

Research on the Decision-Making of the Battery Swapping Supply Chain Considering Battery Standardization under the Battery Swapping Model

Chao Li*

School of Artificial Intelligence, Neijiang Normal University, Neijiang, 641100, China

*Corresponding author: Chao Li, chaolee77@163.com

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Abstract: This paper examines the battery swapping supply chain comprising battery manufacturer, vehicle manufacturer, and battery swapping operator, focusing on scenarios where battery standardization is led either by the battery manufacturer or by the battery swapping operator. Optimal decisions are derived for both battery standard-setting modes, followed by a comparative analysis. The findings reveal that when the battery swapping operator leads the formulation of battery standards, it results in greater benefits for both the battery manufacturer and battery swapping operator, while also facilitating the adoption of battery-swapping vehicles. However, the optimal strategy for the vehicle manufacturer is influenced by the battery standardization cost coefficient. Although battery swapping operator-led battery standardization enhances the level of battery standardization, it also increases the cost of battery-swappable vehicle bodies. Furthermore, an increase in the battery standardization cost coefficient reduces firm profitability, whereas greater sensitivity to battery standardization positively impacts corporate profits.

Keywords: Battery Swapping Model; Battery Standardization; New Energy Vehicle (NEV); Battery Swapping Supply Chain

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1.Introduction

The NEV industry plays a pivotal role in driving the new wave of scientific and technological innovation and industrial transformation. It serves as a critical foundation for building a strong manufacturing nation and remains a cornerstone of the national economy. According to data from the China Association of Automobile Manufacturers, China's NEV sales reached 12.8 million units in 2024, signaling that the NEV sector has entered a stage of steady growth. Nevertheless, despite this rapid expansion, the NEV market continues to face several significant challenges. These include high vehicle purchase costs, limited resale value due to battery depreciation risks, and persistent consumer concerns such as range anxiety, charging inconvenience, and low vehicle value retention. Together, these issues form key bottlenecks hindering the widespread adoption of NEVs^[1].

As an innovative solution to these challenges, the battery swapping model is emerging as a promising approach to enhance NEV market penetration. By enabling consumers to lease rather than purchase batteries, this model significantly lowers the upfront cost of vehicle ownership, thereby addressing affordability concerns^[2]. Moreover, battery swapping technology allows for rapid energy replenishment, reducing charging time, easing range anxiety, and improving the overall user experience.

Additionally, the centralized management and recycling of batteries under this model contribute to the green, low-carbon, and sustainable development of the NEV industry^[3].

However, the promotion of the battery swapping model faces a major obstacle: the lack of unified battery swapping standards. The lack of standardization has seriously restricted the interchange and sharing of batteries between different brands and models, and hindered the popularization and application of the battery swapping model. Therefore, the proposal of battery standardization has become an effective way to solve this problem. By formulating unified technical standards and specifications, and achieving standardization of batteries in terms of size, interface, communication protocol, etc., it will help improve the compatibility of battery swap equipment, improve battery swap efficiency, optimize user experience, and promote the coordinated development of the NEV industry chain.

The advancement of battery standardization under the battery swapping model will have a profound impact on the decision-making of the battery swapping supply chain. Faced with the new trend of deep integration of battery leasing services in the battery swapping model, companies in the battery swapping supply chain need to re-examine their pricing strategies and competitive situations, and explore how to achieve win-win results in all links of the supply chain while protecting the interests of consumers. For the supply chain composed of the battery manufacturer, battery swapping operator and vehicle company, research on the supply chain decision-making considering battery standardization under the battery swapping model have far-reaching strategic significance for promoting the healthy and sustainable development of the NEV industry.

2.Literature Review

Research related to this paper focuses on two aspects: battery swapping model and battery standardization.

Regarding the battery swapping model, Huang and Qian^[4] explored the psychological premises and influencing mechanisms of consumers' purchase of electric vehicles in different business models and found that consumers' demand for unique features of cars, such as car leasing models, increased their willingness to purchase NEVs in innovative business models. Considering the impact of consumer mileage anxiety and resale anxiety on the adoption of electric vehicles, Lim et al.^[5] developed a two-period model in the secondary market to compare the battery leasing model with the traditional battery purchasing model. Considering the quality of recycled batteries, Li et al.^[6] analyzed the decision-making of NEV power battery sellers under both battery leasing and direct sales models. Furthermore, in a supply chain comprising two automobile manufacturers and one battery swapping operator, Yang et al.^[7] investigated the strategic decision-making of vehicle manufacturers regarding whether to self-operate or authorize battery swap services. Shi and Hu^[8] took NIO BaaS model as an example, discussed the vehicle-battery separation model based on game theory, and explored the boundary conditions that are beneficial to manufacturers, customers and the environment by introducing flexible battery leasing in the BaaS model.

Research on battery standardization remains in its early exploratory stage, and relevant academic studies are still limited. Choi et al.^[9] proposed a set of battery standardization strategies designed to meet the diverse requirements of battery capacity and power across various NEV applications. Liu et al.^[10] explored potential scenarios for the development of battery swapping based on standardization and proposed a joint construction strategy for battery swapping stations and charging infrastructure. Brem et al.^[11] observed that the focus of electric vehicle standardization has gradually shifted—from engines to batteries, and more recently, to broader mobility solutions. They suggest that firms adopt different strategic postures—cooperation, competition, or compliance—depending on the stage of standardization. Fallah et al.^[12] assessed the economic viability of standardized battery recycling and cascade utilization. Tornheim et al.^[13] introduced two standardized testing protocols for battery materials, aimed at accelerating the evaluation of critical electrochemical properties.

The existing literature primarily addresses either battery leasing or battery swapping services individually within the battery swapping model, without considering the battery standardization. Furthermore, research on battery standardization has mainly concentrated on battery testing and cascade utilization, with little attention paid to its implications within the battery swapping model or its broader impact on the NEV industry chain. In response to these gaps, this study focuses on the battery swapping supply chain under the framework of battery leasing services, and conducts an analysis of the combined effects of battery leasing services and battery standardization on supply chain decision-making. The findings aim to offer both theoretical insights and practical guidance to support the sustainable development of the NEV industry.

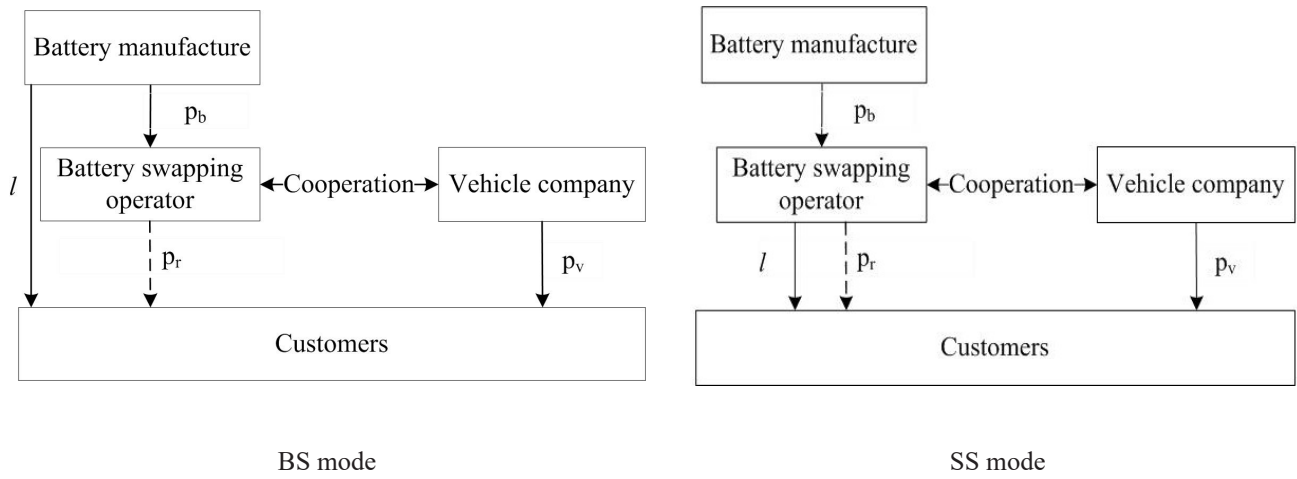
3. Problem Description and Model Assumptions

3.1 Problem Description

The battery swapping supply chain examined in this paper comprises a battery manufacturer, a vehicle manufacturer, and a battery swapping operator, as illustrated in Figure 1. In this supply chain, the battery manufacturer supplies batteries at the price of p_b to the battery swapping operator, who centrally manages the batteries and provide battery leasing services at the price of p_r (including the battery swapping fee) to consumers. The vehicle manufacturer is responsible for producing the bodies of battery-swappable vehicles at the price of p_v to consumers. However, due to technical limitations, the vehicle manufacturer lacks the capability to independently develop and produce standardized battery packs, and can only participate in the battery swapping sector through collaboration with the battery swapping operator.

For battery standardization, there are situations where either battery manufacturers or battery swapping operators are the dominant player. Specifically, battery manufacturers actively set battery standardization at the level l to facilitate battery sales (BS mode); and battery swapping operators pursue setting battery standardization at the level l to streamline operations and improve service efficiency (SS mode).

Figure 1: battery standardization dominant mode in battery swapping supply chain



3.2 Model Assumptions

In practice, the life cycle of a battery-swapping vehicle is significantly longer than that of a power battery. This implies that, over the vehicle's life cycle, more than one battery will be used. In this paper, the life cycle of the battery-swapping vehicle is taken as the reference period. The total duration of battery usage throughout this period is defined as the average battery leasing time (referred to as battery leasing time, the same below). For analytical simplicity, the number of batteries consumed over the vehicle's life cycle is normalized to one. Moreover, the demand for battery-swapping vehicles is affected by the price of the vehicle body, the price of battery leasing service and the battery standardization level. So the demand function for battery-swapping vehicles is: $D_v = a - t_s p_r - p_v + \beta l$. Among them, α ($\alpha > 0$) is the battery swapping vehicle market size, t_s ($t_s > 0$) is the battery leasing time, p_r ($p_r > 0$) is the price of battery leasing services, p_v ($p_v > 0$) is the price of the vehicle body, β ($\beta > 0$) is the battery standardization level sensitivity coefficient, l ($l > 0$) is the battery standardization level.

The investment cost of the battery swapping station c_B primarily includes the battery swapping infrastructure cost and battery cost. According to Wang and Du^[14], assuming that the balanced battery ratio is δ and the battery price is p_b , so the battery cost is $\delta p_b D_v$. Moreover, let γ be the proportion of battery cost to battery swapping station investment cost, then $c_B = \frac{\delta p_b D_v}{\gamma}$. To simplify the model, let balanced battery cost ratio $\lambda = \frac{\delta}{\gamma}$, then $c_B = \lambda p_b D_v$. In addition, the battery standardized cost is $\frac{1}{2} k l^2$. Among them, k is battery standardization cost coefficient.

Table 1 Notations

Parameter	Meaning	Parameter	Meaning
α	Battery swapping vehicle market size	λ	Balanced battery cost ratio
t_s	Battery leasing time	D_v	Battery swapping vehicle demand
c_v	Battery swapping vehicle body production cost	π_b	Battery manufacturer profit
c_b	Standard battery pack production cost	π_v	vehicle company profit
k	Battery standardization cost coefficient	π_s	Battery swapping operator profit
c_s	Battery swapping operation cost	p_v	Vehicle Body price
l	Battery standardization level	p_b	Battery price
β	Battery standardization level sensitivity coefficient	p_r	Battery leasing price

4. Model Construction and Solution

4.1 Battery Manufacturers Determine the Battery Standardization (BS mode)

Under the BS mode, the battery manufacturer determines the battery standardization level l and provides batteries to battery swapping operator at a price of p_b ; the battery swapping operator centrally manages batteries and provides battery leasing services to consumers at a price of p_r ; the vehicle company provides battery swapping vehicle bodies to consumers at a price of p_v . The decision-making order is: first, the battery manufacturer decides the battery standardization level l and battery price p_b , then the battery swapping operator decides the battery leasing price p_r , and finally, the vehicle company decides the vehicle body price p_v . The objective functions of the battery manufacturer, the battery swapping operator and the vehicle company, are as follows:

$$\pi_b^{BS} = (p_b - c_b)D_v - \frac{1}{2}kl^2 \quad (1)$$

$$\pi_s^{BS} = (t_s p_r - c_s - p_b)D_v - \lambda p_b D_v \quad (2)$$

$$\pi_v^{BS} = (p_v - c_v)D_v \quad (3)$$

Proposition 1: The optimal price, demand and profit of the battery manufacturer, the battery swapping operator and the vehicle company under the BS model are:

$$p_v^{BS} = -\frac{ak\lambda - k\lambda^2 c_b - \beta^2 c_v - 2k\lambda c_b - k\lambda c_s + 7k\lambda c_v + ak - kc_b - kc_s + 7kc_v}{\beta^2 - 8k\lambda - 8k} \quad (4)$$

$$p_r^{BS} = -\frac{-\beta^2 \lambda c_b + 2k\lambda^2 c_b + 6ak\lambda - \beta^2 c_b - \beta^2 c_s + 4k\lambda c_b + 2k\lambda c_s - 6k\lambda c_v + 6ak + 2kc_b + 2kc_s - 6kc_v}{t_s(\beta^2 - 8k\lambda - 8k)} \quad (5)$$

$$p_b^{BS} = -\frac{4k\lambda c_b + 4ak + 4kc_b - \beta^2 c_b - 4kc_s - 4kc_v}{\beta^2 - 8k\lambda - 8k} \quad (6)$$

$$l^{BS} = -\frac{\beta(a - c_b\lambda - c_b - c_s - c_v)}{\beta^2 - 8k\lambda - 8k} \quad (7)$$

$$D_v^{BS} = -\frac{k(\lambda + 1)(a - c_b\lambda - c_b - c_s - c_v)}{\beta^2 - 8k\lambda - 8k} \quad (8)$$

$$\pi_b^{BS} = -\frac{k(a - c_b\lambda - c_b - c_s - c_v)^2}{2(\beta^2 - 8k\lambda - 8k)} \quad (9)$$

$$\pi_s^{BS} = \frac{2k^2(\lambda+1)^2(a-c_b\lambda-c_b-c_s-c_v)^2}{(\beta^2-8k\lambda-8k)^2} \quad (10)$$

$$\pi_v^{BS} = \frac{k^2(\lambda+1)^2(a-c_b\lambda-c_b-c_s-c_v)^2}{(\beta^2-8k\lambda-8k)^2} \quad (11)$$

4.2 Battery Swapping Operators Determine the Battery Standardization (SS mode)

Under the SS mode, the battery manufacturer provides batteries to battery swapping operators at a price of p_b ; the battery swapping operator determines the battery standardization level l and provides battery leasing services to consumers at a price of p_r ; and the vehicle company provides battery swapping vehicle bodies to consumers at a price of p_v . The decision-making order is: first, the battery manufacturer decides the battery price p_b , then the battery swapping operator decides the battery standardization level l and the battery leasing price p_r , and finally, the vehicle company decides the vehicle body price p_v . The objective functions of the battery manufacturer, the battery swapping operator and the vehicle company are as follows:

$$\pi_b^{SS} = (p_b - c_b)D_v \quad (12)$$

$$\pi_s^{SS} = (t_s p_r - c_s - p_b)D_v - \lambda p_b D_v - \frac{1}{2}kl^2 \quad (13)$$

$$\pi_v^{SS} = (p_v - c_v)D_v \quad (14)$$

Proposition 2: The optimal price, demand and profit of the battery manufacturer, the battery swapping operator and the vehicle company under the SS model are:

$$p_v^{SS} = -\frac{ak - 2\beta^2 c_v - k\lambda c_b - kc_b - kc_s + 7kc_v}{2(\beta^2 - 4k)} \quad (15)$$

$$p_r^{SS} = \frac{\beta^2 \lambda c_b + a\beta^2 + \beta^2 c_b + \beta^2 c_s - \beta^2 c_v - 2k\lambda c_b - 6ak - 2kc_b - 2kc_s + 6kc_v}{2t_s(\beta^2 - 4k)} \quad (16)$$

$$p_b^{SS} = \frac{\lambda c_b + a + c_b - c_s - c_v}{2(\lambda + 1)} \quad (17)$$

$$l^{SS} = -\frac{(a - \lambda c_b - c_b - c_s - c_v)\beta}{2(\beta^2 - 4k)} \quad (18)$$

$$D_v^{SS} = -\frac{k(a - \lambda c_b - c_b - c_s - c_v)}{2(\beta^2 - 4k)} \quad (19)$$

$$\pi_b^{SS} = -\frac{(a - \lambda c_b - c_b - c_s - c_v)^2 k}{4(\beta^2 - 4k)(\lambda + 1)} \quad (20)$$

$$\pi_s^{SS} = -\frac{(a - \lambda c_b - c_b - c_s - c_v)^2 k}{8(\beta^2 - 4k)} \quad (21)$$

$$\pi_v^{SS} = \frac{k^2(a - \lambda c_b - c_b - c_s - c_v)^2}{4(\beta^2 - 4k)^2} \quad (22)$$

5. Model Comparison and Analysis

5.1 Model Comparison

Corollary 1 Comparison of prices and battery standardization level in the battery swapping supply chain:

- (1) $p_v^{BS} < p_v^{SS}$;
- (2) When $0 < \lambda < \frac{1}{2}$, $p_r^{BS} > p_r^{SS}$; when $\frac{1}{2} \leq \lambda < 1$, $p_r^{BS} < p_r^{SS}$;
- (3) $I^{BS} < I^{SS}$.

According to Corollary 1(1), when battery standards are formulated by battery swapping operators, this indirectly leads to an increase in vehicle body prices. Corollary 1(2) suggests that the pricing strategy for battery leasing services is influenced by the balanced battery cost ratio. Specifically, only when this cost ratio is relatively low will battery standards set by battery manufacturers indirectly incentivize battery swapping operators to raise battery leasing prices. Otherwise, it can help offer more competitively priced battery leasing services. Corollary 1(3) indicates that battery standards established by battery swapping operators are more conducive to enhancing the overall level of battery standardization.

Corollary 2 Comparison of battery swapping vehicle demand: $D_v^{BS} < D_v^{SS}$

According to Corollary 2, the SS model—where battery swapping operators are responsible for setting battery standards—is more effective in promoting the adoption of battery-swapping vehicles. This is because, as supported by Corollary 1(3), battery standards formulated by battery swapping operators are more conducive to enhancing the overall level of battery standardization compared to those set by battery manufacturers. Higher levels of battery standardization reduce compatibility barriers and increase consumer confidence and willingness to adopt battery-swapping vehicles, thereby accelerating their market penetration. A practical example of this is Aulton New Energy, a leading battery-swapping operator in China. The company has actively taken the lead in formulating and reviewing numerous national and industry standards related to battery swapping, thereby playing a key role in advancing the widespread deployment of battery-swapping vehicles.

Corollary 3 Profit comparison of supply chain companies:

- (1) Profit comparison of vehicle companies: when $k^1 < k < k^2$, $\pi_v^{BS} > \pi_v^{SS}$; when $k \geq k^2$, $\pi_v^{BS} \leq \pi_v^{SS}$;
- (2) Profit comparison of battery swapping operators: $\pi_s^{BS} < \pi_s^{SS}$;
- (3) Profit comparison of battery manufacturers: $\pi_b^{BS} < \pi_b^{SS}$;
- (4) Profit comparison of supply chain systems: when $k^1 < k < k^3$, $\pi_T^{BS} > \pi_T^{SS}$; when $k \geq k^3$, $\pi_T^{BS} \leq \pi_T^{SS}$.

$$\text{Here, } k^1 = \frac{\beta^2}{8(\lambda+1)}, k^2 = \frac{\beta^2(2\lambda+3)}{16(\lambda+1)}, k^3 = \frac{\left(\sqrt{(36\lambda^4 + 228\lambda^3 + 445\lambda^2 + 310\lambda + 73)(1+2\lambda)^2} + 12\lambda^3 + 44\lambda^2 + 49\lambda + 13\right)\beta^2}{32(4\lambda^3 + 13\lambda^2 + 12\lambda + 3)}.$$

According to Corollary 3(1), the optimal strategy of vehicle manufacturers is influenced by the battery standardization cost coefficient. When the cost coefficient is low, although battery swapping operators formulating battery standards leads to higher demand for battery-swapping vehicles, it also raises the vehicle total production cost, thereby reducing vehicle manufacturers' profits. In contrast, when the cost coefficient is high, battery swapping operator' standard-setting results in higher profitability for vehicle manufacturers. Corollary 3(2) and 3(3) indicate that it is more advantageous for both battery manufacturers and battery swapping operators when battery standards are set by battery swapping operators. This is because battery swapping operators can enhance the level of battery standardization more effectively, thereby accelerating the adoption of battery-swapping vehicles. The improved market penetration of these vehicles creates a win-win outcome for both battery manufacturers and battery swapping operators. According to Corollary 3(4), the optimal standard-setting strategy for the battery swapping supply chain is also affected by the battery standardization cost coefficient. When the cost coefficient is low, having battery manufacturers lead standardization is more beneficial to the overall development of the supply chain. Conversely, when the cost coefficient is high, battery swapping operators taking the lead becomes more advantageous. This is because changes in vehicle manufacturers' profitability under different standardization schemes directly impact the total profit of the supply chain.

Taken together, Corollary 3 suggests that although battery manufacturers and battery swapping operators generally achieve higher profits under the SS model, the profitability of vehicle manufacturers—and thus the supply chain profit—varies depending on the battery standardization cost coefficient. Therefore, to promote the long-term and sustainable development of the battery swapping supply chain, all participating entities should closely care about shifts in the standardization cost coefficient and adopt corresponding battery standardization strategies accordingly.

5.2 Model Analysis

Corollary 4 The impact of battery standardization cost coefficient k

$$(1) \frac{\partial l^{BS}}{\partial k} < 0, \frac{\partial p_b^{BS}}{\partial k} < 0, \frac{\partial p_r^{BS}}{\partial k} < 0, \frac{\partial p_v^{BS}}{\partial k} < 0, \frac{\partial D_v^{BS}}{\partial k} < 0, \frac{\partial \pi_b^{BS}}{\partial k} < 0, \frac{\partial \pi_s^{BS}}{\partial k} < 0, \frac{\partial \pi_v^{BS}}{\partial k} < 0.$$

$$(2) \frac{\partial l^{SS}}{\partial k} < 0, \frac{\partial p_b^{SS}}{\partial k} = 0, \frac{\partial p_r^{SS}}{\partial k} < 0, \frac{\partial p_v^{SS}}{\partial k} < 0, \frac{\partial D_v^{SS}}{\partial k} < 0, \frac{\partial \pi_b^{SS}}{\partial k} < 0, \frac{\partial \pi_s^{SS}}{\partial k} < 0, \frac{\partial \pi_v^{SS}}{\partial k} < 0.$$

According to Corollary 4, as the battery standardization cost coefficient increases, the level of battery standardization declines, leading to reductions in battery leasing prices and vehicle body prices. However, this also results in a decrease in demand for battery-swapping vehicles, which in turn reduces the profitability of firms across the supply chain. The underlying reason is that a higher cost coefficient raises the overall cost of achieving battery standardization, thereby hindering the advancement of standardization efforts. This impedes the widespread adoption of battery-swapping vehicles and negatively impacts firm performance.

Currently, the growth of battery-swapping vehicles in China remains relatively slow. A key contributing factor is the low level of battery standardization—batteries are often restricted to circulation within a single enterprise or a limited group of allied companies, resulting in poor market liquidity. Therefore, identifying effective strategies to reduce the battery standardization cost coefficient, lower standardization costs, and promote the market-oriented development of battery standards is essential. These efforts are critical for enhancing the scalability, efficiency, and sustainability of the battery-swapping vehicle sector.

Corollary 5 The impact of battery standardization level sensitivity coefficient β

$$(1) \frac{\partial l^{BS}}{\partial \beta} > 0, \frac{\partial p_b^{BS}}{\partial \beta} > 0, \frac{\partial p_r^{BS}}{\partial \beta} > 0, \frac{\partial p_v^{BS}}{\partial \beta} > 0, \frac{\partial D_v^{BS}}{\partial \beta} > 0, \frac{\partial \pi_b^{BS}}{\partial \beta} > 0, \frac{\partial \pi_s^{BS}}{\partial \beta} > 0, \frac{\partial \pi_v^{BS}}{\partial \beta} > 0.$$

$$(2) \frac{\partial l^{SS}}{\partial \beta} > 0, \frac{\partial p_b^{SS}}{\partial \beta} = 0, \frac{\partial p_r^{SS}}{\partial \beta} > 0, \frac{\partial p_v^{SS}}{\partial \beta} > 0, \frac{\partial D_v^{SS}}{\partial \beta} > 0, \frac{\partial \pi_b^{SS}}{\partial \beta} > 0, \frac{\partial \pi_s^{SS}}{\partial \beta} > 0, \frac{\partial \pi_v^{SS}}{\partial \beta} > 0.$$

According to Corollary 5, as consumer sensitivity to battery standardization level increases, the level of battery standardization improves. This, in turn, leads to higher battery leasing prices, vehicle body prices and demand for battery-swapping vehicles, resulting in higher profits for firms within the supply chain. This is because greater consumer sensitivity to battery standardization incentivizes companies to enhance standardization levels. While improved battery standardization raises prices of vehicle body and battery leasing, it also boosts consumer confidence and willingness to adopt battery-swapping vehicles, thereby expanding market demand and enhancing profitability.

Therefore, in the current context of increasing consumer expectations for battery standardized, efforts by firms to improve battery standardization will not only promote the adoption of battery-swapping vehicles but also generate significant economic benefits. Enhancing battery standardization can thus serve as a strategic lever for both market expansion and profit growth.

6. Numerical Examples

To further explore the impact of the battery standardization cost coefficient and battery standardization sensitivity coefficient on battery standardization level and supply chain profitability, this paper employs numerical simulations. Based on the practical operation data of battery swapping model in Neijiang, Sichuan Province, China, and with reference to the research

of Hu et al.^[15], the parameters are assumed that $\alpha=100$, $t_s=8$, $\beta=0.8$, $k=100$, $c_v=4$, $c_b=3$, $c_s=6$, $\lambda=0.1$.

6.1 Impact of Battery Standardization Cost Coefficient k

Figure 2: The impact of k on battery standardization level l

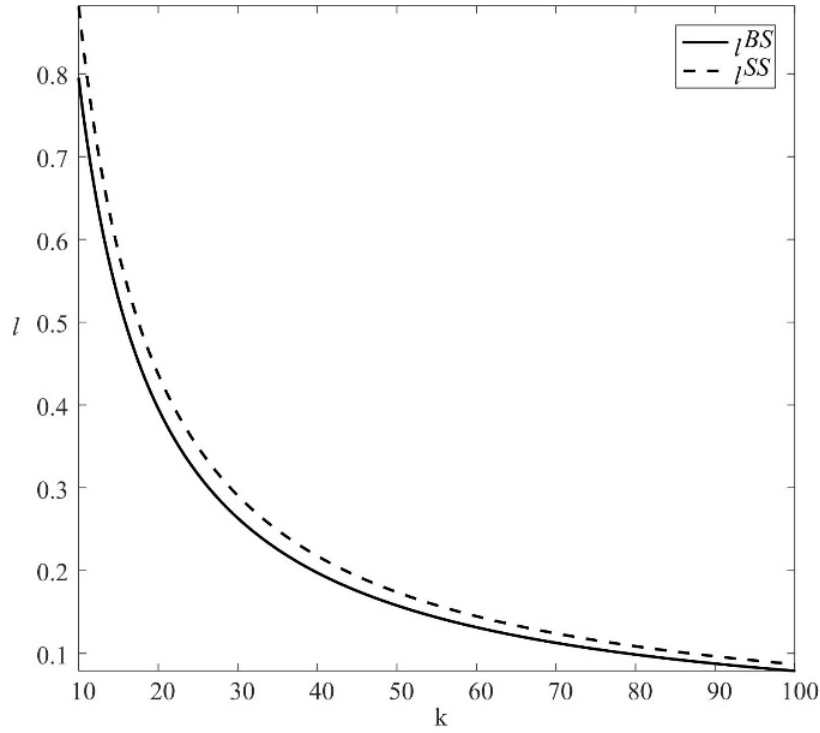
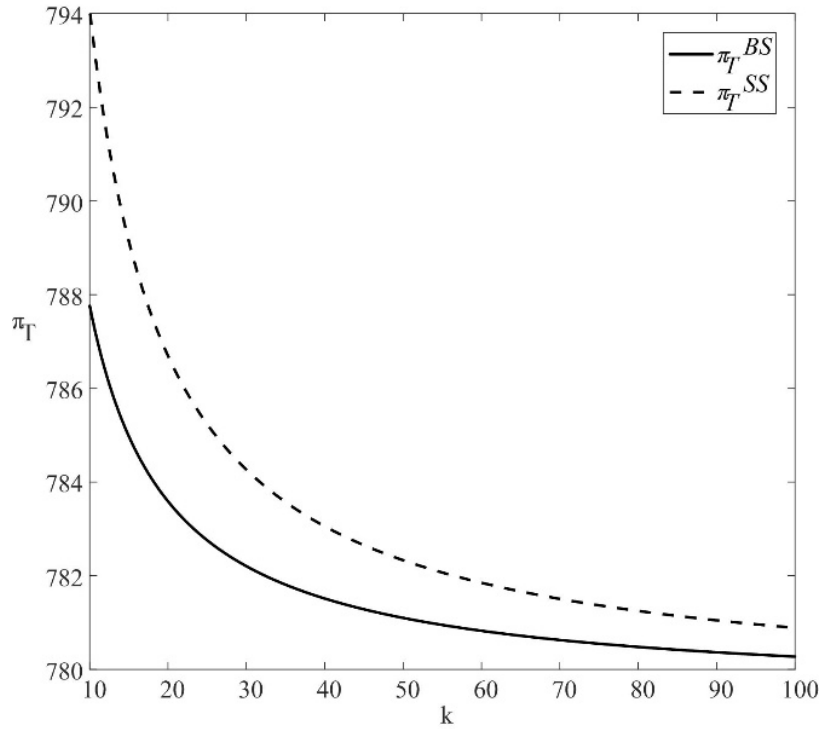


Figure 3: The impact of k on supply chain system profit π_T



According to Figures 2 and 3, as the battery standardization cost coefficient increases, the level of battery standardization decreases, resulting in a decline in supply chain profit. This indicates that higher battery standardization costs hinder efforts to improve battery standardization, which subsequently reduces overall profitability in the supply chain. The rising cost burden restricts standardization initiatives, ultimately impacting the performance of individual firms and the supply chain. These findings provide empirical support for Corollary 4.

6.2 Impact of Battery Standardization Level Sensitivity Coefficient β

Figure 4: The impact of β on battery standardization level l

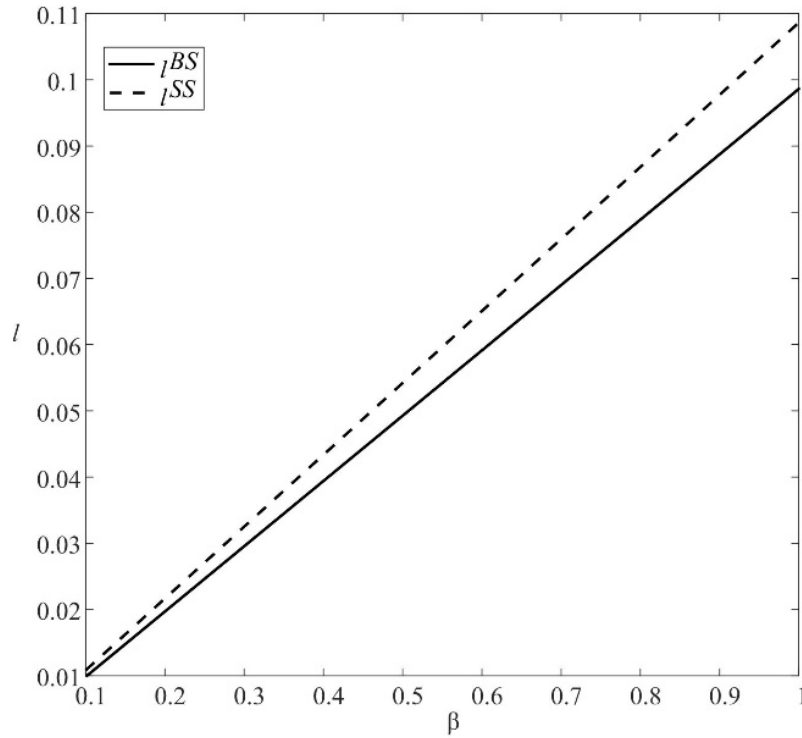
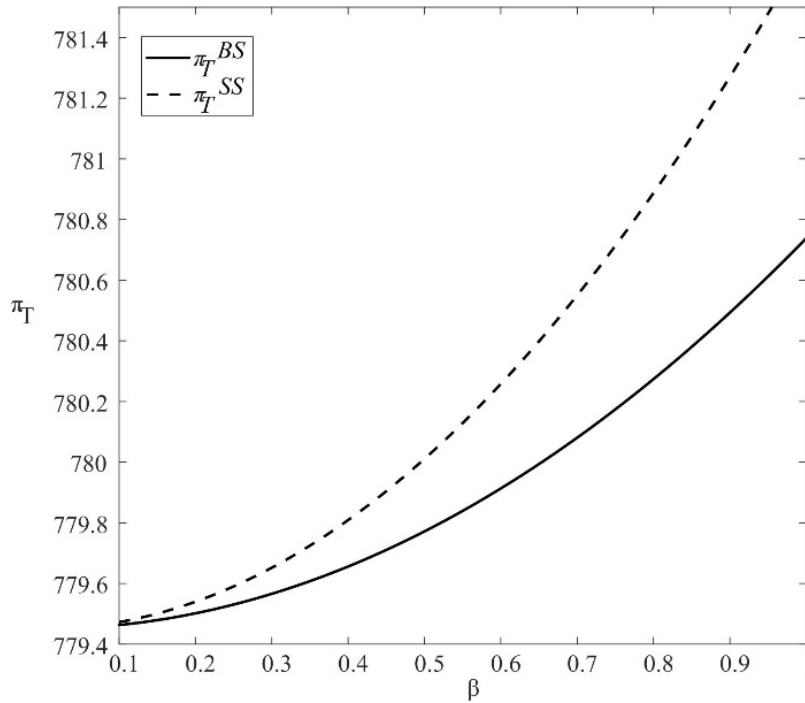


Figure 5: The impact of β on supply chain system profit π_T



According to Figures 4 and 5, as battery standardization sensitivity increases, the level of battery standardization improves, leading to a rise in supply chain profit. This demonstrates that a higher consumer sensitivity to battery standardization facilitates improvements in standardization levels, which in turn boosts demand for battery-swapping vehicles. The resulting increase in corporate profits contributes to enhanced overall supply chain profitability. These results provide support for the Corollary 5.

7. Conclusions

Battery standardization has emerged as a core issue influencing the promotion and scalability of the battery swapping model.

To explore the decision-making related to battery standardization, this paper constructs battery swapping supply chain composed of battery manufacturer, vehicle manufacturer, and battery swapping operator. Two modes are analyzed: one in which battery standards are set by battery manufacturers and another in which they are set by battery swapping operators. Game-theoretic models are developed for each scenario, and optimal decisions are derived using backward induction. A comparative analysis of the two modes is conducted, followed by numerical simulations for further validation and discussion. The study found that: (1) When battery standards are formulated by battery swapping operators, it is more beneficial for both battery manufacturers and battery swapping operators, and this mode also facilitates the wider adoption of battery-swapping vehicles. However, the optimal strategy of vehicle manufacturers is influenced by the battery standardization cost coefficient. (2) Battery swapping operators' involvement in setting battery standards enhances the level of battery standardization, but may indirectly lead to an increase in the vehicle body price of battery-swapping vehicles. (3) An increase in the battery standardization cost coefficient leads to a decline in firm-level and supply chain profits, whereas an increase in consumer sensitivity to battery standardization positively impacts corporate profitability.

Based on the above research conclusions, the following management insights can be obtained: (1) Battery swapping operators should take the lead in advancing battery standardization by building open, compatible, and widely accepted standard systems, thereby promoting the adoption of battery-swapping vehicles and creating mutual benefits across the supply chain. (2) While it is generally advantageous for battery swapping operators to determine battery standards, stakeholders should recognize that such a strategy may indirectly raise the vehicle body price, potentially affecting consumer adoption in price-sensitive markets. (3) Given that battery standardization in China is still in its early stages and the battery standardization cost coefficient remains high, firms should actively explore strategies to lower these costs. One feasible approach is the formation of battery swapping standard alliances to jointly develop and implement standardization documents. Additionally, companies should enhance consumers' perceived value of battery swapping services—for example, by emphasizing the convenience and speed of three-minute battery swaps.

This study focuses on a battery swapping supply chain consisting of a single battery manufacturer, a single vehicle manufacturer, and a single battery swapping operator. Future research could extend the model to incorporate competitive dynamics among multiple battery manufacturers, vehicle manufacturers, and battery swapping operators, thereby offering a more comprehensive understanding of strategic interactions and supply chain decision-making in a competitive market environment.

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Conflict of Interests

The authors declare that there is no conflict of interest regarding the publication of this paper.

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