg game models for supply chains under distinct power structures—one for battery manufacturers and another for battery swapping operators. It examines the cascading utilisation of power batteries under these varying power structures, making decisions regarding the technical level of cascading utilisation, pricing of cascaded products, and consumer battery leasing rates. The study delves into how parameters such as battery leasing duration, cascading sensitivity coefficient, and cascading R&D cost coefficient influence both parties' profits and technical advancement. Findings reveal: (1) Extending consumer battery leasing durations reduces leasing costs while simultaneously increasing profits for both swapping operators and manufacturers. (2) At elevated re-use sensitivity coefficients, profits remain relatively high even with substantial re-use R&D cost coefficients, though sensitivity coefficients exert greater influence on profitability. (3) Battery manufacturers leading secondary technology R&D enhances secondary technology standards and reduces secondary product prices, whereas battery swapping operators leading such efforts benefits supply chain system profitability. (4) A battery manufacturer-dominated supply chain proves more advantageous for consumers in both the battery swapping and secondary markets.

Keywords: Battery swapping model, secondary use technology, power battery recycling, power structure, pricing strategy.

1. Introduction

In recent years, the contradiction between human development and resource utilisation has become increasingly prominent [1]. To effectively alleviate resource scarcity and achieve sustainable development goals, governments worldwide have proposed low-carbon development strategies. The United States has formulated a green development strategy aiming for 100% clean energy electricity generation by 2035.The Chinese government has pledged to the world to achieve carbon peak by 2030 and carbon neutrality by 2060 [2]. Against this backdrop, new energy vehicles powered by power batteries have become the future direction for the automotive industry [3]. Since 2015, China has ranked first globally in both electric vehicle production and sales for seven consecutive years.In 2023, China's electric vehicle sales exceeded 9.4 million units, with market share soaring to 31.6% [4]. However, alongside this growth, a substantial volume of power batteries will enter the end-of-life phase. China's automotive power battery retirement volume is projected to reach 800,000 tonnes by 2025 [5]. Therefore, the effective management of these retired power batteries is an urgent priority. There are two primary approaches to recycling retired power batteries: (1) Secondary use, which maximises the residual energy value of spent power batteries. If retired batteries are found to be in poor overall condition but retain some capacity, they can be repurposed for secondary applications. Examples include deploying retired batteries in distributed energy storage systems or microgrids. (2) Regenerative utilisation, maximising the raw material value of retired power batteries. Batteries unsuitable for secondary use can be repurposed in new battery production, yielding remanufactured batteries. Implementing secondary use before regenerative utilisation effectively enhances resource efficiency [6, 21].

Moreover, inadequate charging infrastructure and prolonged energy replenishment times persistently trouble consumers. As subsidies for the new energy vehicle sector phase out, rising vehicle prices further deter many buyers. Confronted with these challenges, numerous enterprises are shifting focus towards battery swapping models for new energy vehicles [7]. The application of the battery swapping model not only alleviates consumer range anxiety and shortens energy replenishment times but also extends the service life of power batteries [8] and facilitates the implementation of power battery cascading utilisation, thereby reducing the full lifecycle costs of batteries. To promote the battery swapping model, numerous policies have been introduced at the national level. The 2021 publication of Key Points for Automotive Standardisation Work in 2022 further advanced standardisation and unification of battery swapping-related products and technologies. The 2023 Measures for Restoring and Expanding Consumption further propelled the development of the battery swapping market. Consequently, integrating battery swapping with secondary utilisation not only extends battery lifespan and enhances efficiency but also reduces costs and environmental impact, providing crucial support for the sustainable development of electric vehicles and energy systems.

In summary, a substantial volume of power batteries will enter the end-of-life phase, making the effective management of these retired batteries an urgent issue. With the deepening advancement of the "dual carbon" goals, the battery swapping model is being vigorously promoted. Consequently, under the context of this model, researching the pricing issues associated with the secondary utilisation of power batteries in recycling has become a pressing topic requiring immediate exploration. However, literature examining the secondary utilisation process of power battery recycling within the battery swapping model remains scarce. Compared to existing studies, this paper focuses on depicting the secondary utilisation process of power battery recycling under the battery swapping model. It conducts research and discussion on the secondary utilisation of power batteries under different power structures, making decisions on the technical level of secondary utilisation, pricing of secondary products, and consumer battery leasing pricing. It delves into the impact of battery leasing duration, secondary utilisation sensitivity coefficient, and the technical R&D cost coefficient for secondary utilisation. It derives the optimal scenario for the long-term development of the secondary utilisation market under the battery swapping model and provides theoretical recommendations for management decisions by battery manufacturers and swapping operators. To this end, this paper primarily addresses the following questions: (1) Which model achieves the highest level of secondary utilisation technology? (2) Which model yields the lowest tiered product prices and battery leasing rates? (3) How do the tiered technology investment cost coefficient and consumer sensitivity to tiered technology levels influence tiered technology standards and supply chain pricing? (4) Among the two tiered utilisation models for battery manufacturers and battery swapping operators respectively, which model best serves consumer interests?

Relevant literature encompasses both battery swapping models and power battery recycling approaches.

Research on battery swapping models has been conducted by numerous scholars from the perspectives of swapping station siting, operations, and new energy vehicle pricing. Yang Lei et al. [9] investigated the siting of charging and swapping facilities for electric logistics vehicles under both charging and swapping modes, finding that these modes exert differing impacts on delivery costs. Yang Yacai et al. [10] proposed a method for locating and sizing centralised charging stations under multiple charging modes (charging, swapping, and mobile charging), finding that both the number of vehicles requiring charging and variations in charging power significantly affect centralised station costs. Rao et al. [11] dentified substantial benefits for the power grid and generating units from Optimised Charging Mode (OCM).Regarding pricing decisions in new energy vehicle supply chains, Yuan et al. [12] examined the impact of battery leasing and battery swapping services on vehicle supply chain operational models, deriving and comparing optimal decisions for vehicle manufacturers and battery asset companies providing these services. Lu Zhiping et al. [8] analysed differences in supply chain structures under battery swapping models, exploring how average consumer battery leasing duration and R&D cost-sharing ratios influence mutual profits and battery swapping technology development levels.Du Jianguo et al. [7] identified the equilibrium battery ratio in the swapping market and the residual value of retired batteries for secondary use as critical determinants of corporate profits and decision-making, with more pronounced effects on swapping operators. Xu Suxiu et al. [13] found that collaboration between swappable vehicle manufacturers and swapping station investors reduces profits for competitors (charging vehicle manufacturers).

Regarding power battery recycling, researchers primarily examine battery recycling model selection and the impact of secondary utilisation on closed-loop supply chains. Gu et al. [14] argue that battery recycling and reuse reduce raw material consumption, thereby mitigating environmental impacts. Zhang et al. [15] found that manufacturer-retailer collaboration achieves the highest practical recycling rates and total welfare; while intensifying incentive schemes boosts collection rates, total welfare may still decline. Tang et al. [16] proposed incentive-penalty mechanisms and policies, comparing three single-channel recycling models with three competitive dual-channel models. They identified significant advantages in models where manufacturers and retailers compete over recycling channels. Zhang Chuan et al. [17, 18] examined optimal decision-making and coordination among closed-loop supply chain participants for power batteries under government subsidies, alongside recycling model selection under carbon quota trading policies. They found government subsidies reduce retail prices, increase recycling rates, and boost profits for all participants. When recycling price sensitivity coefficients and recycling competition coefficients fall within specific thresholds, the optimal recycling model for manufacturers involves joint recycling by manufacturers, retailers, and third-party recyclers. Li et al. [19] found that battery manufacturers offering battery swapping services achieve greater profit growth, with the number of spare batteries and secondary utilisation revenue being key factors influencing swapping profitability. Jiao Jianling et al. [20] identified that the optimal recycling entity varies across different thresholds for recycled material revenue, and supply chain profit coordination can achieve a long-term consistent optimal recycling model. Yuan, K.F. et al. [21] developed a pricing decision model for power battery supply chains incorporating recycling under the BaaS model. They found that when lease durations exceed a certain threshold, battery asset companies prefer selling more end-of-life batteries to manufacturers rather than secondary consumers.

Research on power battery supply chain power structures predominantly adopts a battery swapping perspective. Du Jianguo et al. [7] developed Stackelberg game models for supply chains with distinct power structures between vehicle manufacturers and swapping operators, finding that collaborative R&D and secondary utilisation both enhance swapping station service efficiency. Yuan et al. [22] compared scenarios dominated by intelligent vehicle manufacturers versus software providers. They found that in the market's early stages, manufacturer-dominated supply chains favour market expansion and higher supply chain profits, while software provider dominance enhances vehicle intelligence and reduces vehicle prices. Li et al. [19], considering cascading utilisation, analysed comparative power structures and found that supply chain dominance determines BSM enterprises' profit levels, with battery swapping models offering greater profit growth potential for battery manufacturers. Fan et al. [23] examined battery outsourcing decisions and product selection strategies for electric vehicle manufacturers within a two-stage supply chain comprising battery suppliers and manufacturers with varying power structures. They determined that the electric vehicle manufacturer's product selection strategy hinges on two thresholds: battery production costs, and the manufacturing and assembly costs of electric vehicles, alongside government subsidies and range anxiety.

In summary, research on battery swapping models predominantly addresses station siting, operations, and new energy vehicle pricing. Studies on power battery recycling primarily focus on model selection and the impact of secondary utilisation on closed-loop supply chains, with limited consideration of how secondary utilisation technology levels influence outcomes. Concerning power structures, most scholars approach the subject from the perspective of battery swapping, with few considering how different power structures influence the pricing of secondary-use products and the level of secondary-use technology within the context of battery swapping. Given that secondary-use and dismantling within the closed-loop supply chain for retired power batteries constitute crucial segments of its reverse supply chain, and in light of this research gap, this paper constructs Stackelberg game models for supply chains under distinct power structures—one for battery manufacturers and another for battery swapping operators. It examines the cascading utilisation of power batteries under these structures, making decisions regarding cascading technology levels, cascading product pricing, and consumer battery leasing rates. The study delves into how parameters such as battery leasing duration, cascading sensitivity coefficients, and cascading R&D cost coefficients influence both parties' profits and technological advancement.

2. Problem Description and Assumptions

2.1. Problem Description

This study examines a closed-loop supply chain comprising a power battery manufacturer, a battery swapping operator, battery swapping consumers, and secondary utilisation consumers. In the forward chain, the battery manufacturer wholesales batteries to the swapping operator, who then leases them to swapping consumers. In the reverse chain, the swapping operator recovers retired power batteries from swapping consumers, after which the dominant player in secondary utilisation technology employs them for secondary applications, selling the resulting secondary utilisation products. In light of this, two operational models are established, as illustrated in Figure 1.

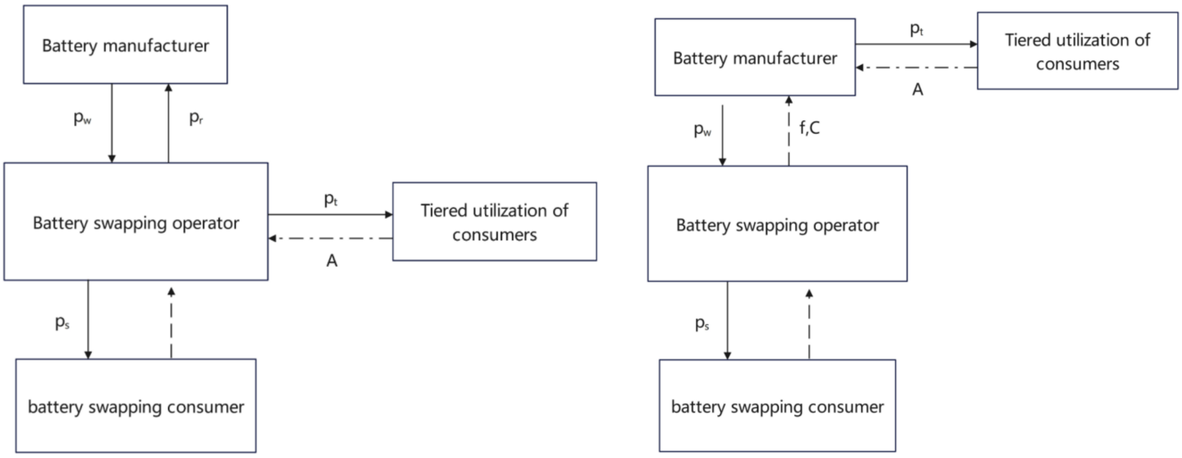


Figure 1. Closed-loop supply chain with two modes of cascading utilization

(1) Mode 1

Battery swapping operators lead the research and development of cascading technology. Battery manufacturers wholesale power batteries to swapping operators at a price of p_w, and then lease the batteries to consumers at a price of p_s. Therefore, the ownership of the batteries belongs to the swapping operators. After the power batteries meet the retirement conditions, consumers return them all to the swapping operators. The swapping operators carry out cascading utilization, sell them at a price of p_t, and recycle all retired cascading batteries at a price of A. Finally, the battery manufacturers recycle them at a price of p_r. The battery manufacturers can produce power batteries from recycled materials extracted from scrapped power batteries.

(1) Mode 2

Battery manufacturers lead the research and development of cascading technology. Battery manufacturers wholesale power batteries to battery swapping operators at a price of p_w, who rent the batteries to consumers at a price of p_s. The ownership of the batteries belongs to the battery swapping operators. After the power batteries meet the retirement conditions, consumers return them all to the battery swapping operators. Then, the battery manufacturers recover the old batteries from the battery swapping operators at a cost of f and pay for the battery data information cost of C. Finally, the retired cascading batteries are fully recovered at a price of A. Recycled materials can be extracted from scrapped power batteries to produce power batteries.

2.2. Basic Assumptions

Table 1. Parameter Assumptions

parameter	Parameter Description
q	New energy vehicle demand function $q = a - b(p + p_s)$
a	Market size of battery swapping vehicles
b	Consumer price sensitivity coefficient for battery-swap vehicles
p	Body price of battery-swap vehicles. Given the proportional relationship between body price and battery price, the body price can be expressed in terms of battery price $p = \theta p_w$
q_t	Secondary market demand function $q_t = k - lp_t + \mu h$
k	Secondary product market size
l	Consumer price sensitivity coefficient for tiered products
μ	Consumer sensitivity coefficient to tiered technology, reflecting environmental awareness
λ	Ratio of battery quantity required to demand in the battery swapping market
t	Battery leasing duration
A	Recycling cost of end-of-life batteries
p_r	Battery manufacturer's buyback price for low-capacity batteries
C_m	Manufacturer's unit cost of producing power batteries using raw materials
C_r	Manufacturer's unit cost of producing power batteries using recycled materials
C_s	Battery swapping service provider's operational costs
g	Research and development cost coefficient for secondary use technology
Decision variable	
p_w	Wholesale price of power batteries for battery swapping operators
p_s	Battery rental price for battery swapping consumers
p_t	Unit resale price for end-of-life batteries
$\boldsymbol{h}$	Technical proficiency of secondary battery technology developers

3. Model Establishment and Solution

3.1. Battery Swapping Operators Leading the Recovery and Secondary Utilisation

Battery swapping operator profit function

$$\pi_s^S(p_s, p_t, h) = [(p_s - C_s)t - p_w\lambda]q + (p_t - A)q_t + p_r\lambda q - \frac{1}{2}g_1h^2$$

Battery manufacturer profit function

$$\pi_b^S(p_w) = (p_w - C_m + \Delta - p_r)\lambda q$$

Under Model 1, the battery swapping operator first determines the swapping unit price, the unit price for end-of-life battery secondary utilisation, and the level of secondary technology R&D based on the battery manufacturer's response function. Subsequently, the battery manufacturer responds by setting the wholesale battery price p_w. The profit functions for the battery swapping operator and battery manufacturer are respectively:

$$\pi_s^S = \frac{\theta b[\theta t(C_r + p_r) + \lambda C_r + C_s t]^2 - 2at\lambda C_r\theta - 2at^2\theta[(C_r + p_r)\theta - C_s]}{(8\theta t + 4\lambda)} + \frac{4tAg_1l\theta(2k - Al) - 4k^2g_1t\theta - 4t\lambda g_1(k - Al)^2}{(8\theta t + 4\lambda)(\mu^2 - 2g_1l)} + \frac{a^2t^2\theta}{(8\theta t + 4\lambda)b}$$

$$\pi_b^S = \frac{\lambda\theta\left(\left(((-C_r - p_r)\theta - C_s)t - \lambda C_r\right)b + at\right)^2}{4b(2t\theta + \lambda)^2}$$

$$p_w^S = \frac{\{[(3C_r + 3p_r)\theta - C_s]t + \lambda(C_r + 2p_r)\}b + at}{2b(\lambda + 2t\theta)}$$

$$p_t = \frac{A(g_1l - \mu^2) + g_1k}{2g_1l - \mu^2}$$

$$h = \frac{\mu(k - Al)}{2g_1l - \mu^2}$$

$$p_s = \frac{-bt(C_r + p_r)\theta^2 + [(C_st - \lambda p_r)b + at]\theta + a\lambda}{b(\lambda + 2t\theta)}$$

Proof: Solve inversely; first take the partial derivative of the battery manufacturer's profit with respect to p_w.

$$p_w = \frac{\theta bC_r + \theta bp_r - bp_s + a}{2b\theta}$$

Substituting p_w into the profit function of the battery swapping operator, the Hessian matrix with respect to p_t, h, and p_s is:

$$H_s^1 = \begin{pmatrix} \frac{\partial^2 \pi_s^S}{\partial {p_t}^2} & \frac{\partial^2 \pi_s^S}{\partial p_t \, \partial h} & \frac{\partial^2 \pi_s^S}{\partial p_t \, \partial p_s} \\ \frac{\partial^2 \pi_s^S}{\partial h \, \partial p_t} & \frac{\partial^2 \pi_s^S}{\partial h^2} & \frac{\partial^2 \pi_s^S}{\partial h \, \partial p_s} \\ \frac{\partial^2 \pi_s^S}{\partial p_s \, \partial p_t} & \frac{\partial^2 \pi_s^S}{\partial p_s \, \partial h} & \frac{\partial^2 \pi_s^S}{\partial {p_s}^2} \end{pmatrix} = \begin{pmatrix} -2l & \mu & 0 \\ \mu & -g_1 & 0 \\ 0 & 0 & -b(t + \frac{\lambda}{2\theta}) \end{pmatrix}$$

Reference: Lu Zhiping et al. [8] Additionally, considering practical circumstances where the R&D cost coefficient for secondary utilisation technology is unlikely to be negligible, the R&D cost coefficient satisfies: $2g_1 l - \mu^2 > 0$.

At this point, the first-order sequential principal subformula$-2l < 0$, the second-order sequential principal subformula $2g_1 l - \mu^2 > 0$, the third-order sequential principal subformula $|H_s^1| = -b(t + \frac{\lambda}{2\theta})(2g_1 l - \mu^2) < 0$, This Hessian matrix is negative definite.

It can be determinedElectricity exchange operatorProfit function π_s^S is a concave function with respect to p_t and h, possessing a maximum value. Solving simultaneously $\frac{\partial \pi_S^1}{\partial p_t} = 0$, $\frac{\partial \pi_S^1}{\partial h} = 0$, $\frac{\partial \pi_S^1}{\partial p_S} = 0$ yields

$$p_t = \frac{A(g_1 l - \mu^2) + g_1 k}{2g_1 l - \mu^2},\ h = \frac{\mu(k - Al)}{2g_1 l - \mu^2},$$

$$p_s = \frac{-bt(C_r + p_r)\theta^2 + [(C_s t - \lambda p_r)b + at]\theta + a\lambda}{b(\lambda + 2t\theta)}$$

Substitute into p_w,

obtained: $p_w^1 = \frac{\{[(3C_r + 3p_r)\theta - C_s]t + \lambda(C_r + 2p_r)\}b + at}{2b(\lambda + 2t\theta)}$

Substituting into the demand function $q = a - b(p + p_s)$, $q_t = k - lp_t + \mu h$

obtained:

$$\pi_s^1 = \frac{\theta b[\theta t(C_r + p_r) + \lambda C_r + C_s t]^2 - 2at\lambda C_r \theta - 2at^2\theta[(C_r + p_r)\theta - C_s]}{(8\theta t + 4\lambda)} + \frac{4tAg_1 l\theta(2k - Al) - 4k^2 g_1 t\theta - 4t\lambda g_1 (k - Al)^2}{(8\theta t + 4\lambda)(\mu^2 - 2g_1 l)} + \frac{a^2 t^2 \theta}{(8\theta t + 4\lambda)b}$$

$$\pi_b^1 = \frac{\lambda\theta\left(\left(\left((-C_r - p_r)\theta - C_s\right)t - \lambda C_r\right)b + at\right)^2}{4b(2t\theta + \lambda)^2}$$

$$p_w^1 = \frac{\{[(3C_r + 3p_r)\theta - C_s]t + \lambda(C_r + 2p_r)\}b + at}{2b(\lambda + 2t\theta)}$$

$$p_t = \frac{A(g_1 l - \mu^2) + g_1 k}{2g_1 l - \mu^2}$$

$$h_1 = \frac{\mu(k - Al)}{2g_1 l - \mu^2}$$

$$p_s = \frac{-bt(C_r + p_r)\theta^2 + [(C_s t - \lambda p_r)b + at]\theta + a\lambda}{b(\lambda + 2t\theta)}$$

Simultaneously obtaining the constraints $k > Al, 2g_1 l - \mu^2 > 0$

3.2. Battery Manufacturers Leading Recycling and Secondary Utilisation

Battery manufacturer profit function

$$\pi_b^2(p_w, p_t, h) = (p_w - C_m + \varDelta - f - C)\lambda q + (P_t - A)q_t - \frac{1}{2} g_2 h^2$$

Exchange platform profit function

$$\pi_s^2(p_s) = [(p_s - C_s)t - \lambda p_w]q + (f + C)\lambda q$$

Derive the optimal solution

$$h = \frac{\mu(k - lA)}{2g_2 l - \mu^2}$$

$$p_t = \frac{A(g_2 l - \mu^2) + g_2 k}{2g_2 l - \mu^2}$$

$$p_w = \frac{b(\theta + 1)\left((2c + 2f + C_r)\lambda - C_s t\right) + at}{2\lambda b(\theta + 1)}$$

$$p_s^2 = \frac{(\theta + 1)(\lambda C_r + C_s t)b + 3at}{4bt(\theta + 1)}$$

$$\pi_b^2 = \frac{b(\theta + 1)(\lambda C_r + C_s t)^2}{8t} + \frac{g_2 lA(Al - 2k) + g_2 k^2}{2(\mu^2 - 2g_2 l)} + \frac{a^2 t^2}{8bt(\theta + 1)} - \frac{aC_s t}{4} + a\lambda C_r$$

$$\pi_s^2 = \frac{(at - (\theta + 1)(C_r\lambda + C_s t)b)^2}{16bt(\theta + 1)}$$

Proof: Solving in reverse, first take the partial derivative of the battery swapper's profit with respect to p_s, yielding

$$p_s = \frac{-\left((C + f - p_w)\lambda - C_s t\right)(\theta + 1)b + at}{2bt(\theta + 1)}$$

Then $$H_b^B = \begin{pmatrix} \frac{\partial^2 \pi_b^B}{\partial {p_w}^2} & \frac{\partial^2 \pi_b^B}{\partial p_w \, \partial p_t} & \frac{\partial^2 \pi_b^B}{\partial p_w \, \partial h} \\ \frac{\partial^2 \pi_b^B}{\partial p_t \, \partial p_w} & \frac{\partial^2 \pi_b^B}{\partial {p_t}^2} & \frac{\partial^2 \pi_b^B}{\partial p_t \, \partial h} \\ \frac{\partial^2 \pi_b^B}{\partial h \, \partial p_w} & \frac{\partial^2 \pi_b^B}{\partial h \, \partial p_t} & \frac{\partial^2 \pi_b^B}{\partial h^2} \end{pmatrix} = \begin{pmatrix} -\frac{b\lambda^2(\theta+1)}{t} & 0 & 0 \\ 0 & -2l & \mu \\ 0 & \mu & -g_2 \end{pmatrix}$$

Tertiary determinant $-\frac{b\lambda^2(\theta+1)}{t}(2g_2 l - \mu^2) < 0$, Second-order determinant $2l\frac{b\lambda^2(\theta+1)}{t} > 0$

First-order determinant $-\frac{b\lambda^2(\theta+1)}{t} < 0$, yields:

$$h = \frac{\mu(k - lA)}{2g_2 l - \mu^2}$$

$$p_t = \frac{A(g_2 l - \mu^2) + g_2 k}{2g_2 l - \mu^2}$$

$$p_w = \frac{b(\theta + 1)\left((2c + 2f + C_r)\lambda - C_s t\right) + at}{2\lambda b(\theta + 1)}$$

Substituting yields $p_s^B = \frac{(\theta+1)(\lambda C_r + C_s t)b + 3at}{4bt(\theta+1)}$

$$\pi_b^B = \frac{b(\theta+1)(\lambda C_r + C_s t)^2}{8t} + \frac{g_2 lA(Al - 2k) + g_2 k^2}{2(\mu^2 - 2g_2 l)} + \frac{a^2 t^2}{8bt(\theta+1)} - \frac{aC_s t}{4} + a\lambda C_r$$

$$\pi_s^B = \frac{(at - (\theta+1)(C_r\lambda + C_s t)b)^2}{16bt(\theta+1)}$$

Constraints are simultaneously obtained $k > Al, 2g_2 l - \mu^2 > 0$

4. Analysis of Key Parameter Influences

4.1. Impact of *t* on Battery Rental Price and Wholesale Battery Price

Theorem 1 $\frac{\partial p_s^1}{\partial t} < 0,\ \frac{\partial p_w^1}{\partial t} > 0;\ \frac{\partial p_s^2}{\partial t} < 0,\ \frac{\partial p_w^2}{\partial t} > 0$

As the battery rental period increases, the battery rental price charged by the battery swapping operator decreases progressively, while the battery wholesale price charged by the battery manufacturer increases accordingly.

Theorem 1 indicates that when the rental revenue payback period is sufficiently long, battery swapping operators will attract more consumers to choose swapping services by lowering battery rental prices. As the swapping market expands, battery manufacturers—a key stakeholder in this market—will correspondingly raise the wholesale price of power batteries to benefit from the growth. Thus, longer consumer rental periods are conducive to the long-term development of the battery swapping market.

4.2. Impact of the Secondary Technology R&D Cost Coefficient *g* on Decision Variables and Profitability

Theorem 2 $\frac{\partial p_t^1}{\partial g_1} = \frac{\partial p_t^2}{\partial g_2} < 0;\ \frac{\partial h^1}{\partial g_1} = \frac{\partial h^2}{\partial g_2} < 0;\ \frac{\partial \pi_S^1}{\partial g_1} = \frac{\partial \pi_B^2}{\partial g_2} < 0$

$$\frac{\partial p_s^1}{\partial g_1} = \frac{\partial p_s^2}{\partial g_2} = 0, \frac{\partial p_w^1}{\partial g_1} = \frac{\partial p_w^2}{\partial g_2} = 0, \frac{\partial \pi_B^1}{\partial g_1} = \frac{\partial \pi_s^2}{\partial g_2} = 0$$

As the secondary technology R&D cost coefficient increases, the level of secondary technology and the price of secondary products decrease, while the battery rental price charged by battery swapping operators, the wholesale battery price set by battery manufacturers, and the profit of the party not undertaking secondary technology R&D remain unchanged.

Theorem 2 indicates: During the market's initial phase, when consumer sensitivity to secondary utilisation levels is low, the costs of dismantling, sorting, and reconfiguring retired batteries into secondary products remain high. Constrained by limited R&D funding, the dominant player in secondary technology will reduce the level of R&D investment. Simultaneously, to stimulate consumer demand for secondary products, they will rationally lower the prices of these products to maximise their own profits. However, the profits of non-leading players in secondary-use technology remain unchanged. Furthermore, consumer demand for secondary-use products does not affect demand for the battery swapping market. Consequently, consumer battery rental prices and wholesale prices for power batteries are unaffected by the secondary-use technology R&D cost coefficient.

4.3. Impact of Secondary Product Recovery Price A on Decision Variables and Profit

Theorem 3 $\frac{\partial p_t^1}{\partial A} = \frac{\partial p_t^2}{\partial A} > 0;\ \frac{\partial h_1}{\partial A} = \frac{\partial h_2}{\partial A} < 0;\ \frac{\partial \pi_S^1}{\partial A} = \frac{\partial \pi_B^2}{\partial A} < 0$

$$\frac{\partial p_s^1}{\partial A} = \frac{\partial p_s^2}{\partial A} = 0, \frac{\partial p_w^1}{\partial A} = \frac{\partial p_w^2}{\partial A} = 0, \frac{\partial \pi_B^{1*}}{\partial A} = \frac{\partial \pi_s^2}{\partial A} = 0$$

The higher the secondary product recovery price, the higher the secondary product sales price, the lower the secondary technology R&D level, and the lower the profit of the secondary technology R&D party. Battery rental prices, battery wholesale prices, and the profit of the party not conducting secondary technology R&D remain unchanged.

Theorem 3 indicates that: Beyond selling secondary-use products, the R&D provider is also responsible for their recovery. As recovery prices increase, the provider will raise product prices to maximise profits. Concurrently, elevated recovery costs prompt battery swapping operators to reduce R&D investment, thereby diminishing technological advancement. Consequently, the R&D provider's profits are impacted by recovery costs and will also decrease.

4.4. Impact of Consumer Sensitivity Coefficient μ to Tiered Utilisation Levels on Decision Variables and Profit

Theorem 4 $\frac{\partial p_t^1}{\partial \mu} = \frac{\partial p_t^2}{\partial \mu} > 0;\ \frac{\partial h^1}{\partial \mu} = \frac{\partial h^2}{\partial \mu} > 0;\ \frac{\partial \pi_S^1}{\partial \mu} = \frac{\partial \pi_B^2}{\partial \mu} > 0;$

$$\frac{\partial {p_w}^1}{\partial \mu} = \frac{\partial {p_w}^2}{\partial \mu} = 0; \frac{\partial {p_s}^1}{\partial \mu} = \frac{\partial {p_s}^2}{\partial \mu} = 0, \frac{\partial \pi_B^1}{\partial \mu} = \frac{\partial \pi_s^2}{\partial \mu} = 0$$

The higher the consumer sensitivity coefficient μ towards secondary utilisation levels, the greater the improvement in both battery swapping operators' and manufacturers' secondary technology capabilities, alongside increased secondary product prices under both operational models. Meanwhile, battery leasing prices for swapping operators and wholesale battery prices for manufacturers remain unchanged. The profit of the party undertaking secondary technology R&D also increases, while the profit of the party not undertaking such R&D remains unchanged.

Theorem 4 indicates that higher consumer sensitivity to secondary utilisation levels signifies greater environmental awareness, meaning consumers are more inclined to choose secondary products. Consequently, when consumer sensitivity to reprocessing levels is high, the reprocessing technology developer will enhance both the technical standard and the price of reprocessed products to maximise profits. Conversely, when consumer sensitivity is low, the market demand for reprocessed products diminishes and R&D funding becomes constrained. To avoid losses, the reprocessing technology developer will rationally reduce both the technical standard and the price of reprocessed products.

5. Decision Variable Comparison

Theorem 5: $p_t^1 < p_t^2,\ h_1 < h_2,\ p_w^1 < p_w^2$

Table 2. Decision Variable Comparison comparing

Constraints	$p_s^1 - p_s^2$	$p_t^1 - p_t^2$	$p_w^1 - p_w^2$	$h_1 - h_2$
0<a <6	-	-	-	-
a >6	+	-	-	-

Proof: $p_s^1 - p_s^2 = \frac{-bt(C_r+p_r)\theta^2+\left((C_st-p_r\lambda)b+at\right)\theta+a\lambda}{(2\theta t+\lambda)b} - \frac{(\theta+1)(\lambda C_r+C_st)b+3at}{4bt(\theta+1)}$

$$4(2\theta t+\lambda)bt(\theta+1) > 0$$

$$(4\theta^2t^2+4\theta\lambda t-2\theta t^2+\lambda t)a - 4\theta^3bC_rt^2 - 4\theta^3bp_rt^2 - 2\theta^2bC_r\lambda t - 4\theta^2bC_rt^2 + 2\theta^2bC_st^2 - 4\theta^2b\lambda p_rt - 4\theta^2bp_rt^2 - \theta bC_r\lambda^2 - 2\theta bC_r\lambda t - \theta bC_s\lambda t + 2\theta bC_st^2 - 4\theta b\lambda p_rt - bC_r\lambda^2 - bC_s\lambda t$$

$$a_0 = \frac{b\begin{pmatrix}4\theta^3C_rt^2+4\theta^3p_rt^2+2\theta C_r\lambda t+4\theta^2C_rt^2-2\theta^2C_st^2+4\theta^2\lambda p_rt+4\theta^2p_rt^2\\ +\theta C_r\lambda^2+2\theta C_r\lambda t+\theta C_s\lambda t-2\theta C_st^2+4\theta\lambda p_rt+C_r\lambda^2+C_s\lambda t\end{pmatrix}}{t(4\theta^2t+4\theta\lambda-2\theta t+\lambda)}$$

Theorem 5 indicates that battery swapping operators leading secondary battery technology R&D is more conducive to reducing secondary product prices and wholesale power battery prices, but has the opposite effect on secondary technology R&D levels and battery leasing prices. On the one hand, compared to battery manufacturers taking the lead, secondary product prices are lower when swapping operators dominate. This occurs because battery swapping operators, whilst facilitating swaps, generate new revenue streams through battery recycling and secondary utilisation of retired batteries. However, given the secondary market's relatively smaller scale compared to the swapping market, operators lower secondary product prices to stimulate demand growth. Conversely, once the swapping market reaches a certain scale, supply chain leaders exercising first-mover decision rights adopt high-price strategies. In response, swapping operators raise battery leasing prices to secure greater profits. Similarly, when battery manufacturers dominate secondary technology R&D, they raise wholesale prices for power batteries to secure greater profits. However, compared to swapping operators, battery manufacturers achieve higher secondary technology levels with the same investment costs due to their accumulated expertise from years of battery production. Yet, as profit comparisons between these scenarios are relatively complex, analysis is conducted through illustrative examples.

6. Case Study Analysis

To investigate the impact of parameters such as downgrading sensitivity coefficients and lease duration on pricing and profitability, and to validate the accuracy of preceding conclusions, the following system parameters were established. This approach satisfies model assumptions and constraints while incorporating research findings from the battery manufacturing sector and several battery swapping enterprises. Data from iResearch Consulting's "China New Energy Vehicle Battery Swapping Market Research" served as the foundation, supplemented by references [24], [21], and [7].

Table 3. Parameter Assumptions

Parameter	a	b	k	l	μ	λ	t	A	p_r	$c+f$	C_m	C_r	C_s	g_1	g_2	θ
Value	45	0.5	30	0.5	0.3	1.2	12	0.8	1.5	2.3	6	2	0.1	120	100	1.5

6.1. Influence of Parameters on Decision Variables

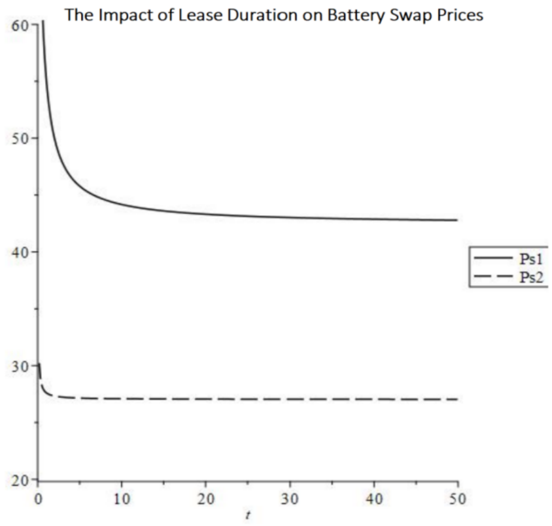


Figure 2. Impact of Rental Period t on Battery Rental Price

As illustrated in Figure 2, battery rental prices decrease with increasing rental duration across all power structures. As consumers opt for longer rental periods, the payback period for battery rental revenue extends, enabling battery swapping operators to sustain profits. Consequently, operators reduce rental prices to attract more new energy vehicle consumers to adopt battery swapping. Battery rental prices are higher when battery swapping operators lead the development of secondary battery technology. This occurs because, in addition to providing rental services, operators must bear the pressure of R&D costs for secondary battery technology. Given the high R&D expenses, operators prioritise profit maximisation by raising rental prices and channelling funds into technological innovation.

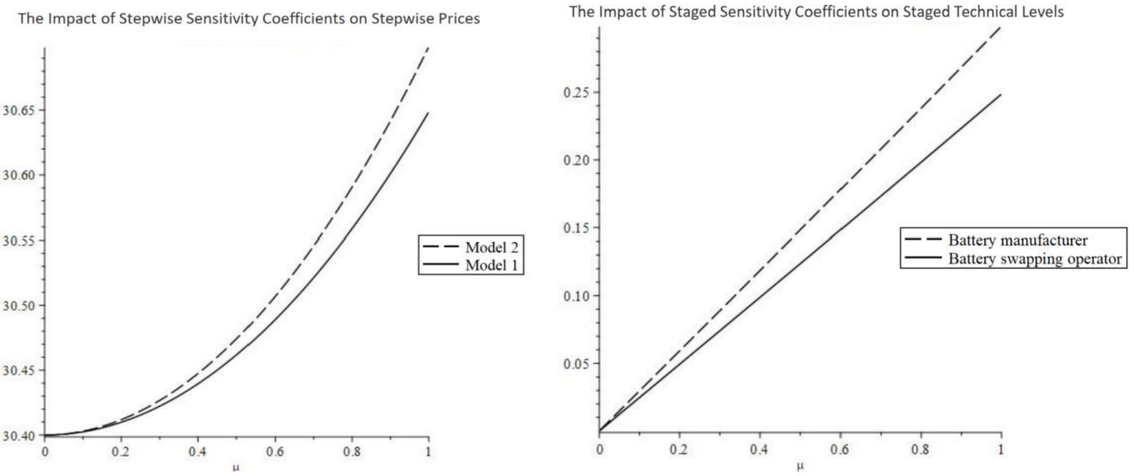


Figure 3. Impact of Tier Sensitivity Coefficient on Tier Utilisation Decisions

As illustrated in Figure 3, when consumers exhibit greater sensitivity to secondary utilisation technology, their recognition and expectations for such technology are elevated. Therefore, regardless of whether R&D is led by battery manufacturers or battery swapping operators, both parties should strive to enhance secondary technology standards and adopt premium pricing strategies. However, secondary product pricing and technological standards are higher when battery manufacturers lead R&D compared to when swapping operators take the lead. This disparity stems from differing levels of investment and innovation drive between swapping operators and battery manufacturers in R&D. Battery manufacturers, being directly involved in battery R&D and production, possess deeper insights into and greater control over battery performance and technological innovation. Consequently, they can more effectively drive innovation and advancement in secondary-use technology. Battery swapping operators, however, invest less in R&D and lack the same depth of involvement, resulting in lower secondary-use technology standards. Nevertheless, in market environments where consumers demonstrate significant sensitivity to secondary-use technology performance, operator-led scenarios are more conducive to reducing purchase costs for secondary-use consumers.

6.2. Impact of Parameters on Profitability

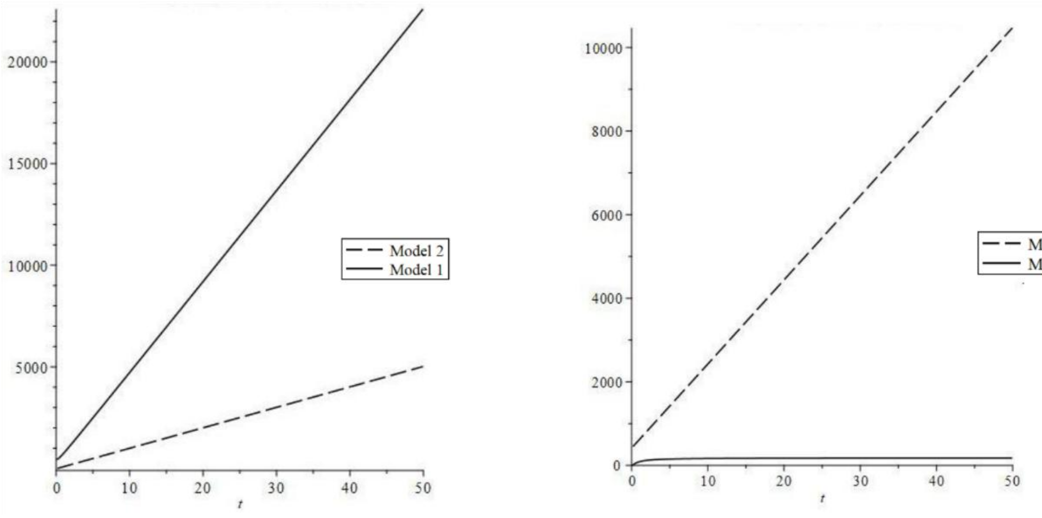


Figure 4. Impact of Rental Duration on Profitability

Figure 4 demonstrates that extended leasing periods positively impact profits for both battery swapping operators and manufacturers, validating Theorem 1. When battery swapping operators lead secondary technology R&D, they can leverage big data and internet-based methodologies to enable real-time monitoring and maintenance of power batteries at swapping stations and by consumers. This approach strives to maximise the residual secondary utilisation value of retired batteries. Thus, when the leasing revenue payback period is sufficiently extended, battery swapping operators may opt to reduce battery rental prices to incentivise more potential new energy vehicle consumers to adopt swapping services. This further stimulates the secondary battery market, leading to the continuous expansion of both the swapping and secondary battery markets. Consequently, the sales volume of power batteries and the demand for remanufacturing end-of-life batteries increase, thereby boosting the profits of battery manufacturers. When battery manufacturers lead the development of secondary battery technology, their profits significantly exceed those achieved as followers. It is evident that even with substantial R&D costs for secondary-use technology, battery swapping operators and manufacturers can achieve higher profit returns by leading such technological development.

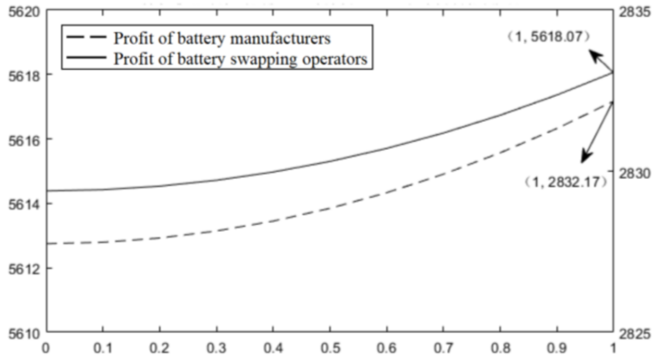
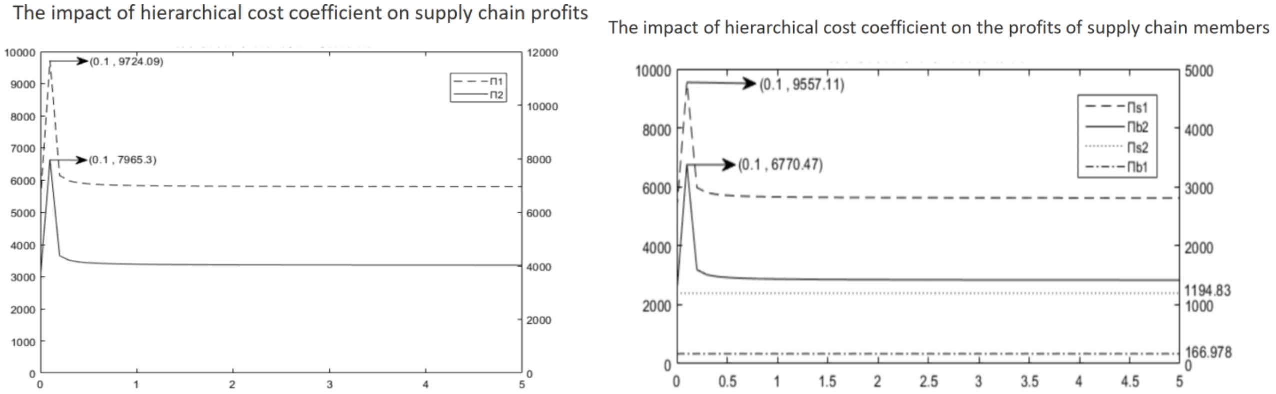


Figure 5. The impact of cascade sensitivity coefficient on the profits of battery swapping operators and battery manufacturers

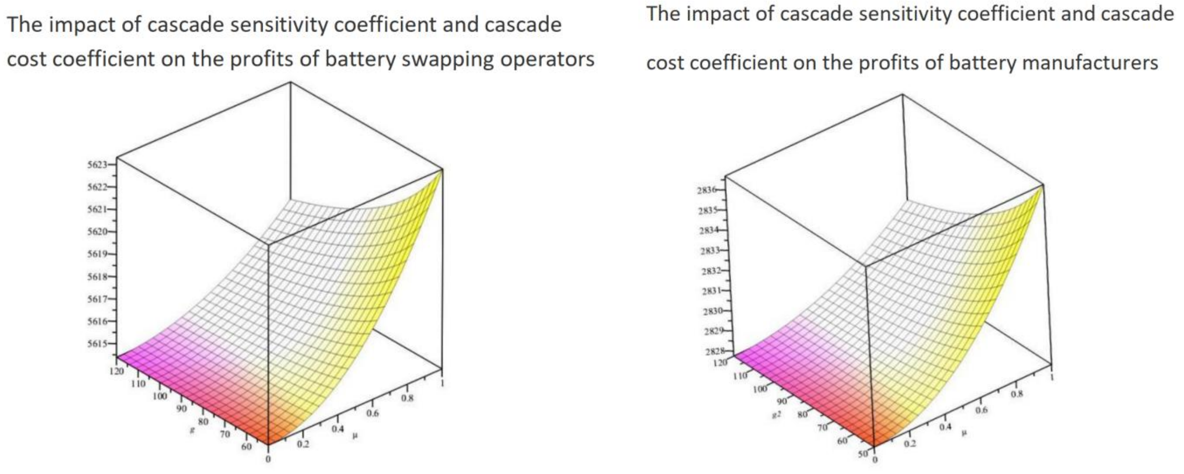
Figure 5 demonstrates that the secondary use sensitivity coefficient exerts a significant positive influence on both battery swapping operators' and manufacturers' profits, validating Theorem 4. Consumers increasingly recognise that batteries employing secondary use technology deliver equivalent energy services at lower costs, thereby favouring secondary use technology and driving market demand growth. This constitutes a positive signal for both battery swapping operators and manufacturers, who can continuously increase profits by expanding production scale, reducing costs, and enhancing market competitiveness. When battery swapping operators dominate the market, their profits far exceed those achieved by battery manufacturers in a dominant position. Consequently, swapping operators secure substantial profits while manufacturers gain relatively less. This disparity inevitably drives swapping operators to vie for supply chain dominance.


The impact of hierarchical cost coefficient on supply chain profits

The impact of hierarchical cost coefficient on the profits of supply chain members

Figure 6. Impact of Secondary Technology Cost Coefficient g on Profitability

Figure 6 indicates that as the secondary technology cost coefficient increases, profits under battery manufacturer and battery swapping operator dominance do not always decline. Instead, they initially rise before falling. This may also relate to R&D investment efficiency: resources allocated during the early R&D phase are fully utilised, thereby increasing profits. When $g > 0.1$, production scale expands and unit costs rise, causing profits to gradually decrease and approach equilibrium. Secondly, when battery swapping operators dominate, their profits consistently exceed both battery manufacturers' profits and the profits they would achieve as followers. In this scenario, battery manufacturers' profits derive solely from battery sales, unaffected by the cascading cost coefficient. When battery manufacturers take the lead, their profits exceed both those of battery swapping operators and their own profits as followers. Similarly, the profits of battery swapping operators at this stage derive from battery leasing services and are unaffected by the tiered cost coefficient. However, it is evident that when battery swapping operators lead the development of tiered technology, supply chain profits are higher than when battery manufacturers take the lead.


The impact of cascade sensitivity coefficient and cascade cost coefficient on the profits of battery swapping operators

The impact of cascade sensitivity coefficient and cascade cost coefficient on the profits of battery manufacturers

Figure 7. Impact of degradation sensitivity coefficient μ and degradation technology cost coefficients g, g_2 on profits

Figure 7 demonstrates that under different power structures, both battery swapping operators and manufacturers are similarly affected by g and μ. Both parties' profits are more significantly influenced by μ, as it directly impacts consumer choice. A higher degradation sensitivity coefficient μ indicates greater consumer preference for degraded products, thereby increasing profits for degradation technology developers. This suggests that stronger environmental awareness among consumers may lead to greater preference for degraded products, ultimately generating higher profits for degradation technology developers. As the cost coefficient of secondary-use technology increases, the profit curve exhibits a downward trend, attributable to higher R&D costs reducing secondary-use technology developers' profits. Secondly, when the secondary-use sensitivity coefficient μ is high, profits remain at a relatively elevated level even with a high cost coefficient g . This indicates that under certain circumstances, despite higher costs, sufficient users can still be attracted due to consumer preference for secondary-use products. However, when both indicators are low, profit levels decline significantly. Therefore, to enhance profitability, operators must balance these two metrics, ensuring reasonable costs are maintained while attracting sufficient consumer uptake of tiered products.

7. Concluding Remarks

Against the backdrop of global carbon neutrality targets and green development strategies, the new energy vehicle industry has gained opportunities for rapid advancement. The battery swapping model, as an emerging energy replenishment approach, is garnering increasing attention and support. Battery swapping offers a swift and convenient means of replenishing energy, significantly enhancing the user experience of electric vehicles while alleviating range anxiety. Meanwhile, the application of secondary utilisation technology maximises the exploitation of battery resources, extends battery lifespan, and reduces both battery disposal and environmental impact. To address battery recycling challenges, the integrated application of battery swapping and tiered utilisation enhances both economic efficiency and environmental performance, providing crucial support for the sustainable development of new energy vehicles. Consequently, determining optimal pricing strategies and technical standards for battery swapping and tiered utilisation is paramount. This study therefore examines the relationship between tiered utilisation standards and pricing strategies within the battery swapping model, comparing scenarios dominated by swapping operators versus battery manufacturers. It further analyses the impact of factors such as lease duration and tiered sensitivity coefficients on equilibrium solutions. The findings reveal: (1) Under different power structures, as consumers opt for longer battery leasing periods, battery rental prices decrease while both battery swapping operators and manufacturers achieve higher profits. To secure greater returns, the dominant player in the supply chain will adopt a high-price strategy, making competition for supply chain dominance inevitable. (2) A higher degradation sensitivity coefficient correlates with greater profits for both battery swapping operators and manufacturers. While manufacturer dominance in degradation technology R&D enhances degradation technology levels and reduces degradation product prices, operator dominance proves more advantageous for boosting overall supply chain profits. (3) Battery leasing prices are lower under manufacturer dominance, making this supply chain structure more beneficial for consumers in both the battery swapping and degradation markets. (4) When the secondary use sensitivity coefficient is high, profits remain at a relatively elevated level even with a high secondary use cost coefficient, though the sensitivity coefficient exerts a greater influence on profitability. (5) As consumer sensitivity to secondary use technology increases, both power structures should elevate the technical standards of secondary use technology.

This study offers the following insights: Within the battery-swapping vehicle industry, power battery manufacturers may emerge as supply chain leaders while serving as battery suppliers. Government should provide corresponding support to enable capable battery providers to assume supply chain leadership, thereby facilitating reductions in battery leasing costs and tiered product pricing, alongside advancing tiered technology R&D. For battery swapping operators, offering diverse leasing packages—such as long-term rental discounts, instalment plans, or loyalty rewards—can incentivise consumers towards extended leases and generate greater profits.

A limitation of this study lies in its exclusive focus on battery swapping under leasing arrangements. Future research should explore scenarios involving different charging models and the impact of competition, as these influencing factors warrant further investigation and expansion. Such avenues will be pursued in subsequent studies.

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