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THE IMPACT OF GOVERNMENT SUBSIDIES ON BATTERY SWAPPING MODE: FROM THE PERSPECTIVE OF BATTERY SWAPPING SUPPLY CHAIN

Wenxuan Wang and Jianguo Du*

School of Management
Jiangsu University
Zhenjiang, China
*Corresponding author's e-mail: djg@ujs.edu.cn

Battery Swapping Stations (BSSs) encountered several problems, such as an insufficient quantity and high construction costs, which restricted the development of the Battery Swapping Mode (BSM). This paper addresses these issues by examining government subsidies for the construction of BSSs and establishing a battery-swapping supply chain comprising the vehicle manufacturer, the battery-swapping operator, and the consumer. It employs a game model to investigate the impact of subsidy policies on the BSM, solving for the optimal battery-swapping electric vehicle selling price, battery rental price, comprehensive construction level of BSS, and government subsidy proportion. The study simulates the game equilibrium using real-world battery-swapping market data and analyzes the enhancement brought by government subsidies on the BSM. The findings reveal that: (1) The effect of government subsidies does not consistently improve with an increase in the subsidy proportion. Based on changes in social welfare, there exists a reasonable range for government subsidies, with the highest social welfare observed at a subsidy proportion of approximately 85%. (2) Sensible government subsidies for the construction of BSSs effectively boost their numbers, expand market demand, increase social welfare, elevate construction standards, and enhance manufacturer and operator profits. (3) For the battery-swapping operator, the impact of a balanced battery ratio on profits far outweighs the subsidy proportion. Furthermore, a higher battery ratio is not conducive to the long-term sustainability of the BSM.

Keywords: Battery Swapping Mode; Government Subsidy; Electric Vehicle; Supply Chain; Battery Swapping Station

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1. INTRODUCTION

The automobile industry has recently undergone a major transformation, and governments and institutions worldwide are planning for carbon peak and neutrality (Harper *et al*., 2019). Eliminating traditional fuel vehicles has become an important trend of future development. The Ministry of Industry and Information Technology of the People's Republic of China data showed that the EV market keeps elevating, with production and sales increasing by more than 160% yearly. However, such a huge market for EVs has also brought new problems to relevant enterprises, especially in supporting infrastructure. The construction of charging stations requires a lot of time, and with the increase in the number of EVs, the popularization scale of existing charging stations is significantly insufficient. Consumers often wait too long to recharge. Therefore, the problem is that the EV industry urgently needs a new business model.

Battery Swapping Mode (BSM) is a new business model that stores, charges, and distributes batteries in a centralized station and provides battery-swapping services for battery-swapping electric vehicles (BSEVs) in the battery-swapping station (BSS) (Vallera *et al*., 2021). Compared with charging, battery swapping can reduce the replenishment time of EVs and alleviate consumers' anxiety about the battery life of EVs. In addition, the "separation of vehicle and battery" sales can effectively reduce the threshold for consumers to buy cars (Yang *et al*., 2020). More importantly, the centralized detection and management of batteries in the BSS significantly improve the service life, thereby reducing the pollution caused by waste batteries to the environment and is conducive to the sustainable development of our society.

In recent years, the exploration of BSM in China has not stopped. As early as 2019, "BAIC New Energy" began to develop the public transport BSM based on taxis. In 2020, the BaaS service initiated by "NIO" in private cars let consumers enjoy the convenience of battery swapping service. In addition, third-party battery-swapping operators (BSO) such as "GCL Energy Technology", "EVOGO," and "Lifan Technology" are also accelerating the layout and building an integrated battery-swapping ecosystem. In the BSM, the vehicle manufacturer (VM) only needs to sell the vehicle model without batteries to consumers, and the battery-swapping operator (BSO) provides battery rental services to meet normal usage. This paper uses this special supply chain structure called the battery-swapping supply chain (BSSC).

Unlike the traditional EV supply chain, it is worth noting that there is a certain balanced battery ratio in the battery swapping market to ensure the normal operation of the BSSs, which determines the cost input of the BSO, also affecting the long-term development of the BSM indirectly. So, this study considers the balanced battery ratio in the BSSC model and

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explores its impact on the BSM.

However, at the primary stage, the BSSs also face problems of insufficient quantity, uneven distribution, and high construction costs, which seriously restrict the development of the BSM (Li, 2016). That's when we realized government subsidies are an important way to promote EV development, expand market demand, and guide consumer behavior (Kong *et al*., 2020). They can also play an important role in promoting the construction of infrastructure, thus helping to solve the problem of the layout of BSSs, which greatly accelerates the development of BSM.

Using traditional EVs as a reference, government subsidies have a huge impact on the pricing decision, business profit, and R&D strategy of each member in the supply chain, thus changing the final decision of each member. Although many scholars have studied the impact of government subsidies on EVs, existing literature still lacks attention to the BSM. Therefore, studying the impact of government subsidies on the development of BSM is of great significance for developing the EV industry and policy improvement.

Given the situation mentioned above, according to the structural characteristics of the BSSC, this paper considers the government subsidies for the construction of the BSSs, regarding factors such as battery rental months and balanced battery ratio, uses the game model to explore the impact of the subsidy policy on the BSM.

Specifically, the following significant and practical questions are put forward:

(1) What is the impact of government subsidies on the BSM? Especially for pricing decisions, business profits, and the number of BSSs?
(2) Which has the greater impact on the BSM between government subsidies and a balanced battery ratio?
(3) Is there a government subsidy range that maximizes the benefits of the BSM? Can we calculate the most favorable government subsidy proportion?

To solve these problems, we construct a BSSC composed of the vehicle manufacturer (VM), the battery-swapping operator (BSO), and the consumer. Based on this model, we determine their optimal solutions and identify the corresponding strategy equilibrium, thereby obtaining interesting results and contributions.

First, the research shows that government subsidies significantly impact the BSM, like increasing the number of BSSs and improving service efficiency. With the increase in government subsidy, the selling price of BSEVs and battery rental prices continue to decrease. Conversely, the comprehensive construction level of BSSs and market demand continue to increase. Importantly, according to the changes in social welfare, there is a reasonable range of government subsidies. For the BSO, the impact of the balanced battery ratio on profits is far greater than the subsidy proportion. These findings provide a reference for relevant government departments and enterprises to expand the market for the BSM, which has practical meanings.

The rest of this research is structured as follows. In the next section, the literature review is presented. Then, we describe the research problem and modeling assumptions in Section 3. The game models are developed and solved in Section 4, and the impacts of government subsidies on different parameters are discussed. Further, we conduct comparative and numerical analyses in Section 5. Finally, the conclusions and some latent research directions are presented. In summary, the paper's overall structure is shown in Figure 1.

Step 1: Industry Status Analysis 1. EV market keeps elevating 2. Insufficient charging facilities 3. NIO as enterprise sample in BSM 4. Government policy support 5. Existing literature gaps	**Step 2: Establishing Game Model** 1. Parameter setting 2. Game model 3. Model solution & Proposition 4. Contrastive analysis
Step 3: Numerical and Sensitivity Analysis 1. Parameter value setting 2. Effect of each parameter 3. CATL's 2021 annual financial statement 4. Comparative analysis	**Step 4: Conclusion** 1. BSM benefits 2. Government subsidy impact 3. Critical factor 4. Managerial insights

Figure 1. Research methodology diagram

2. LITERATURE REVIEW

This research is closely related to the existing literature in three aspects: the operational strategy of BSM, the impact of government subsidies and Game Theory in the supply chain, and the influence of battery ratio on BSM. The related studies are reviewed below.

2.1.The operational strategy of BSM

As an innovative business model, many scholars have researched BSM, especially in operating BSSs. Yang *et al*. (2014)found that the BSS makes decisions in the market environment by tracing the number of batteries and acquires additional revenue by responding actively to the price fluctuation in the market. According to Cheng *et al*. (2022), the fund allocation and compensation mechanism can encourage BSSs to report their actual operation level. Mahoor *et al*. (2019), on the other hand, considered that the random demand of users for batteries can reduce the operation cost of the BSSs.

In addition to improving the BSM operation, many scholars have also found that the BSM is better than charging (Zaher *et al*., 2021). Specifically, Tan *et al*. (2022) found that people with high-income levels or households with EVs are more willing to pay to construct BSSs. Sun *et al*. (2019) found that when the demand function is not synchronized with the price function, it can simultaneously reduce the charging and waiting costs. Zhang *et al*. (2023) proposed a cluster scheduling model for BSSs and found that the day-ahead dispatching model is optimal. These are the same findings as Wang and Hou (2023), who have proposed improvement strategies for enterprises to promote the development of BSM. Yang *et al*. (2023) established a Hoteling model to find that incentive plans usually contribute to the development of battery swapping and the improvement of social welfare, considering the subsidy policy in the model.

Fewer scholars have investigated the pricing strategy of BSM. Liang and Zhang (2018) concluded that peak-to-valley pricing has optimal energy efficiency and economic effects by simulating consumer responses to battery-swapping prices. Liang *et al*. (2021) present that the battery cost and swapping price are the key factors affecting the net revenue of the battery system over its whole life cycle. Hu *et al*. (2023) found that subscription strategies are beneficial for initial market development but later tend to favor consumer-friendly pay-for-swap strategies. It is not difficult to find that existing scholars have conducted extensive research on the BSM. However, they seem to have overlooked a supply chain comprising Vehicle Manufacturers and battery-swapping operators under the BSM. To maximize the benefits of the BSM, existing scholars lack attention to research the decision-making of battery-swapping supply chain.

2.2.The impact of government subsidies and Game theory in the supply chain

In the early stage of the development of EVs, government subsidies played a key role in expanding the market. Many scholars have used Game theory to explore and study the subsidy policy for the development of EVs, providing an important reference for the research on the subsidy for the BSSs in this paper.

Yang *et al*. (2020) used the Game model to study the impact of subsidies on charging facilities. They found that the diversity of construction subsidies and the uncertainty of profits limit the large-scale construction of charging facilities. Fang *et al*. (2020) concluded that balanced dynamic subsidies and tax policies can effectively promote the development of charging infrastructure. Song *et al*. (2020) confirmed that the basic setting subsidy is an important supplementary policy to ensure the market of EVs. Both Baumgarte *et al*. (2021) and Kumar *et al*. (2021) found that the profitability of charging infrastructure is closely related to government subsidies. Li *et al*. (2023) considered that the acquisition subsidy helps to stimulate the sales of EVs more quickly and to a greater extent in the short term. Asgarian *et al*. (2023) introduced that the government should give large subsidies to EV customers to attract them to buy EVs. Yue *et al*. (2021) considered that the government could use subsidy policies as a driving force for developing the charging infrastructure industry to build a comprehensive industry ecosystem. Luo *et al*. (2022) and Shao *et al*. (2023) found that the optimal subsidies achieve the target EV market penetration rate and ensure accessibility to charging infrastructure.

The above research on EV charging infrastructure subsidies proves the feasibility and effectiveness of government subsidies. It provides an important reference for this paper to research the impact of government subsidies on the BSM. Specifically, this paper explores the impact of the subsidy on the construction of BSSs based on the perspective of BSSC decision-making.

2.3.The influence of battery ratio on BSM

The separation of vehicle and battery is the most important feature of the BSM. Therefore, scholars often consider the inventory battery ratio when studying the optimal decision on the BSM.

Asadi and Pinkley(2021) introduced a model of random battery scheduling, allocation, and inventory replenishment at the BSS to study charging, discharging, and replacement decisions over time. Zhang *et al*. (2021) attempted to design an EV charging network with synergistic battery swapping and found that the preferred battery service scheme was superior to BSSs in terms of investment cost and charging flexibility of standby batteries. Zhang *et al*. (2022) concluded that the maximum detouring distance of EV users is the key to determining the battery density of BSSs, and the maximum detouring distance increase makes the battery effect more significant than the required battery stock. Yang *et al*. (2023) confirmed that the user adaptive response model not only increases the benefits of BSS but also ensures the distribution of each battery rapidly and realizes the rational use of batteries. It can be found that the battery ratio is an important influencing factor in the operation of the BSM. Under the government subsidy mechanism, considering the balanced battery ratio affects the decision-making of BSM is also of great importance.

2.4.Literature gap

Existing scholars have conducted in-depth research on BSM's operation and pricing strategy, the impact of government subsidies and Game Theory on the supply chain, and the influence of battery ratio on BSM and solved many meaningful problems. However, they seem to have overlooked the indispensable government subsidies in the development of BSM. In addition, one of the reasons why the BSM did not form a large-scale application is the cost of batteries, which must be considered when studying the impact of government subsidies. Contrarily, this paper constructs the BSSC model to explore the impact of government subsidies on BSM considering the balanced battery ratio in the market and introduces the monthly rental income of batteries, which is in line with reality and one of the innovations of this article. This paper fills the gap in the existing literature and provides theoretical support for the development of battery-swapping supply chain management. We provide a comparison in Table 1 to show the main contributions.

Table 1. Summary of relevant literature.

Authors	Research about BSM	Government subsidy	Game Theory	Considering battery ratio
Mahoor *et al*. (2019)	✓			
Sun *et al*. (2019)	✓			
Song *et al*. (2020)		✓		
Fang *et al*. (2020)	✓	✓	✓	
Zaher *et al*. (2021)	✓			
Tan *et al*. (2021)	✓			
Baumgarte *et al*. (2021)		✓		
Kumar *et al*. (2021)		✓	✓	
Asadi and Pinkley (2021)	✓		✓	✓
Zhang *et al*. (2021)	✓			✓
Zhang *et al*. (2022)	✓			✓
Cheng and Zheng. (2022)	✓		✓	
Hu *et al*. (2023)	✓		✓	
Li *et al*. (2023)		✓		
Asgarian *et al*. (2023)		✓	✓	
Yang *et al*. (2023)	✓			✓
Wang *et al*. (2023)	✓		✓	
This paper	✓	✓	✓	✓

3. MODEL FORMULATION AND ANALYSIS

In the BSM, the VM and the BSO have a complex cooperative relationship involving the battery-swapping interface design, vehicle chassis design, business model, and other aspects. Since the BSO is the actual operator of the BSSs to obtain the income from the battery rental, it is considered that the BSO is the leading party of the BSM and responsible for the investment, construction, and operation of the BSSs, including configuring a certain ratio of batteries to meet consumers' usage and swapping needs. The VM, as a follower, must manufacture the battery-swapping electric vehicle (BSEV, excluding batteries) according to the battery pack specifications.

3.1.Problem description

This paper considers the battery-swapping supply chain consisting of a Vehicle Manufacturer M, a Battery Swapping Operator O, and a consumer. The government provides subsidies to promote the development of BSM. The government, the VM, and the BSO participate in the game; the dynamic game order of the three parties is shown in Figure 2.

Firstly, the government gives a certain proportion of cost subsidies for constructing the BSS based on the goal of maximizing social welfare to promote the development of the BSM.

Afterward, the BSO, as the BSM leader, determines the battery rental price and the construction level of BSS based on the subsidies.

Finally, the VM in the following position is responsible for manufacturing the BSEV and fixing the selling price.

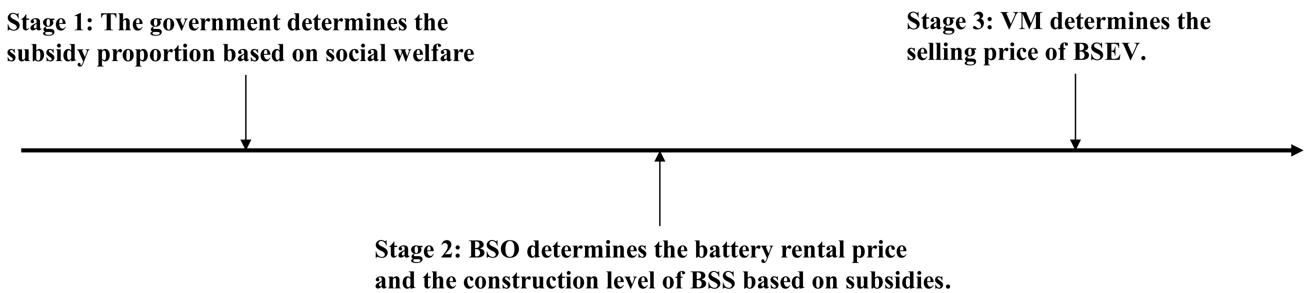

Figure 2. Timeline of events

3.2.Demand functions

In this paper, we regard the demand for battery swapping as the sum of a linear function of the price consumers offered, including the price of buying BSEV, the price for battery rental, and the preferences for the comprehensive construction level of BSSs.

It is assumed that the sales volume of BSEVs in a certain period is ϕ. The consumers have a coefficient for the price of buying BSEV P_m and battery rental P_o, which is represented by a, $a \in [0,1]$. Additionally, considering the number and service efficiency of the BSS is the key to user experiences, we use the consumer preference level for the construction of the BSS θ, as a reference among consumers. Therefore, the improvement of the comprehensive construction level of the BSSs h has a positive impact on demand. So, the demand function in this paper is:

$$Q = \phi - a(P_m + P_o) + \theta h \tag{1}$$

3.3.Basic assumptions

For simplifying mathematical expressions, the following assumptions are proposed. First, all firms are risk-neutral and make pricing decisions to maximize their profits. Secondly, information is completely transparent for all chain members, and we only focus on the battery-swapping electric vehicles, excluding charging. To better ensure the feasibility of the research, make the following additional assumptions:

Assumption 1: Considering “NIO” and “EVOGO”, consumers need to pay the battery rental fee monthly to obtain usage rights in BSSC. We use N to represent the average battery rental months during the service life of the BSEV. So, the profit of the BSO is $N(P_o - C_o)Q$, excluding operating costs. However, it needs to construct the BSS. The input of the construction of the BSSs is an increasing function of the comprehensive construction level h, so setting the investment cost is $1/2\ gh$^2.

Assumption 2: The construction of the BSS costs a lot. To encourage the development of the BSM, the government adopts a proportion $\sigma \in [0,1]$ subsidy for constructing the BSS. Assuming the number of BSSs is k, the fixed cost of each BSS is t, and the total construction cost is kt. So, there are $kt = 1/2\ gh$^2 in mathematical.

Assumption 3: As discussed before, to ensure the normal operation of the BSM, it is necessary to maintain a certain proportion of the balanced battery ratio ρ in the market. The cost of a single battery is C_b, and the total battery cost of the BSO is $\rho C_b Q$.

Assumption 4: The government subsidizes the construction cost of the BSS, which brings corresponding social benefits. The social welfare function expresses the social benefits. Social welfare (SW)=consumer surplus (CS) + producer surplus (PS) - government subsidy. If the producer surplus equals the sum of the profits of manufacturers and operators, the composition of the consumer surplus is shown in Figure 3. Consumer surplus is expressed as:

$$CS = \int_0^Q \left(\frac{\phi + \theta h - Q}{a}\right) dQ - (P_m + P_o)Q = \frac{Q^2}{2a} \tag{2}$$

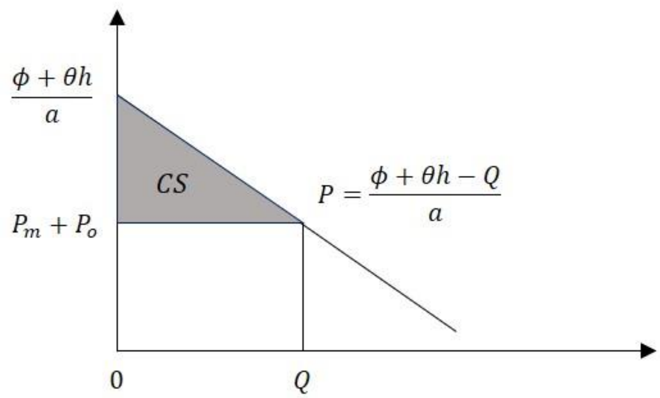

Figure 3. Consumer surplus

In this case, the specific composition of the battery-swapping supply chain is shown in Figure 4, and the other notations are defined and summarized in Table 2.

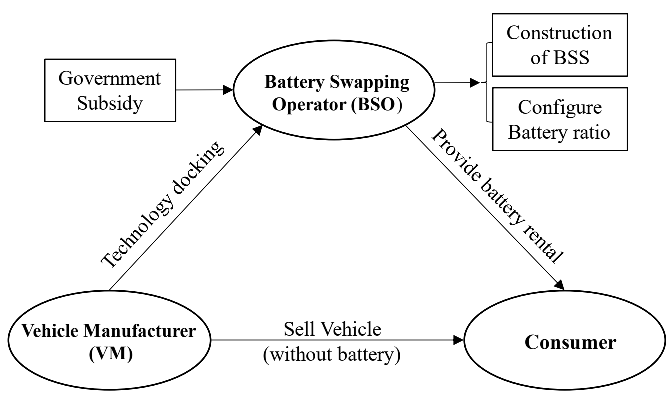

Figure 4. Government subsidy in the BSSC model

Table 2. The description of the symbols.

Symbol	Symbol definition
P_m	Selling price of BSEV
C_m	Manufacturing cost of BSEV
C_b	Battery pack cost
P_o	Battery rental price in a month
C_o	The operation cost of BSS in a month
a	Elastic coefficient to the price on demand, $a \in [0,1]$
θ	Consumer preference level for the construction of BSS
h	Comprehensive construction level of BSSs
N	Battery rental months
σ	Proportion of government subsidy, $\sigma \in [0,1]$
ϕ	Potential sales volume of the market in a certain period
Q	Market demand function of BSEV
g	Construction cost coefficient of BSS
ρ	balanced battery ratio in BSM market, $\rho \in [0,1.2]$
Π_m	Profit of vehicle manufacturer
Π_o	Profit of battery swapping operator

4. GAME MODEL ANALYSIS

The mathematical optimization models are developed in this section, and the optimal analytical solutions are given. Then, we give some propositions to discuss the impacts of government subsidies on different parameters.

According to the premise assumption, the profit function of vehicle manufacturers is obtained:

$$\Pi_m = (P_m - C_m)[\phi - a(P_m + P_o) + \theta h] \tag{3}$$

Battery swapping operator's profit function:

$$\Pi_o = [N(P_o - C_o) - \rho C_b][\phi - a(P_m + P_o) + \theta h] - 1/2(1-\sigma)gh^2 \tag{4}$$

Social welfare function:

$$SW = Q^2/2a + [P_m - C_m + N(P_o - C_o) - \rho C_b][\phi - a(P_m + P_o) + \theta h] - 1/2\sigma gh^2 \tag{5}$$

The optimal pricing decisions can be obtained by solving this problem with a backward induction approach (see Appendix A).

4.1.Calculation results

$$P_m = \frac{C_m N[3\alpha g(1-\sigma) - N\theta^2] + gN(\phi - \alpha C_o)(1-\sigma) - \alpha g\rho C_b(1-\sigma)}{N[4\alpha g(1-\sigma) - N\theta^2]} \tag{6}$$

$$P_o = \frac{\rho C_b[2\alpha g(1-\sigma) - N\theta^2] + N[2g(1-\sigma)(\phi + \alpha C_o - \alpha C_m) - N\theta^2 C_o]}{N[4\alpha g(1-\sigma) - N\theta^2]} \tag{7}$$

$$h = \frac{\theta[N\phi - \alpha N(C_m + C_o) - \alpha\rho C_b]}{4\alpha g(1-\sigma) - N\theta^2} \tag{8}$$

$$\sigma = \frac{6\alpha g + 4\alpha g N + N^2\theta^2}{6\alpha g(2N+1)} \tag{9}$$

By bringing in the above optimal solution, the most profitable result can be obtained:

$$\Pi_m = \frac{\alpha g^2(1-\sigma)^2(\alpha N C_m + \alpha N C_o + \alpha\rho C_b - N\phi)^2}{N^2[4\alpha g(1-\sigma) - N\theta^2]^2} \tag{10}$$

$$\Pi_o = \frac{g(1-\sigma)(\alpha N C_m + \alpha N C_o + \alpha\rho C_b - N\phi)^2}{2N[4\alpha g(1-\sigma) - N\theta^2]} \tag{11}$$

$$SW = \frac{[4\alpha g(4N+3) + N^2\theta^2][N(\alpha C_m + \alpha C_o - \phi) + \alpha\rho C_b]^2}{8\alpha N^2[16\alpha g - (3+8N)\theta^2]} \tag{12}$$

4.2.Comparative analysis

After calculation, we propose some interesting propositions to demonstrate the specific impacts of government subsidies on the BSM. For saving space, we put all proofs and optimal outcomes in the final Appendix of this article.

Proposition 1 After government subsidy, the number of BSSs increases (Δk>0), and the comprehensive construction level of BSSs also improves in the BSM market. See Appendix B for detailed proofs.

Proposition 1 means that the government subsidy has a promoting effect on the construction of the BSSs. Specifically, Proposition 1 indicates that government subsidy alleviates the financial pressure of the BSO. With the relief of capital pressure, operators can invest more money in constructing BSSs. So, the number of BSSs increases, and the comprehensive construction level gradually improves, which is more beneficial to consumers. The increase in the quantity has greatly reduced the time for consumers to search for the BSSs, leading to improved consumer satisfaction, which plays an important role in promoting the development of BSM.

Proposition 2 After government subsidy, the proportion between the number of BSEVs and BSSs decreases. See Appendix C for detailed proofs.

Proposition 2 shows that government subsidies can reduce the proportion between the number of BSEVs and the number of BSSs, which means an increase in the number of BSEVs that a single BSS can service. Like Proposition 1, the main factor is that government subsidies have eased the financial pressure on BSO. By comparison, it can be found that the cost spent on building a BSS significantly impacts the BSO, directly determining the development of the BSM. Therefore, government subsidies are indispensable in the construction of the BSS. The increase in the quantity can improve the service efficiency and quality of the BSM, which is beneficial to the long-term development.

Proposition 3 When the subsidy proportion is met

$$0 < \sigma < (24a^2 g^2 + 16Na^2 g^2 - 6agN\theta^2 - N^3 \theta^4)/\alpha g(3N+4)(8\alpha g - N\theta^2),$$

social welfare increases with the increase of the subsidy proportion. See Appendix D for detailed proofs.

Proposition 3 indicates that within a reasonable range, the proportion of government subsidies for constructing BSSs can improve social welfare. However, when the proportion exceeds a certain range, the government financial expenditure brings negative value-added, reducing overall social welfare. Therefore, the government should adjust the subsidy policy promptly according to the actual situation to ensure that social welfare is maximized.

Proposition 4 The increase in the balanced battery ratio is positively related to the battery rental price and negatively related to the operator's profit. Compared to government subsidies, the impact of the balanced battery ratio is more significant. See Appendix E for detailed proofs.

Proposition 4 means that by increasing the proportion of the balanced battery ratio, the battery cost of the BSO increases significantly, and the operator's profit noticeably decreases. To compensate for its profit loss, the operator could increase the battery rental price accordingly. This leads to the increase of the threshold for consumers to buy cars, which is not conducive to the development of the BSM. In addition, to better control costs, BSO needs to accurately predict the number of batteries because the government subsidies are far from sufficient compared to the battery costs of BSO's expenses.

Proposition 5 The construction cost coefficient of the BSS negatively correlates with the BSEV’s price, the comprehensive construction level of the BSSs, the battery rental price, and the profits of manufacturers and operators. See Appendix F for detailed proofs.

Proposition 5 indicates that higher construction costs for BSSs could hinder the development of BSM under the condition of limited investment costs from BSO. The higher the construction cost coefficient of BSSs, the lower the comprehensive construction level of BSSs. So, the demand in the BSEV market decreases with the decrease in comprehensive construction level, leading to a decrease in profits for VM and BSO, who need to compensate for the decrease in sales volume by lowering prices. It can be imagined that a high-cost coefficient for the construction of BSSs might dampen the enthusiasm of BSOs to invest. In situations where the development of BSM is relatively immature, and the cost of BSSs is relatively high, government subsidies can incentivize the development of BSM.

5. NUMERICAL AND SENSITIVITY ANALYSES

Next, we employ numerical simulation to evaluate the previous findings and propose more useful managerial insights.

According to CATL’s 2021 annual financial statements, the average cost of a standard 100 KWh size battery is about 50,000 CNY, so we set the $C_b = 5$. Using the case of a hot-selling NIO ET5 as an example, the selling price of the vehicle body without the battery is around 280,000 CNY and the manufacturing cost accounts for about 40% of the vehicle price after excluding taxation and operation and sales costs, so the manufacturing cost of which in this paper is 110,000 CNY, set the $C_m = 11$.

Considering the actual operation and construction of NIO battery swapping stations and the theoretical projections, this paper assumes $\phi = 100$, $\rho = 1.2$, $g = 100$, $C_o = 0.1$ to simulate a more mature and larger BSS market than it is today. To control variables and visually reflect trends, assume $N = 12$ to simulate changes within a year. All parameters in this paper are adopted, as shown in Table 3.

Table 3. Parameter value setting.

Symbol	C_m	C_b	C_o	a	θ	g	N	σ	ρ	ϕ
Value Setting	11	5	0.1	0.5	0.5	100	12	0.4	1.2	100

5.1.Changes in the number of BSSs and market demand after subsidy

Firstly, we explore the changes in the number of BSSs and market demand before and after government subsidies. Figure 5 and Figure 6 draw numerical illustrations of the changes in the number of BSSs and market demand with consumer preferences and the cost coefficient of the BSS.

Taken together, without subsidies, the number of BSSs and the market demand is relatively small, and as consumer preferences increase, the growth trend is not obvious, which is in stark contrast to the situation after subsidies. Based on the comprehensive impact, it can be found that government subsidies can achieve the effect of increasing the number of BSSs and market demand, also effective for the promotion and long-term development of the BSM.

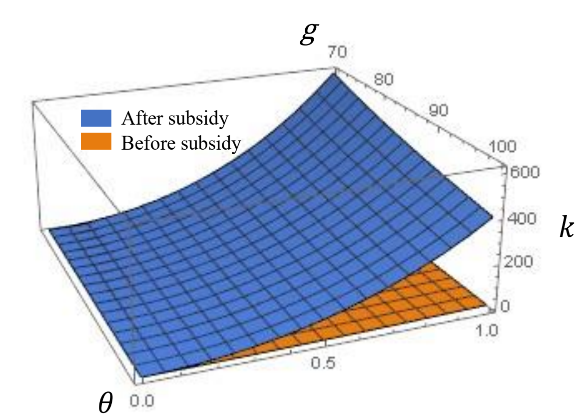

Figure 5. Changes in the number of BSSs

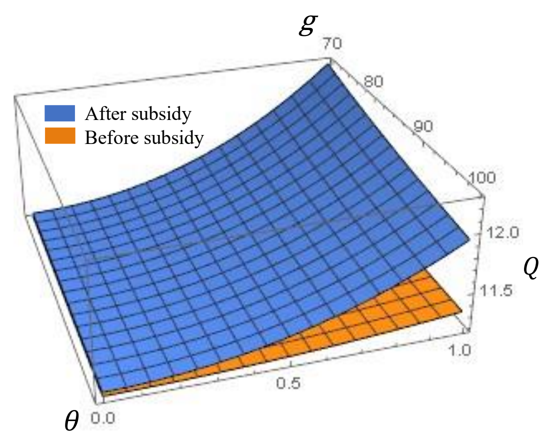

Figure 6. Changes in the market demand

5.2.Impact of subsidy proportion on the BSM

Next, we study how the subsidy proportion affects the profits and different parameters in the BSM.

Figure 7 and Figure 8 shows that compared with no government subsidy, the subsidized BSEV selling price, battery rental price, market demand, comprehensive construction level of the BSSs, the number of BSSs, and the profit of manufacturers and operators all have increased in a certain proportion. With the increasing proportion of subsidies, the increase is getting bigger and bigger, which means that the government subsidy significantly impacts the BSM.

It's not difficult to explain that the government subsidy alleviates the financial pressure on the BSO, so it has more money to build more BSSs. The increase in the number of BSSs has improved the service efficiency and quality for consumers, especially shortening the waiting time for finding the BSSs. When the degree of consumer satisfaction has increased, more and more consumers choose the BSM, and market demand increases. Therefore, VM and BSO can obtain more income and continuously increase profits, forming a positive cycle in the market.

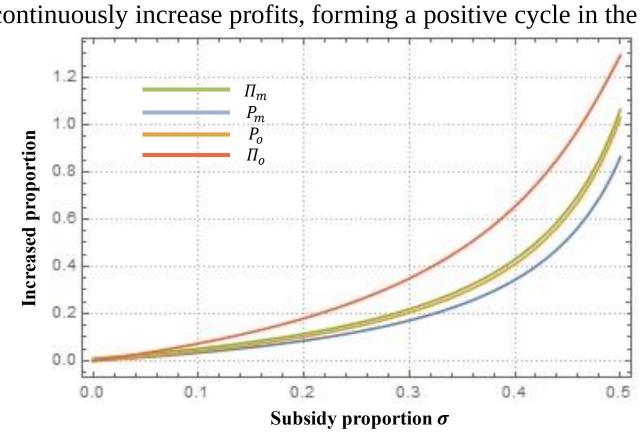

Figure 7. Increase of pricing and profit with subsidy proportion

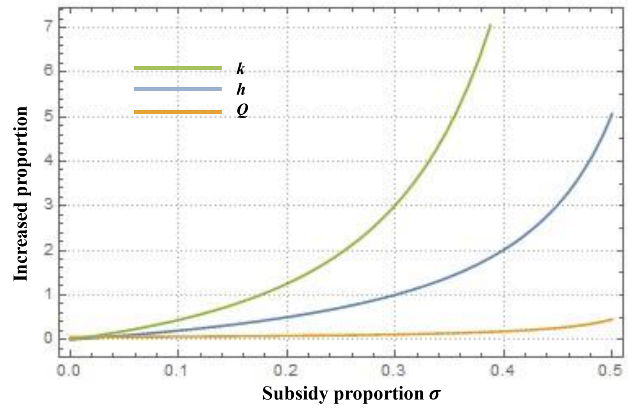

Figure 8. Increase of other parameters with the subsidy proportion

5.3.Impact of balanced battery ratio compared with the subsidy proportion

In contrast, as a direct beneficiary of government subsidies and the operator of BSSs, we explore the influences of balanced battery ratio compared with the subsidy proportion on BSO's profits, intended to analyze which has a greater impact.

From Figure 9, BSO's profit increases with the increase of the subsidy proportion and decreases with the balanced battery ratio. Generally, the impact of a balanced battery ratio on profit is far greater than that of government subsidies. The reason is that government subsidy is mainly for constructing the BSSs, and the amount of government subsidy is limited by fiscal expenditure annually. Compared with the high cost of batteries, government subsidies seem inadequate. Therefore, the profit of BSOs changes greatly with the increase in battery proportion.

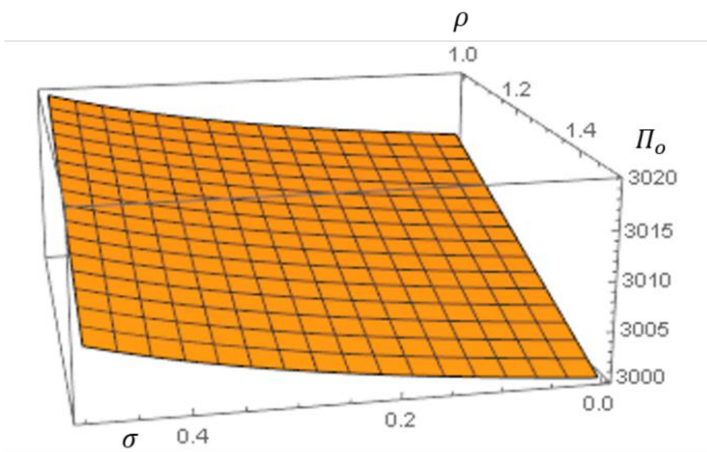

Figure 9. BSO's profit changes with ρ and σ

5.4.Discussion on the optimal range of government subsidies

In this subsection, we aim to investigate how the subsidy proportion affects social welfare and balanced battery ratio, exploring the most optimal solutions to government subsidies and analyzing the trend.

According to Figure 10, within a certain range, social welfare increases with the increase of the subsidy proportion. From the changing trend in the figure, we can see an optimal value for social welfare, around 85%. This also means that the proportion of government subsidies has a reasonable range and should not be unlimited. Conversely, If the subsidy proportion exceeds 90%, the social welfare may not even be as good as without subsidies, which loses the meaning of subsidies. Although the construction cost of the BSS is very high, too many subsidies may also lead to the free-rider behavior of the operators and reduce the construction efforts.

The same situation is also reflected in Figure 11. In the early stages of the BSM, the proportion of government subsidies varied significantly with battery rental months and gradually stabilized around 85% over time. The longer the rental duration of the battery, the longer the return period of the BSM, which means that development tends to saturate.

In this case, government subsidies could not increase anymore, and the impact of government subsidies is also limited. Therefore, the government needs to provide subsidies within a reasonable range, and subsidies are only applicable in the early stages of the development of the BSM, which is consistent with Proposition 3.

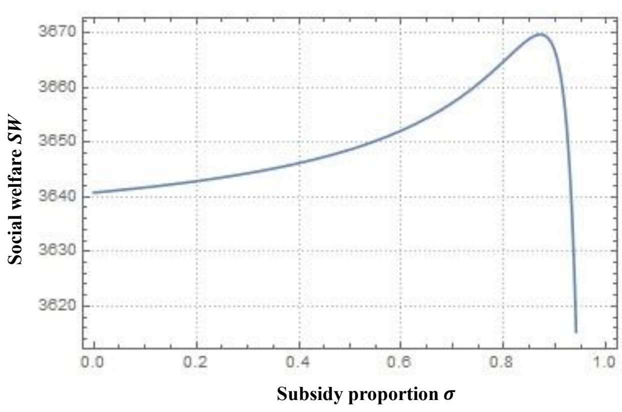

Figure 10. Changes in SW with subsidy proportion

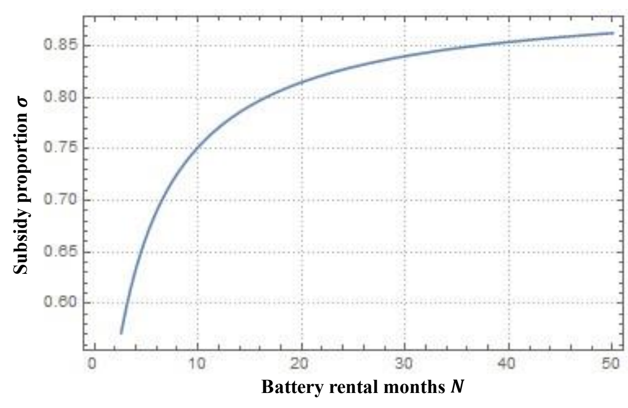

Figure 11. Changes of subsidy proportion with battery rental months

More importantly, as shown in Figure 12, with the subsidy proportion increasing, the balanced battery ratio also continues to increase. When the proportion is around 85%, the balanced battery is around 1.0, consistent with real life. Battery cost is one of the most important expenses for the BSO, which determines whether they can be profitable; a higher battery ratio is not conducive to the long-term development of BSM.

Therefore, efficient energy replenishment technology is usually used in BSSs to achieve rapid battery cycling and stabilize the market battery ratio between 1.0 and 1.2, referring to the data of NIO. It is not difficult to find that when the government subsidy proportion exceeds 85%, the balanced battery ratio in the market increases rapidly. This greatly increases the cost of BSO, resulting in tight cash flow and not conducive to the development of the BSM.

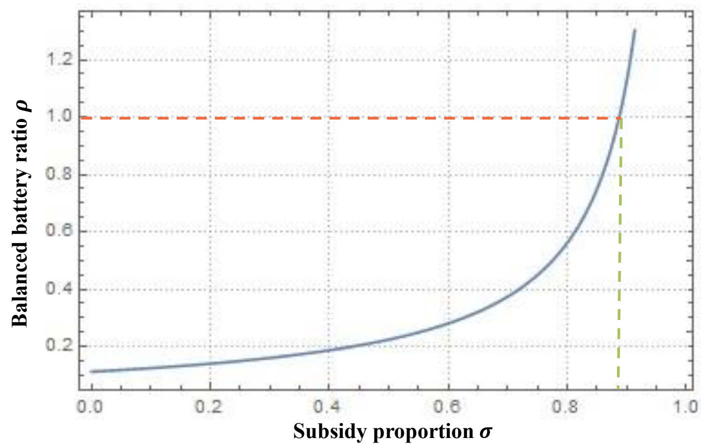

Figure 12. Changes of balanced battery ratio with subsidy proportion

6. CONCLUSIONS

With the popularization of new energy vehicles, research on battery swapping modes is becoming various. Differently from the prior research, we start from the perspective of the battery-swapping supply chain and use the game method to construct a pricing decision model composed of the vehicle manufacturer, battery-swapping operator, and consumer.

Based on this model, we considered government subsidies for constructing BSSs and solved the optimal BSEV selling price, battery rental price, the comprehensive construction level of BSSs, and subsidy proportion. On this basis, the impact of subsidy proportion and the balanced battery ratio on the profits and pricing decisions is further discussed. The research findings are as follows:

(1) The effect of government subsidies could not always improve with the increase of subsidy proportion. In the early stages of the BSM, government subsidies have the best effect. According to the changes in social welfare, there is a reasonable range of government subsidies, and when the subsidy proportion reaches around 85%, social welfare is the highest.

(2) Reasonable government subsidies for BSSs can effectively increase the number of BSSs, expand market demand, increase social welfare, improve the comprehensive construction level of BSSs, increase the profits of manufacturers and operators, and actively promote the development of BSM.

(3) For the BSO, the impact of the balanced battery ratio on profits is far greater than the subsidy proportion. Moreover, the balanced battery ratio always continues to increase with the increase of government subsidies; a higher battery ratio is not conducive to the long-term development of the BSM.

Based on the analytical solutions and numerical simulations, we put forward several interesting management implications as summarized as follows：

Firstly, improve the construction of battery-swapping infrastructure and encourage the development of innovative business models at the primary stage of the BSM. The government must provide subsidies and support for the construction of BSSs. Without subsidies, the number of BSSs is relatively small, and the market demand for the BSM is not fully open. On this basis, gradually improve the subsidy mechanism for BSEV and guide enterprises to conduct independent research and development. The low level of financial subsidies does not significantly impact the promotion and improvement of the BSM, and excessive subsidies seriously reduce the efficiency of government subsidies and increase the financial pressure on the government, reducing social welfare. So, the government should judge whether the subsidy intensity can reach the level of promoting the development of the BSM based on the information on the battery-swapping market.

Additionally, BSO should equip an appropriate ratio of batteries according to the layout of the BSS, which not only meets the minimum balanced battery ratio requirements for consumers to swap batteries but also sets the upper limit of battery ratio based on financial resources and manages the funding chain to resist risks. Therefore, operators should increase their efforts in battery research and development, reduce battery costs, strengthen charging technology, improve battery management systems, increase battery utilization, and allocate battery ratios reasonably.

Finally, manufacturers participate in major activities such as researching and developing battery-swapping technology designing and constructing BSSs. The full scenario layout of the BSM not only relies on government subsidies and the BSO and requires active participation from upstream and downstream members of the BSSC. As beneficiaries of the BSM, manufacturers need to strengthen cooperation with BSO to jointly develop battery-swapping technology and constantly improve the innovation ability of enterprises.

This paper studies the impact of government subsidies on the battery-swapping supply chain, which is a new exploration. There is still a lack of consideration for the influencing factors in the supply chain. For example, consider the waiting time of consumers searching for BSSs in the model or different power structures between VM and BSO. These influencing factors are worthy of further research and development and further explored in subsequent research.

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APPENDIX

Appendix A

Use the reverse induction method to solve the problem. First, seeking the second stage of the game.

$$\frac{\partial \Pi_m}{\partial P_m} = -a(P_m - C_m) - a(P_m + P_o) + \phi + \theta h \tag{A1}$$

Calculating its second derivative numerator $\frac{\partial^2 \Pi_m}{\partial {P_m}^2} = -2\alpha < 0$, We know the profit function can be concave.

Through setting $\frac{\partial \Pi_m}{\partial P_m}$ to zero simultaneously, we can obtain the response function of the VM：

$$P_m^* = \frac{\alpha C_m - \alpha P_m + \phi + \theta h}{2\alpha} \tag{A2}$$

Bring the response function into the operator function.

$$\Pi_o = [N(P_o - C_o) - \rho C_b][\phi - a(\frac{\alpha C_m - \alpha P_m + \phi + \theta h}{2\alpha} + P_o) + \theta h] - \frac{1}{2}(1-\sigma)gh^2 \tag{A3}$$

To confirm the concavity, we carry out the following calculations to build up the Hessian matrix of Π_o.

$$H = \frac{1}{2}\begin{bmatrix} -2a & \theta \\ \theta & -2(1-\sigma)g \end{bmatrix} \tag{A4}$$

The principal minor sequences of the discrimination matrix are$H_1 = -2a < 0, |H| > 0$, which implies that Π_o is a concave function to (P_o, h). Through setting $\frac{\partial \Pi_o}{\partial P_o}$, $\frac{\partial \Pi_o}{\partial h}$ to zero simultaneously, we can obtain the response function of the OM:

$$P_o^* = \frac{-\alpha N C_m + \alpha N C_o + N\phi + N\theta h + \alpha \rho C_b}{2N\alpha} \tag{A5}$$

$$h^* = \frac{\theta(NC_o - NP_o + \rho C_b)}{2g(1-\sigma)} \tag{A6}$$

we combine the three response functions P_m^*, P_o^*, h^*.

$$P_m = \frac{C_m N[3\alpha g(1-\sigma) - N\theta^2] + gN(\phi - \alpha C_o)(1-\sigma) - \alpha g \rho C_b (1-\sigma)}{N[4\alpha g(1-\sigma) - N\theta^2]} \tag{A7}$$

$$P_o = \frac{\rho C_b[2\alpha g(1-\sigma) - N\theta^2] + N[2g(1-\sigma)(\phi + \alpha C_o - \alpha C_m) - N\theta^2 C_o]}{N[4\alpha g(1-\sigma) - N\theta^2]} \tag{A8}$$

$$h = \frac{\theta[N\phi - \alpha N(C_m + C_o) - \alpha \rho C_b]}{4\alpha g(1-\sigma) - N\theta^2} \tag{A9}$$

Bring the three results into the social welfare function and seek derivation on the proportion of subsidies is:

$$\sigma = \frac{6\alpha g + 4\alpha g N + N^2\theta^2}{6\alpha g(2N+1)} \tag{A10}$$

Finally, bring all parameters into the profit function:

$$\Pi_m = \frac{\alpha g^2(1-\sigma)^2(\alpha N C_m + \alpha N C_o + \alpha \rho C_b - N\phi)^2}{N^2[4\alpha g(1-\sigma) - N\theta^2]^2} \tag{A11}$$

$$\Pi_o = \frac{g(1-\sigma)(\alpha N C_m + \alpha N C_o + \alpha \rho C_b - N\phi)^2}{2N[4\alpha g(1-\sigma) - N\theta^2]} \tag{A12}$$

$$SW = \frac{[4\alpha g(4N+3) + N^2\theta^2][N(\alpha C_m + \alpha C_o - \phi) + \alpha \rho C_b]^2}{8\alpha N^2[16\alpha g - (3+8N)\theta^2]} \tag{A13}$$

Appendix B

In the absence of government subsidies, the optimal decision of the cooperation mode between the vehicle manufacturer and the battery swapping operator is:

$$P_m^1 = \frac{(3ag-N\theta^2)NC_m+g[N(\phi-\alpha C_o)-\alpha\rho C_b]}{N(4ag-N\theta^2)} \tag{A14}$$

$$P_o^1 = \frac{N(2g\phi+2agC_o-N\theta^2C_o-2agC_m)+(2ag-N\theta^2)\rho C_b}{N(4ag-N\theta^2)} \tag{A15}$$

$$h^1 = \frac{\theta[N\phi-a\rho C_b-aN(C_m+C_o)]}{4ag-N\theta^2} \tag{A16}$$

According to the formula, the number of battery swapping stations in this case is:

$$k_1 = \frac{g\theta^2[N(\phi-\alpha C_m-\alpha C_o)-a\rho C_b]^2}{2t(4ag-N\theta^2)^2} \tag{A17}$$

After the government subsidies, the number of battery swapping stations is:

$$k = \frac{g\theta^2[N(\phi-\alpha C_m-\alpha C_o)-a\rho C_b]^2}{2t[4\alpha g(1-\sigma)-N\theta^2]^2} \tag{A18}$$

Comparison between k and k_1, due to $4ag - N\theta^2 > 0$, so $2\alpha g(2-\sigma) - N\theta^2 > 0$.

$$\Delta k = \frac{4\alpha g\sigma\left[2\alpha g(2-\sigma)-N\theta^2\right][N(\phi-\alpha C_m-\alpha C_o)-\alpha\rho C_b]^2}{t[4\alpha g(1-\sigma)-N\theta^2]^2(4\alpha g-N\theta^2)^2} > 0 \tag{A19}$$

By the same, comparing the comprehensive construction level of the BSS before and after the subsidy, we can get:

$$\Delta h = \frac{4\alpha g\sigma[N(\phi-\alpha C_m-\alpha C_o)-\alpha\rho C_b]}{(4ag-N\theta^2)(4\alpha g(1-\sigma)-N\theta^2)} > 0 \tag{A20}$$

Appendix C

After the government subsidies, the market demand can be obtained according to the demand function as follows:

$$Q = \frac{\alpha g(1-\sigma)[N(\phi-\alpha C_m-\alpha C_o)-\alpha\rho C_b]}{N[4\alpha g(1-\sigma)-N\theta^2]} \tag{A21}$$

Comparing the market demand with the number of BSSs, we can get:

$$\frac{Q}{k} = \frac{2\alpha tN(1-\sigma)\left(4\alpha g(1-\sigma)-N\theta^2\right)}{\theta^2[N(\phi-\alpha C_m-\alpha C_o)-\alpha\rho C_b]} \tag{A22}$$

When there is no subsidy, we can get:

$$\frac{Q_1}{k_1} = \frac{2\alpha tN\left(4\alpha g-N\theta^2\right)}{\theta^2[N(\phi-\alpha C_m-\alpha C_o)-\alpha\rho C_b]} \tag{A23}$$

After comparison, we can find that:

$$\Delta\frac{Q}{k} = \frac{Q}{k} - \frac{Q_1}{k_1} = -\frac{2\alpha t\sigma N\left[4\alpha g(2-\sigma)-N\theta^2\right]}{\theta^2[N(\phi-\alpha C_m-\alpha C_o)-\alpha\rho C_b]} < 0 \tag{A24}$$

Appendix D

Bring the decision price and the construction level of the BSS before and after the government subsidy into the social welfare function and compare the two by subtraction:

For the convenience of calculation, $[N(\phi - \alpha C_m - \alpha C_o) - a\rho C_b]^2$=$T$

Before government subsidy:

$$SW^1 = \frac{\alpha g^2(4N+3)[N(\alpha C_m+\alpha C_o-\phi)+\alpha\rho C_b]^2}{2N^2[4\alpha g-N\theta^2]} \tag{A25}$$

After government subsidy:

$$SW = \frac{g[\alpha g^2(4N+3)(1-\sigma)^2-\sigma N^2\theta^2][N(\alpha C_m+\alpha C_o-\phi)+\alpha\rho C_b]^2}{2N^2[4\alpha g(1-\sigma)-N\theta^2]} \tag{A26}$$

$$\Delta SW = -\frac{\sigma\theta^2 g^2 T[N^3\theta^4+8\alpha^2 g^2(4N\sigma+3\sigma-2N-3)+\alpha g N\theta^2(6-3\sigma-4N\sigma)]}{2N(4\alpha g-N\theta^2)^2(4\alpha g(1-\sigma)-N\theta^2)^2} \tag{A27}$$

By setting ΔSW to zero simultaneously, we can obtain the proportion of government subsidies:

$$\sigma_1 = 0 \tag{A28}$$

$$\sigma_2 = \frac{24\alpha^2 g^2+16N\alpha^2 g^2-6\alpha g N\theta^2-N^3\theta^4}{\alpha g(3N+4)(8\alpha g-N\theta^2)} \tag{A29}$$

Appendix E

Derivation of battery rental cost and operator profit on balanced battery ratio:

$$\frac{\partial\Pi_o}{\partial\rho} = -\frac{\alpha g\rho C_b(1-\sigma)[N(\phi-\alpha C_m-\alpha C_o)-\alpha\rho C_b]}{N[4\alpha g(1-\sigma)-N\theta^2]} < 0 \tag{A30}$$

$$\frac{\partial P_o}{\partial\rho} = \frac{C_b[2\alpha g(1-\sigma)-N\theta^2]}{N[4\alpha g(1-\sigma)-N\theta^2]} > 0 \tag{A31}$$

$$\frac{\frac{\partial\Pi_o}{\partial\sigma}}{\frac{\partial\Pi_o}{\partial\rho}} = \frac{[2\alpha g(1-\sigma)-N\theta^2]}{N[4\alpha g(1-\sigma)-N\theta^2]} < 1 \tag{A32}$$

Appendix F

Derivation of BSEV selling price, battery rental price, comprehensive construction level of the BSS, manufacturer, and operator profit on construction cost coefficient:

$$\frac{\partial P_m}{\partial g} = -\frac{2(1-\sigma)\theta^2[N(\phi-\alpha C_m-\alpha C_o)-\alpha\rho C_b]}{N[4\alpha g(1-\sigma)-N\theta^2]} < 0 \tag{A33}$$

$$\frac{\partial P_o}{\partial g} = -\frac{(1-\sigma)a\theta^2[N(\phi-\alpha C_m-\alpha C_o)-\alpha\rho C_b]}{aN[4\alpha g(1-\sigma)-N\theta^2]} < 0 \tag{A34}$$

$$\frac{\partial h}{\partial g} = -\frac{4(1-\sigma)a\theta[N(\phi-\alpha C_m-\alpha C_o)-\alpha\rho C_b]}{N[4\alpha g(1-\sigma)-N\theta^2]} < 0 \tag{A35}$$

$$\frac{\partial\Pi_m}{\partial g} = -\frac{(1-\sigma)\theta^2[N(\phi-\alpha C_m-\alpha C_o)-\alpha\rho C_b]}{2N^2[4\alpha g(1-\sigma)-N\theta^2]} < 0 \tag{A36}$$

$$\frac{\partial\Pi_o}{\partial g} = -\frac{2(1-\sigma)a^2 g\theta^2[N(\phi-\alpha C_m-\alpha C_o)-\alpha\rho C_b]}{aN[4\alpha g(1-\sigma)-N\theta^2]} < 0 \tag{A37}$$