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Strategizing battery swap service: Self-operation or authorization?

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Abstract: Electric vehicle (EV) charging is still time-consuming compared with traditional vehicle refueling, causing many consumers hesitant to make the switch. As a solution, battery swapping allows EVs to get energized within minutes. As economies like China embrace the emerging battery swap market, relevant automakers face strategic choices between self-operation and authorization. This study establishes game-theoretic models of a duopoly EV market comprising two automakers and a battery swap market involving an additional third-party operator. Each automaker may run its own battery swap service entirely or license at least part of it to the third-party operator. The results suggest that authorization is typically optimal for a competitive automaker, as its collaboration with the third-party operator enhances both EV market demand and battery swap serviceability, leading to increased social welfare in 99% of simulated cases. Practical implications are discussed for promoting EV industry chain development with the new link of battery swapping.

Keywords: electric vehicle; battery swapping; third-party operator; self-operation; authorization.

1. Introduction

To tackle the issues of fossil fuel consumption and environment pollution, countries around the world promote the diffusion of electric vehicles (EVs) with incentive programs and supportive policies. More than a decade ago, for instance German government championed the emerging EV market with its National Platform for Electric Mobility (NPE) (Daniel, 2010). Similarly, China is promoting battery swapping to address the bottleneck of time-consuming charging that hinders further EV diffusion (ChinaDaily, 2021a).

Based on battery-separable EVs instead of plug-in ones, battery swapping replaces depleted battery packs with fully-charged ones even quicker than traditional refueling. In addition, it allows consumers to enjoy reduced EV purchase cost, extended battery life, and off-peak electricity rate (EVreporter, 2019). For the utility industry, battery swapping also eases the real-time imbalance between power generation and consumption demand (Vallera, Nunes, & Brito, 2021). In 2007, Better Place took the lead in launching battery swap stations in Europe, but the effort ended in failure. Later, Tesla released its battery swap technology in the United States, but eventually gave it up due to cost and utilization concerns (Tesla, 2013).

Nevertheless, the emerging battery swap service has found its place in China where there are millions of time-sensitive consumers, such as taxi and ride-hailing drivers. Automakers like NIO and Geely are engaged in the development of battery swap technology. Geely's smart battery swap stations can complete each service in 60 seconds (Tom, 2021). NIO has already performed more than 4,000,000 battery swaps at NIO Power Swap stations in China (Mark, 2021). NIO launched its first second-generation battery swap station in Beijing, and signed a strategic agreement with Sinopec to establish 5,000 such stations by 2025 (Nora, 2021). To date, NIO has 609 battery swap stations and plans to install more than 700 by the end of this year (ChinaDaily, 2021b). For the fast-developing battery swap market in China, policy makers compiled the National Standard for Battery Swap Safety Requirements for Electric Vehicles (GB/T 40032-2021), making it the first mandate governing the industrial development of battery swap technology (Phate, 2021).

Similarly, more and more automakers around the world recognize the great potential of battery swap service. For example, French automaker Renault announced its intent to incorporate battery swap into EV design (Franz, 2021). In addition, third-party battery swap service operators start to partner with automakers, battery manufacturers, and fleet operators. India's Sun Mobility developed battery swap solutions for buses, two-wheelers and three-wheelers, and announced the plan to launch 100 battery swap stations in Bangalore by the end of 2021 (Promeet, 2020). The German urban light EV startup Adaptive City Mobility (ACM) launched a platform to share a large number of batteries for its relatively simple manual swap solution (David, 2017). Ample, a Silicon Valley EV startup in the USA, cooperates with five automakers to build EVs compatible with its battery packs and swap stations (Jonathan, 2021).

With market readiness and industry involvement, battery swap stands a chance to take off. Due to previous failures, however, the existing literature focuses on the dilemma and issues associated with the development of battery swap mode, such as scale, standardization, and profitability (A., A., A., & S., 2020). To help automakers capitalize on the rejuvenated battery swap market, this study explores potential business models considering third-party operators.

Based on modularization, providers like Ample, Sun Mobility, and Geely build open and compatible platforms to accommodate different EV brands and models, leading to the establishment of battery swap ecosystems (Deepak, 2020; Geely, 2021; Lora, 2021). To avoid "strategic losses" due to long-term capital investment in areas other than production, automakers such as Tesla and Xpeng Motors collaborate with third-party operators like Yunkuaichong Clean Energy Technologies (YKC Charging) (Eva, 2020; Prnewswire, 2021; Xpeng, 2021). YKC Charging is one of the pioneers in the Chinese EV charging sector and one of the few Chinese internet firms with both technical expertise and an open attitude towards collaboration with other industry players. Since 2016, YKC Charging has built the largest third-party EV charging SaaS platform in China. By the same token, automakers may partner with third-party operators in the battery swap market.

License-based authorization represents a collaborative model that allows automakers to devote more capital, human, and technology resources to their core business while capitalizing on relevant service markets (Weidenbaum, 2005). In the emerging battery swap market, automakers can seek partnerships with third-party operators as win-win solutions for all stakeholders. Therefore, the meaningful research question is: which strategy is optimal for automakers to adopt, self-operation or authorization? This study attempts to address the question with game-theoretical modeling to compare corporate profitability and social welfare under different choices. To accommodate different demand functions, it develops a linear model for the EV market as well as a Hotelling model for the battery swap market. The contributions to the literature comprise multiple folds: 1) the proposal of a battery swap business model involving third-party operators; 2) the evaluation of strategic choices for automakers in the battery swap service market; and 3) the comparison of overall social welfare under different battery swap strategies.

The remainder of this article is organized as follows. Based on a literature review, it establishes game-theoretical models incorporating market demand, service price and corporate profit. Model evaluation leads to equilibrium solutions under four different battery swap service strategies. Focusing on the total profit function of automakers, the subsequent numerical simulation reveals how the change in each variable affects service strategy choice-making. Then, this study examines the impacts of automaker decisions on social welfare. The next section extends the modeling to the exclusive-agreement scenario in which each third-party operator can only partner with one automaker. The conclusion summarizes major findings and discusses their implications.

2. Research background

As an emerging phenomenon, battery swap draws researchers' attention. To EV drivers, it makes energy replenishment almost instant, greatly boosting the sustainability of transportation ecosystem (Revankar & Kalkhambkar, 2021). In mainland China, for instance, battery swapping provides an alternative refueling option to time-sensitive users such as taxi-drivers and ride-hailers (A. Q. Huang, Zhang, He, Hua, & Shi, 2021), who also benefit from off-peak electricity rate for battery charging (Liang & Zhang, 2018). In Taiwan, battery swap also facilitates the electrification of motorbikes by millions to ease air pollution (F. H. Huang, 2020). For mass transportation, battery swap is by far the best charging approach for electric buses (W. X. Li, Li, Deng, & Bao, 2018), which also enables the use of the target mixed integer nonlinear programming model to minimize their capital investment and operating cost (Ayad, El-Taweel, & Farag, 2021).

As more and more automakers enter the battery swap arena, each must expand its market share quickly in order to survive the fierce competition. The official statistics of the China Electric Vehicle Charging Infrastructure Promotion Alliance indicated that China had a total of 716 battery swap stations as of June 2021, a leap from 161 in 2020.

Listed companies in China's EV battery swap industry mainly include NIO, BAIC Blue Valley, Contemporary Amperex Technology Co., Ltd. (CATL) and Lifan Technology. Owning the largest domestic market share, NIO recently opened its first battery swap station in Europe, along with a plan to provide the same service in the USA by 2025. In April 2022, CATL announced the launch of EVOGO battery swap service, and will complete the construction of 30 battery swap stations by the end of 2022.

Through management optimization and location planning, battery swap service can yield tremendous economic and social benefits compared with traditional refueling and regular charging (Schneider, Thonemann, & Klabjan, 2018; Sun, Sun, Tsang, & Whitt, 2019; Widrick, Nurre, & Robbins, 2018; Wu, Pang, Choy, & Lam, 2018; F. Zhang et al., 2021; B. H. Zhou & Tan, 2018). This is of great significance to the promotion of battery-separable EVs (T. Y. Zhang, Chen, Yu, Zhu, & Shi, 2018), as service providers can hardly survive the market competition without profitability and sustainability (X. P. Zhang & Rao, 2016). Nevertheless, the extant research on battery swapping mainly addresses station construction and service configuration.

Site selection remains the primary consideration in the establishment of a battery swap station, as service demand hinges on the location. Based on population density and traffic flow, for instance, stochastic planning models are employed to determine service locations (An, Jing, & Kim, 2020; M. D. Lin, Liu, Yang, & Lin, 2021). Additional factors like land acquisition cost and grid load impact can be incorporated in multi-criteria decision making (MCDM) to enhance decision robustness (Wang, Li, Xu, & Li, 2020). The data-driven approach based on GPS tracking of EV traffic further enhances the prediction of service demand for candidate locations (Yang et al., 2021; Zeng, Pan, Zhang, Lu, & Li, 2019). The location optimization of battery swap stations reduces the range anxiety of EV drivers and increases their service usage.

Following site selection is the determination of service capacity for each battery swap station considering random EV arrivals and battery charging status (Sun, Tan, & Tsang, 2018). As charger and battery costs are the main constraints (Jing, Kim, & An, 2018), optimization models are used to design cost-effective battery charging schemes, as demonstrated by the Hong Kong Airport Bus Station case (W, P, C, & L, 2015). To control capital, maintenance, and operation expenses, in particular, the number of batteries assigned to each swap station must be carefully planned (Liu, Lin, Chen, Zou, & Chen, 2017). Service rendering to EVs arriving at a battery swap station is a hybrid queuing network problem, the solving of which helps managers plan service capacity (Tan, Sun, Wu, & Tsang, 2018).

Once a battery swap station is established, its operating cost bears on the service competitiveness that dictates investor confidence. Battery turnover and electricity consumption are the main cost factors that need to be taken into account (Nie, Chung, Chen, Wang, & Qin, 2014). To streamline battery turnover, the queuing theory is employed to detect and remedy service bottlenecks (Asadi & Pinkley, 2021). For electricity expense reduction and grid load smoothing, off-peak charging is preferred (Zhao, Guo, & Qiang, 2017). Battery swap stations must strike a balance between service reliability and economic viability (Sepetanc & Pandzic, 2020).

Extant studies focus on the construction and operation of battery swap stations, yet few address different business models and strategic choices of parties involved. To fill in the research gap, this study explores different battery swap service strategies of automakers: self-operation and authorization. Widely adopted in many industries, authorization is a business model in which an original provider authorizes a third-party operator to provide a service based on a license agreement. In a close-loop supply chain, the authorization model is conducive to the overall profitability of participants (Y. M. Zhang, Chen, & Li, 2021). Due to capacity and emission constraints, third-party authorization becomes a viable means for major companies to outsource remanufacturing and other green activities (B. A. Li, Geng, Xia, Qiao, & Wang, 2021).

Third-party operators have been involved in various aspects of EV ecosystem, such as consumer service, charging, and battery recycling. By authorizing another company to use its intellectual property for a licensing fee, an automaker can improve productivity and branding, as well as service quality. To better serve its EV customers, for example, Xpeng Motor provides technical standards and authorizes TELD to build and operate supercharger stations (Gasgoo, 2019). By examining the equilibrium solutions under different scenarios, game-theoretical modeling enables benchmarking the effectiveness of authorization against self-operation in terms of consumer surplus, social welfare and environmental protection (Q. Zhou, Meng, & Yuen, 2021; Zou, Wang, Deng, & Chen, 2016). For the exploration of potential collaboration between automakers and third-party operators, therefore, this study establishes game-theoretical models to compare self-operation and authorization strategies in terms of corporate profit and social welfare. The insights obtained may help automakers choose the best strategy to capitalize on the emerging battery swap market.

3. Problem Description and Model Setup

In a battery swap market, there are two competing automakers A and B, the former having a bigger customer base than the latter, as well as a third-party operator C. Each automaker may provide the service by itself or sign a non-exclusive authorization agreement with operator C who has a certain edge such as existing facilities. Figure 1 shows the two alternative strategies for each automaker: self-operation (i.e., providing its own battery swap service), and authorization (i.e., licensing technology and equipment to operator C). Under the self-operation strategy, an automaker fulfills both EV market demand q_i and battery swap demand h_i, and determine EV price p_i and battery swap price r_i respectively. Under the authorization strategy, an automaker still takes care of its EV market, but let the third-party operator render at least part of battery swap service. The total battery swap demand is the sum of each automaker's, h_i, and the third-party operator's, $h_{i,3p}$. Under the authorization agreement with an automaker, the third-party operator offers licensed battery swap service at price $r_{i,3p}$. To find out whether there is a win-win solution, this study compares corporate profitability and social welfare under different scenarios.

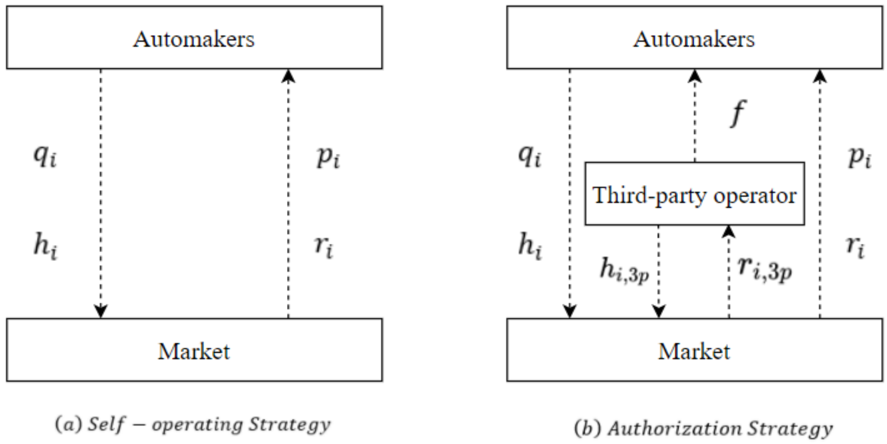


Figure 1. Market structure

When a third-party operator is present, each automaker makes three decisions sequentially: setting EV retail price, choosing a battery swap service strategy (self-operation or authorization), and determining service price. Concerning the combinations of strategies, there are four possibilities: (1) both automaker A and B choose self-operation; (2) both automaker A and B choose authorization; (3) automaker A chooses self-operation, automaker B chooses authorization; (4) automaker A chooses authorization, automaker B chooses self-operation.

Table 1 gives the main parameters used in modeling. Corresponding to either participant in the EV market, the subscript $i \in \{1,2\}$ stands for automaker A and automaker B, the subscript $3p$ stands for the third-party operator C.

Table 1. Model parameters

Parameter	Definition	Unit
q_i	Automaker i's current EV demand	10^7
p_i	Automaker i's EV retail price	10^5 USD
s_i	Automaker i's profit from EV sales	10^12 USD
c_i	Automaker i's EV marginal cost	10^5 USD
a_i	Automaker i's potential EV demand	10^7
b_i	Automaker i's substitution intensity from the competing EV brand	-
${\rho_i}^m$	Impact of battery swap service strategy on potential EV demand, $m \in \{A, S\}$, where A stands for authorization, and S stands for self-operation	-
o_i	Automaker i's battery swap operating cost	10^2 USD
o_{3p}	The third-party operator's battery swap operating cost	10^2 USD
l_i	Automaker i's unit battery procurement cost	10^5 USD
l_{3p}	The third-party operator's unit battery procurement cost	10^5 USD
n_i	The maximum service capacity of each battery swap station of	10^5

	automaker i during an EV service life	
n_{3p}	The maximum service capacity of each battery swap station of the third-party operator during an EV service life	10^5
δ_i	Automaker i's battery swap station utilization rate	-
δ_{3p}	The third-party operator's battery swap station utilization rate	-
μ	The average number of batteries stored at each battery swap station	10^2
r_i	Automaker i's price of self-operated battery swap service	10^2 USD
$r_{i,3p}$	The third-party operator' price of the battery swap service authorized by automaker i	10^2 USD
h_i	The demand for automaker i's self-operated battery swap service	10^10
$h_{i,3p}$	The demand for the third-party operator's battery swap service authorized by automaker i	10^10
h_{3p}	The total demand for the third-party operator's battery swap service	10^10
w_i	Automaker i's profit from self-operated battery swap service	10^12 USD
$w_{i,3p}$	The third-party operator's profit from the battery swap service authorized by automaker i	10^12 USD
w_{3p}	The third-party operator's total profit from battery swap service	10^12 USD
π_i	Automaker i's overall profit	10^12 USD
τ	Average number of battery swaps during an EV service life (about 8.2 years)	10^3
k	Price adjustment factor	-
t	Unit preference distance cost coefficient	10^2 USD
v	Consumer's perceived valuation of battery swap service	-
f	Unit licensing fee	10^2 USD
CS	Overall consumer surplus	10^12 USD
CS_{ev}	Consumer surplus from the EV purchase	10^12 USD
$CS_{bs,i}$	Consumer surplus from automaker i's battery swap service	10^12 USD
$CS_{bs,3p}$	Consumer surplus from the third-party operator's battery swap service	10^12 USD
SW	Social welfare	10^12 USD

Note: Units are derived from realistic values as described in Section 5. For simplification, scientific notations are used. For example, when $c_i = 0.2$, it is actually 0.2*10^5 USD, or $20,000.

3.1 EV market

The modeling of EV market is based on the following assumptions: (1) EV market demand is a linear function of price. Such an assumption is widely used in recent literature (Beranek & Buscher, 2020; Y. G. Li, Sun, Ling, Lu, & Liu, 2020; Xi & Zhang, 2020); (2) The battery swap service strategy of automakers will affect their EV market demand to some extent. In a dual poly, the demand function of automakers A and B can be expressed as follows:

$$q_i(p_i, p_j) = \rho_i{}^m a_i - p_i + b_i p_j\ , \tag{1}$$

where $i,\ j \in \{1, 2\}$ with $i \neq j$. Respectively, p_i and p_j are automakers A's and B's EV prices. Meanwhile, $\rho_i{}^m$ with $m \in \{S, A\}$ represents the relative impacts ($\rho_i{}^m \geq 1$) of an automaker's self-operation strategy ($\rho_i{}^S$, set to be 1 as baseline) and authorization ($\rho_i{}^A$) strategy on its potential EV market demand a_i ($a_1 > a_2 > 0$, assuming automaker A has a larger market share than automaker B). Indicating the substitution intensity of the two brands, b_i falls into the range of [0, 1]. When $b_i = 1$, both brands are completely substitutable; when $b_i = 0$, neither is replaceable. Under the game market structure, the profit function of an automaker from EV sales is,

$$s_i = (p_i - c_i) q_i\ . \tag{2}$$

The primary goal of each automaker is to maximize the profit from EV sales, the possibility of which can be evaluated. The evaluation comprises the first-order, second-order, and mixed partial derivatives of the profit function.

$$\frac{\partial s_i}{\partial p_i} = \rho_i{}^m a_i + b_i p_j + c_i - 2p_i\ , \tag{3}$$

$$\frac{\partial^2 s_i}{\partial p_i{}^2} = -2\ , \tag{4}$$

$$\frac{\partial s_i}{\partial p_i \partial p_j} = b_i\ . \tag{5}$$

Based on the condition that the extreme value of the binary function exists ($4 - b_i{}^2 > 0$, and $-2 < 0$), automakers are able to maximize profits. Hence the solution of the algebraic equations with $\frac{\partial l_i}{\partial p_i} = 0$ for profit maximization,

$$p_i{}^* = \frac{2\rho_i{}^m a_i + \rho_j{}^m a_j b_i + b_i c_j + 2c_i}{4 - b_i b_j}\ . \tag{6}$$

Finally, the equilibrium demands for EV can be obtained by putting the results into formula (1).

$$q_i{}^* = \frac{2\rho_i{}^m a_i + \rho_j{}^m a_j b_i + b_i b_j c_i + b_i c_j - 2c_i}{4 - b_1 b_2}\ . \tag{7}$$

3.2 Battery swap market

Battery swap market is divided into two major segments: automaker A's and automaker B's. There are two battery swap service strategies in each market segment: self-operation and authorization. In the case of authorization strategy, an automaker licenses battery swap technology and equipment to the third-party operator, and both will offer the same service to consumers. This article assumes that automaker's equilibrium demand in the battery swap market is $\tau {q_i}^*$, where τ represents the average number of battery swaps in an EV service life. The superscripts S and A indicate different strategies to distinguish price and demand functions under each. Based on real-world scenarios, it is assumed that an EV can undergo battery swaps up to 1,000 times, and a consumer patronizes a service provider every 3 days. Thus, an EV service life is around 3,000 days (or 8.2 years that is also consistent with the median EV life expectancy as per Raustad, 2017), which is used as the parametric duration for battery swap market demand and swap station service capacity.

The Hotelling model was originally proposed to explain how two monopoly firms position their products in a competitive market (Hotelling, 1929). Since then, it has been used to examine the pricing behavior of firms in spatial competition based on typical assumptions: 1) two stores are evenly distributed horizontally; 2) the locations of consumers are fixed; 3) the unit distance cost of travel to each store is the same (Luo & Moschini, 2019; Xing, 2014; J. Zhang, Wang, & Zhao, 2020). Interested in distinct battery swap service strategies, this study constructs a Hotelling model involving two competing automakers, each of whom may opt for self-operating battery swap service or authorizing it to the third-party operator. The service is homogeneous but operating costs and spatial locations vary with strategic choices, leading to different consumer preferences and corporate performances.

At opposite ends of a linear city locate an automaker and a third-party operator offering homogeneous services, while price-sensitive consumers are evenly distributed over the interval of [0,1]. As it takes time and money to reach each service, consumers care about the sum of service price and travel cost in choice-making. A consumer at x

visiting the automaker's and third-party operator's services incurs the travel costs of tx and $t(1-x)$, respectively. The equilibrium condition of the Hotelling model is thus as follows:

$$v - r_i - tx = v - r_{i,3p} - t(1-x). \tag{8}$$

Solve the above formula, consumer decision equilibrium point $\bar{x} = \frac{r_{i,3p} - r_i + t}{2t}$ can 'be obtained. Therefore, the battery swap service demands of automaker and third-party operator are:

$$h_i{}^A = \tau q_i{}^A \bar{x}, \tag{9}$$

$$h_{i,3p} = \tau q_i (1 - \bar{x}). \tag{10}$$

As the authorization strategy involves a licensing fee, the automaker's and third-party operator's battery swap service profit functions are:

$$w_i{}^A = (r_i{}^A - o_i) h_i{}^A - l_i \mu \frac{h_i{}^A}{n_i \delta_i} + f h_{i,3p} \,, \tag{11}$$

$$w_{i,3p} = \left(r_{i,3p} - o_{3p} - f\right) h_{i,3p} - l_{3p} \mu \frac{h_{i,3p}}{n_{3p} \delta_{3p}} \,. \tag{12}$$

Considered as a one-time expense, the depreciation cost is independently borne by each service provider through its battery rental to EV drivers. It can be calculated based on battery reserve size and procurement cost l. The total battery reserve of automakers and the third-party operator is determined by the number of their battery swap stations and the average battery reserve at each μ. The number of battery swap stations is determined by battery swap market demand h, swap station service capacity n, and utilization rate δ: $h/(n * \delta)$. Based on EV market demand (Equations 7), battery swap service demands can be obtained for the automaker and third-party operator respectively (Equations 15 and 16).

In the Hotelling models of this study, therefore, the operating cost of authorized battery swap service comprises the licensing fee and provider-specific expenses like labor and electricity. As licensing is a standard practice, it is assumed that different automakers charge the same fee for the sake of fairness. When the third-party operator works with both automakers, therefore, the operating cost remains equivalent at the average industry level. Meanwhile, automakers compete with each other in the EV market, the game state of which affects their battery swap pricing. This in turn leads to the price competition among the third-party operator and automakers in the battery swap market. To maximize overall profitability, the automaker and third-party operator may adjust their battery swap service prices. Equilibrium service price and demand for each provider can be obtained based on the derivatives of the two profit functions above:

$$r_i^{A*} = \frac{3f + o_{3p} + 2o_i + 3t}{3}, \tag{13}$$

$$r_{i,3p}^{\ *} = \frac{3f + 2o_{3p} + o_i + 3t}{3}, \tag{14}$$

$$h_i^{A*} = \tau q_i^{A} \frac{o_{3p} - o_i + 3t}{6t}, \tag{15}$$

$$h_{i,3p}^{\ *} = \tau q_i^{A} \frac{o_i - o_{3p} + 3t}{6t}. \tag{16}$$

If another automaker adopts the self-operation strategy, it only needs to maximize its own profit:

$$\max_{r_i} \left\{ (r_i - o_i)\tau q_i - l_i \mu \frac{\tau q_i}{n_i \delta_i} \right\}. \tag{17}$$

Once battery swap demand is determined, the profit function is a linear function of service price. For automaker, the key factor in service pricing is the operating cost: $r_i^S = ko_i + \varepsilon$, where k indicates the adjustment coefficient $(k > 1)$, and ε is a random variable of standard normal distribution. As $E(r_i^S) = ko_i$, the profit function of automaker is:

$$w_i^S = (ko_i - o_i)\tau q_i^S - l_i \mu \frac{\tau q_i^S}{n_i \delta_i}. \tag{18}$$

Based on the above analytical solution, the demand for the service offered by the third-party operator may come from two market segments when both automakers choose the authorization strategy. Similarly, the profit function is the sum of market gains:

$$h_{3p}^{\ *} = \sum h_{i,3p}^{\ *}, \qquad w_{3p}^{\ *} = \sum w_{i,3p}^{\ *}. \tag{19}$$

3.3 Corporate overall profit

For solving EV market and battery swap market models, it is necessary to assume that automakers make corresponding decisions in a sequence. In practice, an automaker prioritizes EV pricing over service strategy choice-making. The overall profit of an automaker consists of two parts: EV market profit and battery swap market profit. Its overall profit under self-operation service strategy is:

$$\pi_i{}^S = (p_i{}^{S*} - c_i)q_i{}^{S*} + (ko_i - o_i)\tau q_i{}^{S*} - l_i\mu\frac{\tau q_i{}^{S*}}{n_i\delta_i}. \tag{20}$$

As for authorization, the overall profit is:

$$\pi_i{}^A = (p_i{}^{A*} - c_i)q_i{}^{A*} + (r_i{}^{A*} - o_i)h_i{}^{A*} - l_i\mu\frac{h_i{}^{A*}}{n_i\delta_i} + fh_{i,3p}{}^{*}. \tag{21}$$

Based on the aforementioned equilibrium solutions obtained for the EV market and battery swap market, the profit functions can be evaluated for self-operation and authorization strategies, respectively.

4. Optimal decisions of automakers and third-party operator

Both automakers have 2 strategies corresponding to their respective battery swap markets. The combination of two has 4 results: self-operation and self-operation (SS), authorization and authorization (AA), authorization and self-operation (AS), self-operation and authorization (SA). The equilibrium solutions for different strategy combinations for EV and battery swap markets are solved separately below.

4.1 Symmetric self-operation scenario-SS

When both automakers choose the self-operation strategy, the third-party operator is not involved in the battery swap market, and service demand is fully covered by the former. The equilibrium price, demand and profit can be obtained based on the self-operation profit functions in the battery swap market, as summarized by the following lemma.

Lemma 1. In the SS case, the equilibrium prices are $\mathrm{r_1}^{S*} = \mathrm{ko_1}, \mathrm{r_2}^{S*} = \mathrm{ko_2}$, the equilibrium demands are:

$$\mathrm{h_1}^{S*} = \tau\frac{2\rho_1{}^S a_1 + \rho_2{}^S a_2 b_1 + b_1 b_2 c_1 + b_1 c_2 - 2c_1}{4 - b_1 b_2},$$
$$\mathrm{h_2}^{S*} = \tau\frac{2\rho_2{}^S a_2 + \rho_1{}^S a_1 b_2 + b_1 b_2 c_2 + b_2 c_1 - 2c_2}{4 - b_1 b_2}.$$

and the equilibrium profits are:

$$w_1^{S*} = \left(ko_1 - o_1 - l_1\mu\frac{1}{n_1\delta_1}\right)\tau\frac{2\rho_1{}^S a_1 + \rho_2{}^S a_2 b_1 + b_1 b_2 c_1 + b_1 c_2 - 2c_1}{4 - b_1 b_2},$$

$$w_2^{S*} = \left(ko_2 - o_2 - l_2\mu\frac{1}{n_2\delta_2}\right)\tau\frac{2\rho_2{}^S a_2 + \rho_1{}^S a_1 b_2 + b_1 b_2 c_2 + b_2 c_1 - 2c_2}{4 - b_1 b_2}.$$

4.2 Symmetric authorization scenario-AA

When both automakers choose the authorization strategy, they share battery swap market demand with the third-party operator. The equilibrium service price, demand and profit of each participant in the two market segments can be obtained by solving the first-order conditions based on the profit functions, as summarized by the following lemma.

Lemma 2. In the AA case, the equilibrium prices are $r_1^{A*} = \frac{3f+o_{3\mathrm{p}}+2o_1+3t}{3}$, $r_{1,3\mathrm{p}}{}^* = \frac{3f+2o_{3\mathrm{p}}+o_1+3t}{3}$, $r_2^{A*} = \frac{3f+o_{3\mathrm{p}}+2o_2+3t}{3}$, $r_{2,3\mathrm{p}}{}^* = \frac{3f+2o_{3\mathrm{p}}+o_2+3t}{3}$, the equilibrium demands are:

$$\mathrm{h}_1{}^{A*} = \tau\frac{(2\rho_1{}^A a_1 + \rho_2{}^A a_2 b_1 + b_1 b_2 c_1 + b_1 c_2 - 2c_1)(o_{3p} - o_1 + 3t)}{(4 - b_1 b_2)6t},$$

$$\mathrm{h}_{1,3p}{}^* = \tau\frac{(2\rho_1{}^A a_1 + \rho_2{}^A a_2 b_1 + b_1 b_2 c_1 + b_1 c_2 - 2c_1)(o_1 - o_{3p} + 3t)}{(4 - b_1 b_2)6t},$$

$$\mathrm{h}_2{}^{A*} = \tau\frac{(2\rho_2{}^A a_2 + \rho_1{}^A a_1 b_2 + b_1 b_2 c_2 + b_2 c_1 - 2c_2)(o_{3p} - o_2 + 3t)}{(4 - b_1 b_2)6t},$$

$$\mathrm{h}_{2,3p}{}^* = \tau\frac{(2\rho_2{}^A a_2 + \rho_1{}^A a_1 b_2 + b_1 b_2 c_2 + b_2 c_1 - 2c_2)(o_2 - o_{3p} + 3t)}{(4 - b_1 b_2)6t}.$$

and the equilibrium profits are:

$$w_1^{A*} = \left(r_1^{A*} - o_1 - l_1\mu\frac{1}{n_1\delta_1}\right)h_1^{A*} + f h_{1,3p}{}^*,$$

$$w_{1,3p}{}^* = \left(r_{1,3p}{}^* - o_{3p} - l_{3p}\mu\frac{1}{n_{3p}\delta_{3p}} - f\right)h_{1,3p}{}^*,$$

$$w_2^{A*} = \left(r_2^{A*} - o_2 - l_2\mu\frac{1}{n_2\delta_2}\right)h_2^{A*} + f h_{2,3p}{}^*,$$

$$w_{2,3p}{}^* = \left(r_{2,3p}{}^* - o_{3p} - l_{3p}\mu\frac{1}{n_{3p}\delta_{3p}} - f\right)h_{2,3p}{}^*,$$

$$w_{3p}{}^* = w_{1,3p}{}^* + w_{2,3p}{}^*.$$

4.3 Asymmetric scenario-AS

When automaker A chooses the authorization strategy but automaker B chooses the self-operation strategy, the third-party operator only participates in the former's market segment. The equilibrium price, demand and profit of each participant can be found based on the authorization and self-operation profit functions, as summarized by the following lemma.

Lemma 3. In the AS case, the equilibrium prices are $r_1{}^{A*}=\frac{3f+o_{3p}+2o_1+3t}{3}$, $r_{1,3p}{}^{*}=\frac{3f+2o_{3p}+o_1+3t}{3}$, $r_2{}^{S*}=\mathrm{ko}_2$, the equilibrium demands are:

$$h_1{}^{A*}=\tau\frac{(2\rho_1{}^{A}a_1+\rho_2{}^{S}a_2b_1+b_1b_2c_1+b_1c_2-2c_1)(o_{3p}-o_1+3t)}{(4-b_1b_2)6t},$$

$$h_{1,3p}{}^{*}=\tau\frac{(2\rho_1{}^{A}a_1+\rho_2{}^{S}a_2b_1+b_1b_2c_1+b_1c_2-2c_1)(o_1-o_{3p}+3t)}{(4-b_1b_2)6t},$$

$$h_2{}^{S*}=\tau\frac{2\rho_2{}^{S}a_2+\rho_1{}^{A}a_1b_2+b_1b_2c_2+b_2c_1-2c_2}{4-b_1b_2}.$$

and the equilibrium profits are:

$$w_1{}^{A*}=\left(r_1{}^{A*}-o_1-l_1\mu\frac{1}{n_1\delta_1}\right)h_1{}^{A*}+fh_{1,3p}{}^{*},$$

$$w_2{}^{S*}=\left(ko_2-o_2-l_2\mu\frac{1}{n_2\delta_2}\right)\tau\frac{2\rho_2{}^{S}a_2+\rho_1{}^{A}a_1b_2+b_1b_2c_2+b_2c_1-2c_2}{4-b_1b_2},$$

$$w_{3p}{}^{*}=w_{1,3p}{}^{*}=\left(r_{1,3p}{}^{*}-o_{3p}-l_{3p}\mu\frac{1}{n_{3p}\delta_{3p}}-f\right)h_{1,3p}{}^{*}.$$

4.4 Asymmetric scenario-SA

When automaker A chooses the self-operation strategy but automaker B chooses the authorization strategy, the third-party operator only participates in the latter's market segment. The following lemma summarizes the equilibrium price, demand and profit of each participant.

Lemma 4. In the SA case, the equilibrium prices are $r_1{}^{S*}=\mathrm{ko}_1$, $r_2{}^{A*}=\frac{3f+o_{3p}+2o_2+3t}{3}$, $r_{2,3p}{}^{*}=\frac{3f+2o_{3p}+o_2+3t}{3}$, the equilibrium demands are:

$$h_1{}^{S*}=\tau\frac{2\rho_1{}^{S}a_1+\rho_2{}^{A}a_2b_1+b_1b_2c_1+b_1c_2-2c_1}{4-b_1b_2},$$

$$\mathrm{h_2}^{A*} = \tau \frac{(2\rho_2{}^A a_2 + \rho_1{}^S a_1 b_2 + b_1 b_2 c_2 + b_2 c_1 - 2c_2)(o_{3p} - o_2 + 3t)}{(4 - b_1 b_2)6t},$$

$$\mathrm{h}_{2,3p}{}^{*} = \tau \frac{(2\rho_2{}^A a_2 + \rho_1{}^S a_1 b_2 + b_1 b_2 c_2 + b_2 c_1 - 2c_2)(o_2 - o_{3p} + 3t)}{(4 - b_1 b_2)6t}.$$

and the equilibrium profits are:

$$w_1{}^S = \left(ko_1 - o_1 - l_1\mu\frac{1}{n_1\delta_1}\right)\tau\frac{2\rho_1{}^S a_1 + \rho_2{}^A a_2 b_1 + b_1 b_2 c_1 + b_1 c_2 - 2c_1}{4 - b_1 b_2},$$

$$w_2{}^{A*} = \left(r_2{}^{A*} - o_2 - l_2\mu\frac{1}{n_2\delta_2}\right)h_2{}^{A*} + fh_{2,3p}{}^{*},$$

$$w_{3p}{}^{*} = w_{2,3p}{}^{*} = \left(r_{2,3p}{}^{*} - o_{3p} - l_{3p}\mu\frac{1}{n_{3p}\delta_{3p}} - f\right)h_{2,3p}{}^{*}.$$

5. Authorization as the Equilibrium Strategy

Due to the complexity of profit functions, it is difficult to directly compare profit sizes under different battery swap service strategies. Therefore, the method of numeric analysis is used to examine automakers' profit changes under different strategy combinations. Lemmas 1-4 suggest that the profit functions contain common parameters: substitution intensity, EV production cost, and battery swap market demand. By analyzing the impacts of these parameters on the profits of automakers, the best strategy choice can be determined.

This study consults relevant information sources to determine the values of EV production cost and battery swap operating cost. On average, lithium-ion rechargeable batteries cost \$132/kWh, and EV capacity is 60kWh, leading to the approximate subtotal of \$7,000. As batteries typically account for 35% of plug-in EV production cost (excluding the battery cost), the average production cost of a battery-separable EV is \$20,000. A life-cycle analysis shows that the annual operating cost of a battery swap station is about 4.77 million CNY, covering electricity, facility maintenance, and labor (Chen et al., 2016). NIO's second-generation station can serve up to 312 EVs daily, a leap from the first-generation's 120. Assuming the service volume of 240 times per day and station utilization rate of 60% per year, the average operating cost of a single battery swap is about 90 CNY, or \$13.5 (calculated at the exchange rate of 1 USD ≈ 6.7 CNY).

Based on the daily service capacity of each battery swap station and EV service life, a station can serve about 720,000 swaps during that unit period. Based on the scientific notations shown in Table 1 (\$10^5 for l_i and c_i, \$10^2 for o_i, 10^5 for n_i, and 10^2 for μ), respectively, single battery cost, EV marginal cost, battery swap operating cost, and each battery swap station service capability, and battery reserve at each station are: $l_i = 0.07$, $c_i = 0.2$, $o_i = 0.135$, $n_i = 7.2$, and $\mu = 0.1$ (i.e., the number of batteries that each battery swap station reserves is 10, for instance). Other fixed parameters are assigned values as follows: $a_1 = 0.3$, $a_2 = 0.2$, $b_1 = 0.4$, $b_2 = 0.2$, $o_{3p} = 0.12$, $\tau = 1$, $t = 0.03$, $k = 1.4$, $f = 0.024$, ${\rho_i}^S = 1$, ${\rho_i}^A = 1.1$, and $\delta_i = 0.6$.

5.1 EV production cost

As automakers A and B make game choices at the same time, their decisions are independent. As the authorization strategy helps an automaker focus on the EV market while benefit from the battery swap market, it tends to partner with a third-party operator. Figure 2 shows how the changes in the EV production costs of automakers affect their battery swap service strategies by keeping the other parameters in the profit function constant. The solution space is divided into four subregions, each of which corresponds to the optimal choices of two automakers.

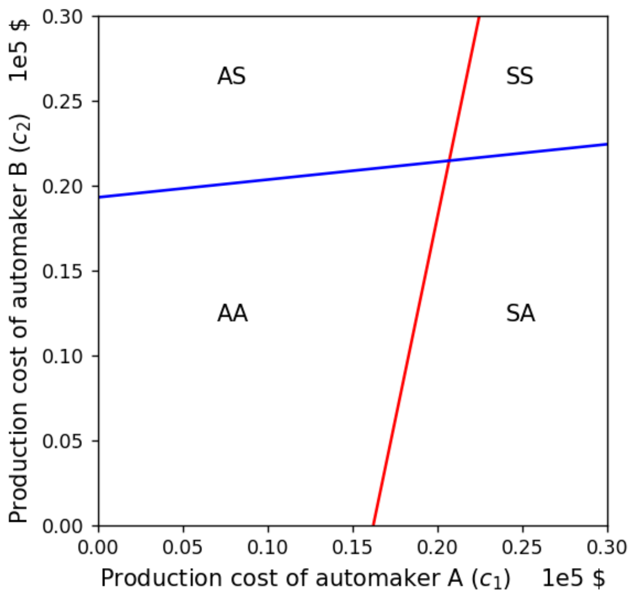


Figure 2. EV production costs and battery swap service strategies

For an automaker, different EV production cost scenarios lead to different strategy choices. When the EV production cost is relatively low, authorization is preferred; otherwise, self-operation is a better choice. A higher cost reduces EV demand, leading to a smaller battery swap market segment that makes the involvement of a third-party operator less necessary. Without the need to share profit in such a case, the self-operation strategy yields more return. In contrast, when an automaker keeps its EV production cost low, the authorization strategy is conducive to battery swap market share expansion and profit margin increase.

In addition, market demand and substitution intensity are also likely to affect battery swap strategies. The subsequent analyses on these two influencing factors follow the same approach as for production cost. If parameter shifts alter corporate profitability levels, automakers are likely to switch strategies to pursue performance improvement.

5.2 EV market demand

Similarly, the results indicate that EV market demands affect battery swap strategy choices of automakers. As shown in Figure 3, when the EV demand of an automaker is high, it will choose the authorization strategy for battery swap service to advance brand influence and profitability. Outsourcing the service to a third-party operator allows the automaker to invest in battery swap technology, increase store accessibility, and enhance consumer loyalty. When the EV market demand is relatively low for an automaker, however, the self-operation strategy saves money and effort.

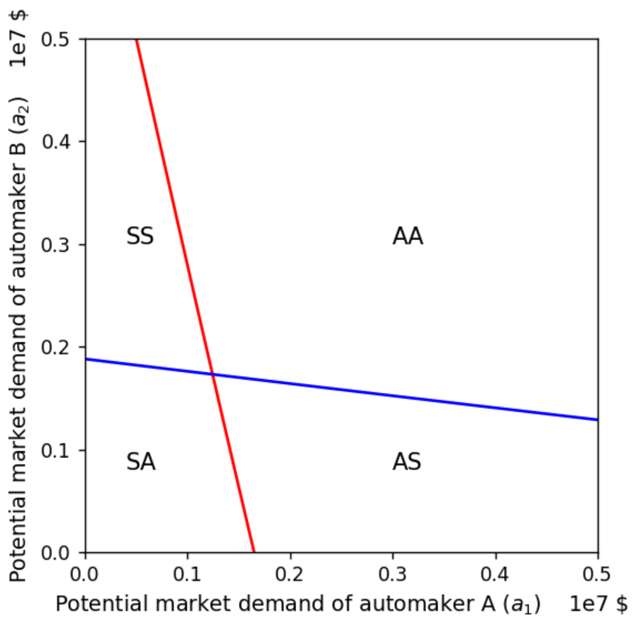
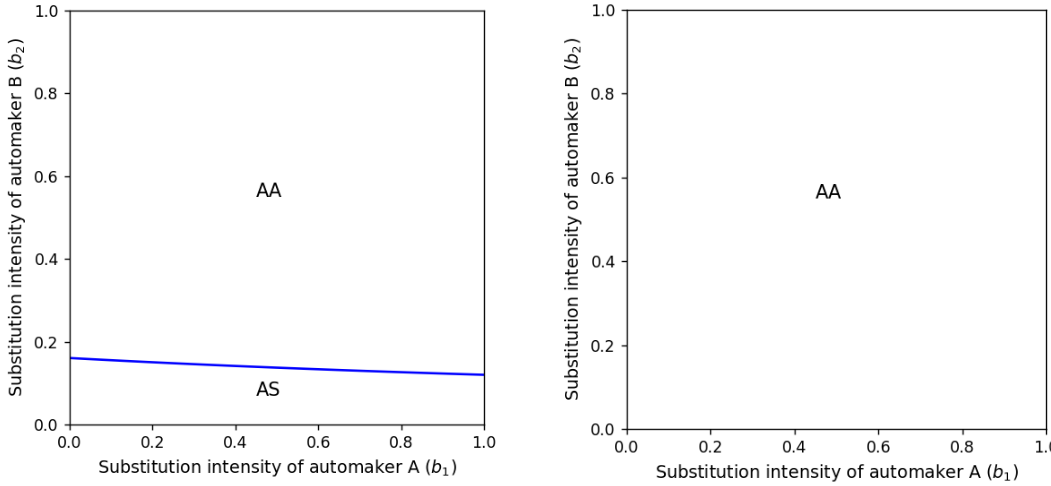


Figure 3. EV market demands and battery swap service strategies

A higher market demand motivates an automaker to choose the authorization strategy, as the active involvement not only increases battery swap market profitability but also expands EV market share. The strategy requires the automaker to continuously invest in the battery swap technology, leading to a faster and cheaper service that attracts more consumers to purchase battery-separable EVs. There are various approaches for boosting up market demand. Through market research, for example, an automaker can design products and services that consumers like to use. It can also partner with other top companies, such as battery manufacturers and fleet operators, to increase brand influence.

5.3 EV substitution intensity

Competition in the battery swap service market is fierce and automaker A has a larger user base. In such an advantageous position, it is likely to choose the authorization battery swap strategy to strengthen its market dominance further. As shown in Figure 4-1, therefore, the variation in EV substitution intensity factors will not affect automaker A's choice of authorization as its battery swap service strategy. For automaker B, however, its EV substitution intensity bears an inverse relationship with the self-operation strategy: the higher intensity factor, the lower chance of self-operation. When automaker B endows its EVs with unique design features that attract and retain consumers, the authorization strategy will help it further expand the loyal user base. Otherwise, it is not worth developing the battery swap technology, and the self-operation strategy is less risky. Considering the scenario that the market shares of two automakers are approximately the same as shown in Figure 4-2, their strategic choices are basically independent of the substitution intensity: they unanimously adopt the authorization strategy for higher profitability.



(1) $a_1 > a_2$ (2) $a_1 = a_2$

Figure 4. EV substitution intensity factors and battery swap service strategies

The competition between automakers is conducive to the healthy development of EV and battery swap markets. Automaker A needs to keep its competitive advantage by continuously investing in R&D, including its battery swap technology. In order to improve overall profitability, automaker B needs to enhance the substitution intensity of its EVs by continuously improving performance, quality, and aesthetics. Based on a sound understanding of consumer needs, both automakers can design better EVs and formulate appropriate marketing strategies. Such consumer-centric product design and marketing must highlight how EVs can bring unique values like convenience and enjoyment to users (Egbue & Long, 2012; Qian & Yin, 2017).

5.4 Battery swap service operating cost

The above analyses suggest that the authorization strategy strikes a balance between battery swap market participation and EV market focus. An automaker can expand its EV market share by authorizing a third-party operator to offer services to consumers in the battery swap market. From the overall profit function, it is clear that the gap in the unit battery swap service operating cost between the technology authorized by an automaker and the third-party operator's own technology will affect the overall profit of the automaker.

Take automaker A as an example, Figure 5 illustrates how the gap in battery swap operating costs affects corporate profitability under the authorization strategy. It can be seen that the profit of automaker A is positively correlated with its relative cost advantage over the third-party operator. Since $|o_{3p} - o_1| < 3t$, the interval range of $o_{3p} - o_1$ is (-0.09, 0.09) assuming $t = 0.03$. At the left limit toward which the automaker is the least cost-efficient (i.e., $o_{3p} - o_1$ =-0.09), the demand for its battery swap service approaches zero, making it a burden to corporate profitability. In such a case, the automaker should rather give up the whole battery swap business but outsource it to the third-party operator. The automaker's battery swap service will turn lucrative when it becomes competitive. Meanwhile, the third-party operator's market share will drop, and its net profit will get eaten away by the licensing fee expenditure.

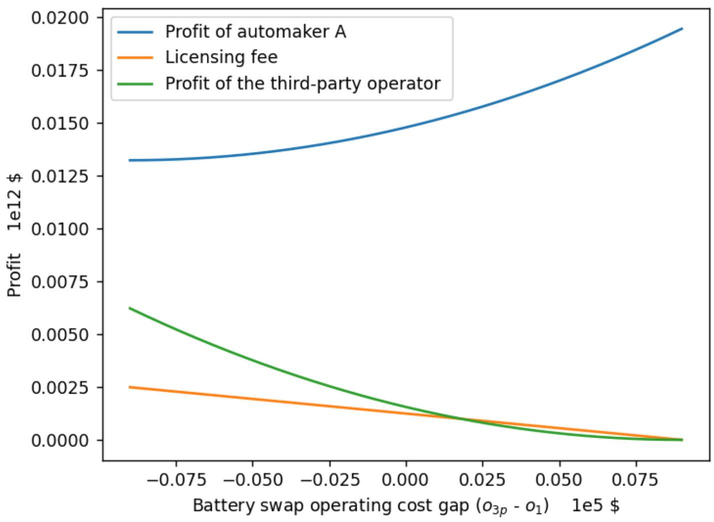


Figure 5. Relative battery swap operating cost and profitability of automaker A.

Thus, automakers and third-party operators can be partners as well as competitors in the battery swap market. Each may decide its role based on relative competitiveness. All else being equal, specialized service providers are generally more cost-efficient. Yet automakers are in a position to upgrade battery swap technologies and take the lead in reducing operating cost. More affordable battery sway service attracts consumers to adopt and use battery-separable EVs. Increasing overall profitability from both EV and battery swap markets, the relatively high battery swap operating cost of capable automakers warrants their authorization strategy.

5.5 Battery reserve size

This section explores how battery reserve varies along with pricing strategies and utilization rates. Using automaker A as an example, Figure 6 gives the numerical estimates. First of all, the battery reserve size of the automaker under the authorization strategy is just shy of half that under the self-operation strategy. Under the authorization strategy, the third-party operator takes care of part of market demand, the automaker may simply cut its battery reserve. Saving a big chunk of battery procurement and maintenance costs, the authorization strategy enhances the automaker's profitability, and outperforms the self-operation strategy in most cases. Secondly, battery reserve size negatively correlates with utilization rate regardless of pricing strategies. When the rate is relatively low at the beginning, automakers and third-party operators have to prepare enough batteries for first-time customers. At 20%, for instance, the automaker needs to set aside around 30,000 batteries under the authorization strategy. As each facility serves more returning customers, the need for extra batteries gradually diminishes.

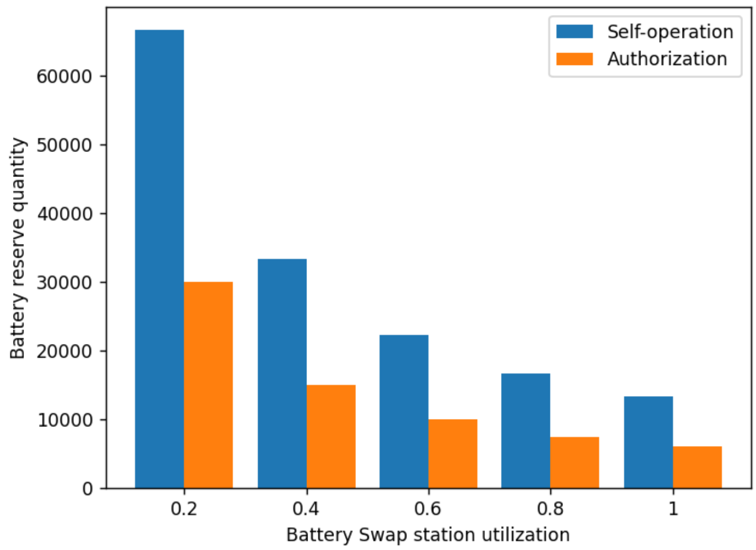


Figure 6. Battery reserve under different pricing strategies and utilization rates

Based on the authorization strategy, Figure 7 further analyzes the shift in market share in terms of the battery reserve ratio between the automaker and third-party operator as the swap service utilization rate increases. Despite the decline from an even split with the third-party operator at the start, the automaker still retains over 40% of battery swap market at its maturity. Striking such a balance, two swap service providers are in a competitive yet collaborative relationship. When the utilization rate of swap stations increases, the third-party operator assumes greater responsibility for battery reserve in terms of capital investment and daily maintenance, and thus becomes an essential link in the industry value chain. In this sense, the authorization strategy provides a win-win solution that is not only mutually beneficial to automakers and third-party operators but also conducive to overall social welfare.

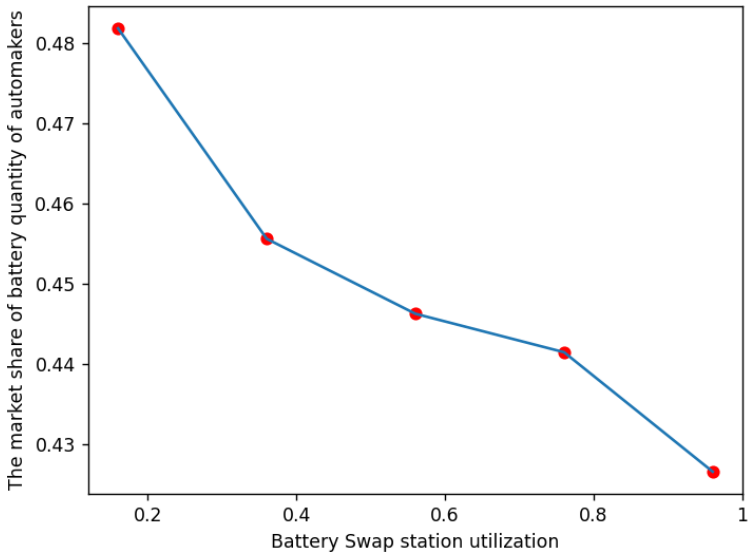


Figure 7. Automaker share of battery reserve under the authorization strategy

6. The Impact of Authorization Strategy on Social Welfare

It is to the benefit of automakers to partner with third-party operators, yet to which extent such collaboration contributes to the overall social welfare is still unknown. This section compares the social welfare with and without the third-party operator to examine the difference it makes. There are four scenarios: both automakers A and B adopt the self-operation strategy (SS); both automakers A and B adopt the authorization strategy (AA); automaker A adopts the self-operation strategy but automaker B adopts the authorization strategy (SA); automaker A adopts the authorization strategy but automaker B adopts the self-operation strategy (AS). Among them, SS is the benchmark scenario corresponding to the self-operation strategy without the third-party operator. The social welfare under the scenario corresponding to each combination of the other strategies involving the third-party operator is compared with the benchmark.

Social welfare (SW) includes consumer surplus (from EV purchase and battery swapping), the overall profit of automakers A and B, and the profit of third-party operator C.

$$SW = CS + \pi_1 + \pi_2 + \pi_{3p}. \tag{22}$$

Consumer surplus from buying products from both automakers in a duopoly is $CS_{ev} = U(q_1, q_2) - p_1 q_1 - p_2 q_2$, where the utility function is $U(q_1, q_2) = \alpha_1 q_1 + \alpha_2 q_2 - \frac{\beta_1 {q_1}^2 + \gamma_1 q_1 q_2 + \gamma_2 q_1 q_2 + \beta_2 {q_2}^2}{2}$ (Singh & Vives, 1984). The utility function produces a linear demand structure,$p_1 = \alpha_1 - \beta_1 q_1 - \gamma_1 q_2$, $p_2 = \alpha_2 - \beta_2 q_2 - \gamma_2 q_1$. From (1),

$$p_1 = \frac{{\rho_1}^m a_1 + {\rho_2}^m a_2 b_1 - b_1 q_2 - q_1}{1 - b_1 b_2}, \tag{23}$$

$$p_2 = \frac{{\rho_2}^m a_2 + {\rho_1}^m a_1 b_2 - b_2 q_1 - q_2}{1 - b_1 b_2}. \tag{24}$$

Therefore, $\alpha_1 = \frac{{\rho_1}^m a_1 + {\rho_2}^m a_2 b_1}{1 - b_1 b_2}$, $\beta_1 = \frac{1}{1 - b_1 b_2}$, $\gamma_1 = \frac{b_1}{1 - b_1 b_2}$, $\alpha_2 = \frac{{\rho_2}^m a_2 + {\rho_1}^m a_1 b_2}{1 - b_1 b_2}$, $\beta_2 = \frac{1}{1 - b_1 b_2}$, $\gamma_2 = \frac{b_2}{1 - b_1 b_2}$.

When there is a third-party operator along with automakers in the market, consumer surplus from battery swapping is ${CS_{bs,i}}^A = \int_0^{\bar{x}} u_i dx + \int_{\bar{x}}^1 u_{i,3p} dx$. In the benchmark case in which only automakers provide the service, the consumer surplus is ${CS_{bs,i}}^S = \int_0^1 u_i dx$. The social welfare under different strategic combinations can be obtained, as shown in Appendix A.

The assignment method for comparative analysis is used for evaluating social welfare. Table 2 lists the 21 parameters that may need to be changed. Each parameter is set with three values (corresponding to columns I, II, Ш). In the process of comparative analysis, one variable remains unchanged, and the others take different values. In order to ensure outcome reliability, a python loop of 3^{11} times evaluated all the 177,147 combinations. Over 99% of them (175,509) outperformed the benchmark case in terms of social welfare. This suggests that the inclusion of third-party operators in a battery swap market is socially beneficial.

Table 2. Parameter setup

Parameter \ Level	I	II	Ш
Δa ($a_1 = 0.5$)	0	0.1	0.2
Δb ($b_1 = 0.4$)	0.1	0	-0.1
Δc ($c_1 = 0.15$)	0.01	0	-0.01
$\Delta o_{3p,2}$ ($o_{3p} = 0.4$)	0.01	0	-0.02
$\Delta o_{3p,1}$ ($o_{3p} = 0.4$)	0.02	0	-0.01
${\rho_i}^S$	1	1	1
${\rho_i}^A$	1.1	1.2	1.3
v	1	1.5	2
t	0.02	0.03	0.04
k	1.5	1.7	2
f	0.02	0.04	0.06
τ	1.4	1.8	2.2
n_1	7.2	7.2	7.2
n_2	7	7	7
n_{3p}	7.5	7.5	7.5
μ	0.1	0.1	0.1
l_1	0.05	0.05	0.05
l_2	0.06	0.06	0.06
l_{3p}	0.055	0.055	0.055
δ_1	0.6	0.6	0.6
δ_2	0.5	0.5	0.5
δ_{3p}	0.7	0.7	0.7

Note: ${\rho_i}^m$ represent the impact of operator C on the potential market demand for EVs of automakers A and B under different strategic combinations. $\Delta o_{3p,i}$ represents the battery swap service operating cost difference between operator C and automaker. Δa represents the EV market demand difference between automakers A and B. Δb represents the substitution intensity difference between automakers A and B. Δc represents the EV production cost difference between automakers A and B.

The inclusion of a third-party operator in the battery swap market is also justified by the recent administrative and industrial trends. For maximizing social welfare, China included the establishment of third-party battery swap stations specifically in its “2020 Government Work Report” (GOV, 2020). In addition, "The New Energy Vehicle (NEV) Industry Development Plan" encourages battery swapping along with charging and hydrogenation for the development of NEV market infrastructure (C. Lin, 2020).

Conducive to their EV market demands, it is a win-win solution for automakers to open the battery swap market to third-party operators. For instance, Geely Technology Group will build 5,000 smart battery swap stations worldwide based on a full-chain open platform that integrates EV manufacturing, battery lifecycle management and battery swap service (florianoconnell, 2021). For automakers, it is not a question of whether to allow third-party operators to enter the market but how to collaborate with them.

7. Model robustness considering an exclusive agreement

The previous modeling is based on the assumption that the third-party operator can cooperate with both automakers. For its EV market dominance, however, automaker A may enter an exclusive agreement with the third-party operator. Whereas automaker A can still choose between authorization and self-operation strategies, automaker B has no choice but self-operation. Therefore, this section examines whether the relationships between influencing factors and automaker A's strategy choice remain largely stable. The updated profit functions of automaker A under self-operation and authorization strategies are as follows:

$$\pi_1{}^S = (p_1{}^{S*} - c_1)q_1{}^{S*} + (ko_1 - o_1)\tau q_1{}^{S*} - l_1\tau q_1{}^{S*}/(n_1 * \delta_1). \qquad (25)$$

$$\pi_1{}^A = (p_1{}^{A*} - c_1)q_1{}^{A*} + (r_1{}^{A*} - o_1)h_1{}^{A*} - l_1 h_1{}^{A*}/(n_1 * \delta_1) + f h_{1,3p}{}^*. \qquad (26)$$

Two functions are compared based on the variations in EV production cost, market demand, and substitution intensity, respectively. Take EV production cost for instance, and Figure 6 shows that it still affects automaker A's choice between authorization and self-operation strategies with the exclusive agreement, in a way close to what Figure 2 illustrates. Similarly, the impacts of EV market demand and substitution intensity on the strategic choice of automaker A remain almost the same (See Appendix B for diagrams). As for the exclusive agreement scenario, therefore, model robustness is supported.

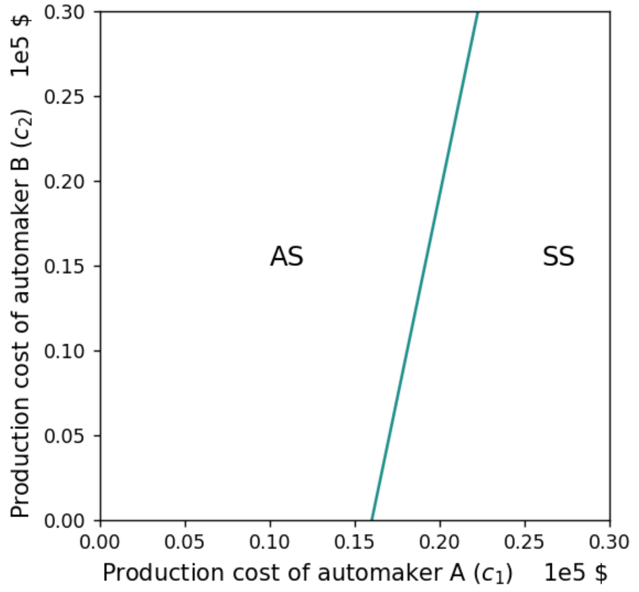


Figure 8. EV production cost and battery swap service strategies of automaker A

8. Conclusion

As battery swap service exhibits great potential, this study explores the service strategies for automakers producing battery-separable EVs to expedite market development. It employs game-theoretical modeling to compare two strategies: self-operation and authorization. Model analyses suggest that the authorization strategy is typically optimal for an automaker to increase its EV market demand and profit from the battery swap market as well. The comparison of social welfare across different strategy combinations also shows the necessity and significance of third-party operators to the healthy development of the battery swap market. The findings yield the following conclusions.

(1) With a highly competitive and substitute battery swap market, partnering with a third-party operator can help automakers gain wider access to the battery swap market and thus increase their EV market share. The results of game-theoretical modeling indicate that when there is a third-party operator in the battery swap market, both automakers are willing to cooperate with it. Under different scenarios, the battery swap service strategies of the two automakers may change accordingly. Whether authorization or self-operation, one automaker's strategic choice is basically independent of the other's. Primary influencing factors include EV production cost,

market demand, and substitution intensity. For both automakers, authorization is a better choice when EV production cost is relatively low and EV market demand is relatively high; otherwise, self-operation is preferred. Meanwhile, EV substitution intensity mainly affects the strategic choice of small market shares (i.e., automaker B). A relatively high level of substitution intensity implies the possibility of expanding the EV market share through battery swap market engagement, leading to the preference for authorization strategy. To maximize the gain from authorization strategy, an automaker needs to develop the battery swap technology of lower operating cost compared with the third-party operator's.

(2) Typically, third-party operators have a cost advantage over automakers due to service specialization. If the gap is too large for some automakers to close, they may let third-party operators take over the battery swap business but focus on the EV market. Nevertheless, capable automakers have the chance to develop sophisticated technologies that lower battery swap operating cost. When this occurs, the automakers enter a game competition with their partnering third-party operators. Such a rivalry is conducive to service process optimization and user experience enhancement, eventually leading to EV market expansion and EV industry advancement. In case of sustained cost advantage, automakers should reduce their licensing fees to support the development of third-party operators.

(3) Based on the development status of battery swap market in terms of service utilization rate, automakers and third-party operators may optimize facility and battery management. This study conducts simulation analyses to assess the battery reserve requirement under different pricing strategy and market status scenarios. Such an approach helps battery swap market participants make strategic and operational decisions. For instance, an automaker may cut battery reserve by choosing the authorization strategy and promoting swap service utilization. The dispersion of capital investments and managerial responsibilities between automakers and third-party operators enhances the healthiness and robustness of battery swap market. Through both cooperation and competition, therefore, different players are likely to maximize

the overall social welfare.

(4) Whether the leading automaker signs an exclusive agreement with a third-party operator or not has little to do with its strategic selection (which is likely authorization). For the purpose of promoting battery swap market development, policy makers should encourage third-party operators to establish a win-win relationship with multiple automakers. In this way, the battery swap service ecosystem becomes healthy and dynamic, accelerating the construction of more battery swap stations in major cities and encouraging more EV consumers to use them.

(5) Numerical simulations show that engaging third-party operators in the battery swap market almost always enhances overall social welfare. Policymakers should encourage more of them to run battery swap stations with all kinds of support. In China, for instance, the government keeps track of battery swap development and provides financial and regulatory incentives. Market leaders including NIO, Geely, Aodong New Energy, and Sinopec set up ambitious goals to build a total of 24,000 battery swap stations by 2025. Together, policy support and capital investment broaden the prospect of battery swap industry.

At present, there are still major obstacles to overcome, and the government can play a critical role in the process. In particular, automakers have incompatible battery standards and are generally unwilling to share technical details, making it hard for a third-party operator to service the EVs of different brands. Relevant administrative agencies may provide guidance on battery swap standardization. They can give it a jump start by working with automakers like NIO and Aodong, which are vigorously promoting battery-separable EVs for taxi and ride-hailing drivers. It is likely that other automakers will join the alliance later and produce compatible EVs for private consumers as well.

Although EV charging is still the mainstream, battery swapping is gaining popularity due to its advantages in resource conservation and environment-friendliness. The centralized and closed-loop battery management enables battery recycling and cascade utilization, preventing waste batteries from polluting the environment.

Compared with EV charging, battery swapping also allows battery charging during off-peak hours, reducing electricity cost as well as grid load. The potential increase of social welfare from multiple folds is motivating policy makers to promote the development of the battery swap market with means like standardization. In addition, the emerging battery swap market provides automakers an opportunity for sales-service integration. With car-battery separation, consumers make a much lower payment in the front, and rent batteries based on usage. Automakers may create new payment schemes to attract more consumers, such as bundling network access and swap service price into one discount package (e.g., 20% off for 50 swaps). The joint effort from both policy makers and industry leaders will speed up the development of the battery swap market while keeping it healthy and sustainable.

This study has limitations that point to future research directions. First of all, the findings are more directly applicable to similar EV markets to that in China. More effort is needed to examine potential business models of battery swap service in different markets in terms of perfect competition, monopolistic competition, oligopoly, and pure monopoly. Secondly, it only includes the partnership between an automaker and a third-party operator without considering the collaboration between two automakers. It is possible that the two automakers and third-party operators form an alliance to work with each other, which requires further analysis. Finally, it does not examine the impacts of subsidization on battery swap service strategizing and social welfare: subsidy policies targeting consumers, automakers and providers are likely to yield different outcomes. To make the analyses more realistic, future studies may include multiple automakers in a polyopoly market as well. In this way, the results can be compared with this study's, which serves as the benchmark due to the lack of prior research.

Appendix A

1. Social welfare when both automakers A and B adopt the self-operation strategy. $SW^{SS} = \sum_{i=1}^{2} \pi_i + CS_{ev} + \sum_{i=1}^{2} CS_{bs,i}{}^{S}$. Where $\pi_i = (p_i - c_i)q_i + (ko_i - o_i)\tau q_i -$

$l_i \mu \tau q_i/(n_i \delta_i)$, $\quad CS_{bs,i}{}^S = \int_0^1 (v - ko_i - tx)dx$.

2. Social welfare when both automakers A and B adopt the authorization strategy.

$SW^{AA} = \sum_{i=1}^{2} \pi_i + \pi_{3p} + CS_{ev} + \sum_{i=1}^{2} CS_{bs,i}{}^A + CS_{bs,3p}$.Where $\pi_i = (p_i - c_i)q_i + (r_i - o_i)h_i - \frac{l_i \mu h_i}{n_i \delta_i} + fh_{i,3p}$,$\pi_{3p} = \sum_{i=1}^{2}\left(r_{i,3p} - o_3\right)h_{i,3p} - fh_{i,3p} - \frac{l_{3p}\mu h_{i,3p}}{n_{3p}\delta_{3p}}$,

$CS_{bs,i}{}^A = \int_0^{\frac{r_{i,3p}-r_i+t}{2t}} (v - r_i - tx)dx$,$CS_{bs,3p} = \int_{\frac{r_{1,3p}-r_1+t}{2t}}^{1} (v - r_{1,3p} - t(1-x))dx + \int_{\frac{r_{2,3p}-r_2+t}{2t}}^{1} (v - r_{2,3p} - t(1-x))dx$.

3. Social welfare when automaker A adopts the self-operation strategy while automaker B adopts the authorization strategy. $SW^{SA} = \sum_{i=1}^{2} \pi_i + \pi_{3p} + CS_{ev} + CS_{bs,1}{}^S + CS_{bs,2}{}^A + CS_{bs,3p}$. Where $\pi_i = (p_1 - c_1)q_1 + (ko_1 - o_1)\tau q_1 - \frac{l_1 \mu \tau q_1}{n_1 \delta_1}$, $\pi_2 = (p_2 - c_2)q_2 + (r_2 - o_2)h_2 - \frac{l_2 \mu h_2}{n_2 \delta_2} + fh_{2,3p}$, $\pi_{3p} = \left(r_{2,3p} - o_3\right)h_{2,3p} - fh_{2,3p} - \frac{l_{3p}\mu h_{2,3p}}{n_{3p}\delta_{3p}}$,

$CS_{bs,1}{}^S = \int_0^1 (v - ko_1 - tx)dx$, $CS_{bs,2}{}^A = \int_0^{\frac{r_{2,3p}-r_2+t}{2t}} (v - r_2 - tx)dx$, $CS_{bs,3p} = \int_{\frac{r_{2,3p}-r_2+t}{2t}}^{1} (v - r_{2,3p} - t(1-x))dx$.

4. Social welfare when automaker A adopts the authorization strategy while automaker B adopts the self-operation strategy. $SW^{AS} = \sum_{i=1}^{2} \pi_i + \pi_{3p} + CS_{ev} + CS_{bs,1}{}^A + CS_{bs,2}{}^S + CS_{bs,3p}$. Where $\pi_1 = (p_1 - c_1)q_1 + (r_1 - o_1)h_1 - l_1 \mu \frac{h_1}{n_1 \delta_1} + fh_{1,3p}$, $\pi_2 = (p_2 - c_2)q_2 + (ko_2 - o_2)\tau q_2 - l_2 \mu \frac{\tau q_2}{n_2 \delta_2}$, $\pi_3 = \left(r_{1,3p} - o_3\right)h_{1,3p} - l_{3p}\mu \frac{h_{1,3p}}{n_{3p}\delta_{3p}}$ $-fh_{1,3p}$, $\quad CS_{bs,1}{}^A = \int_0^{\frac{r_{1,3p}-r_1+t}{2t}} (v - r_1 - tx)dx$, $\quad CS_{bs,2}{}^S = \int_0^1 (v - ko_2 - tx)dx$, $CS_{bs,3p} = \int_{\frac{r_{1,3p}-r_1+t}{2t}}^{1} (v - r_{1,3p} - t(1-x))dx$.

Note: $CS_{\text{ev}} = \alpha_1 q_1 + \alpha_2 q_2 - \frac{\beta_1 q_1{}^2 + \gamma_1 q_1 q_2 + \gamma_2 q_1 q_2 + \beta_2 q_2{}^2}{2} - p_1 q_1 - p_2 q_2$, $\beta_1 = \frac{1}{1-b_1 b_2}$, $\alpha_1 = \frac{\rho_1{}^m a_1 + \rho_2{}^m a_2 b_1}{1-b_1 b_2}$, $\gamma_1 = \frac{b_1}{1-b_1 b_2}$, $\alpha_2 = \frac{\rho_2{}^m a_2 + \rho_1{}^m a_1 b_2}{1-b_1 b_2}$, $\beta_2 = \frac{1}{1-b_1 b_2}$, $\gamma_2 = \frac{b_2}{1-b_1 b_2}$.

Appendix B

The remaining results corresponding to the extensions (Section 7).

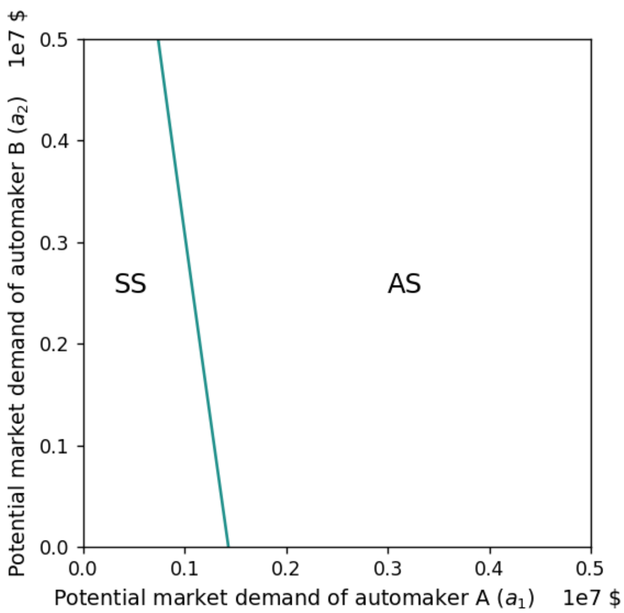


Figure B-1. EV market demand and battery swap strategy of automaker A.

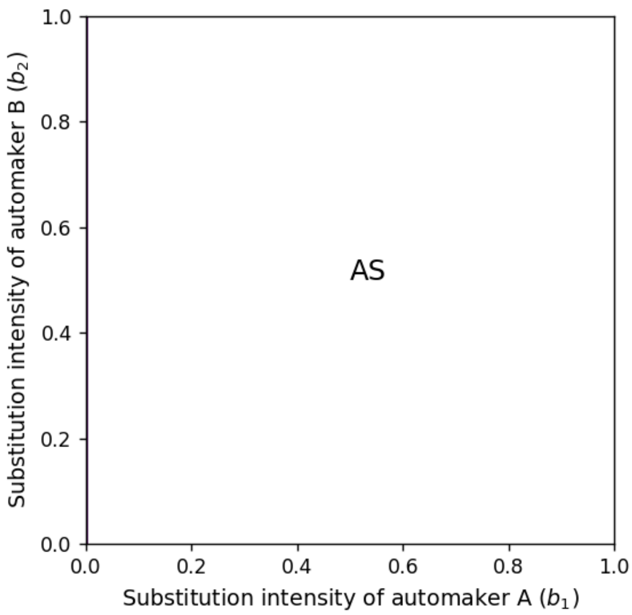


Figure B-2. EV substitution intensity and battery swap strategy of automaker A.

References

A., F., A., M. S., A., I. S., & S., S. M. (2020). Battery swapping station for electric vehicles: opportunities and challenges. *IET Smart Grid, 3*(3), 280-286. doi:http://doi.org/10.1049/iet-stg.2019.0059

An, K., Jing, W., & Kim, I. (2020). Battery-swapping facility planning for electric buses with local charging systems. *INTERNATIONAL JOURNAL OF SUSTAINABLE TRANSPORTATION, 14*(7), 489-502. doi:https://doi.org/10.1080/15568318.2019.1573939

Asadi, A., & Pinkley, S. N. (2021). A stochastic scheduling, allocation, and inventory replenishment problem for battery swap stations. *Transportation Research Part E: Logistics and Transportation Review, 146*. doi:https://doi.org/10.1016/j.tre.2020.102212

Ayad, A., El-Taweel, N. A., & Farag, H. E. Z. (2021). Optimal Design of Battery Swapping-Based

Electrified Public Bus Transit Systems. *IEEE TRANSACTIONS ON TRANSPORTATION ELECTRIFICATION, 7*(4), 2390-2401. doi:https://doi.org/10.1109/TTE.2021.3083106

Beranek, M., & Buscher, U. (2020). Optimal price and quality decisions of a supply chain game considering imperfect quality items and market segmentation. *Applied Mathematical Modelling*. doi:https://doi.org/10.1016/j.apm.2020.10.034

Chen, G. K., Qu, D. P., Hu, X. J., Zhang, H. C., Hu, Z. C., & Wang, K. (2016). Cost Benefit Evaluation of Electric Vehicle Charging / SwappingStation Based on Life Cycle Analysis. *Electric Power Construction, 37*(1), 30-37.

ChinaDaily. (2021a). Battery swaps could boost EV adoption, say industry experts. Retrieved from http://www.ecns.cn/business/2021-05-17/detail-ihamkxtn4492251.shtml

ChinaDaily. (2021b). Oil giant teams up with Aulton to build battery swap stations. Retrieved from http://global.chinadaily.com.cn/a/202111/15/WS6191a703a310cdd39bc7548d.html

Daniel. (2010). Germany Starts National Electric Mobility Platform. Retrieved from https://www.autoevolution.com/news/germany-starts-national-electric-mobility-platform-19976.html

David. (2017). An EV for the City: Swappable Batteries Expand Range of Possibilities. Retrieved from http://www.cleantechconcepts.com/2017/05/an-ev-for-the-city-swappable-batteries-expand-range-and-opportunities/

Deepak, S. (2020). SUN Mobility will set up 100 EV battery Swap Points by the end of 2021. Retrieved from https://bwm.world/electric-vehicle-startups/sun-mobility-100-ev-battery-swap-points-2021-402/

Egbue, O., & Long, S. (2012). Barriers to widespread adoption of electric vehicles: An analysis of consumer attitudes and perceptions. *Energy Policy, 48*, 717-729. doi:https://doi.org/10.1016/j.enpol.2012.06.009

Eva, F. (2020). Tesla includes third-party charging stations in car navigation. Retrieved from https://www.tesmanian.com/blogs/tesmanian-blog/tesla-includes-third-party-charging-stations-in-car-navigation

EVreporter. (2019). Battery Swapping - A Pragmatic Complement to EV Charging. Retrieved from https://evreporter.com/battery-swapping/

florianoconnell. (2021). Geely Holding is focusing on 5,000 battery replacement stations worldwide by 2025. Retrieved from https://autobala.com/geely-holding-is-focusing-on-5000-battery-replacement-stations-worldwide-by-2025/191465/

Franz. (2021). Renault mulls introducing battery-swapping in its electric vehicles. Retrieved from https://newenergyreport.com/2021-05-25-renault-introduces-battery-swapping-electric-vehicles.html

Gasgoo. (2019). Xpeng Motors, charging operator TELD start operation of first co-built supercharger station. Retrieved from https://autonews.gasgoo.com/china_news/70016397.html

Geely. (2021). Geely Auto Group Unveils Smart Geely 2025 Strategy. Retrieved from http://zgh.com/media-center/news/2021-11-01/?lang=en

GOV. (2020). Report on the work of the Government. Retrieved from http://www.gov.cn/guowuyuan/zfgzbg.htm

Hotelling, H. (1929). Stability in competition. *Economic Journal, 153*(39), 41-57. doi:https://doi.org/10.2307/2224214

Huang, A. Q., Zhang, Y. Q., He, Z. F., Hua, G. W., & Shi, X. L. (2021). Recharging and transportation scheduling for electric vehicle battery under the swapping mode. *ADVANCES IN PRODUCTION ENGINEERING & MANAGEMENT, 16*(3), 359-371. doi:https://doi.org/10.14743/apem2021.3.406

Huang, F. H. (2020). Understanding user acceptance of battery swapping service of sustainable transport: An empirical study of a battery swap station for electric scooters, Taiwan. *INTERNATIONAL JOURNAL OF SUSTAINABLE TRANSPORTATION, 14*(4), 294-307. doi:https://doi.org/10.1080/15568318.2018.1547464

Jing, W. T., Kim, I., & An, K. (2018). The Uncapacitated Battery Swapping Facility Location Problem with Localized Charging System Serving Electric Bus Fleet. *Transportation Research Procedia, 34*, 227-234. doi:https://doi.org/10.1016/j.trpro.2018.11.036

Jonathan. (2021). This startup has an intriguing concept for EV battery swaps. Retrieved from https://arstechnica.com/cars/2021/03/this-startup-has-an-intriguing-concept-for-ev-battery-swaps/

Li, B. A., Geng, Y., Xia, X. Q., Qiao, D., & Wang, H. (2021). Comparatively Analyzing the Impact of Government Subsidy and Carbon Tax Policy on Authorized Remanufacturing. *INTERNATIONAL JOURNAL OF ENVIRONMENTAL RESEARCH AND PUBLIC HEALTH, 18*(16). doi:https://doi.org/10.3390/ijerph18168293

Li, W. X., Li, Y., Deng, H. P., & Bao, L. (2018). Planning of Electric Public Transport System under Battery Swap Mode. *SUSTAINABILITY, 10*(7). doi:https://doi.org/10.3390/su10072528

Li, Y. G., Sun, C. H., Ling, H. F., Lu, A., & Liu, Y. Z. (2020). Oligopolies price game in fractional order system. *Chaos, Solitons & Fractals, 132*, 109583. doi:https://doi.org/10.1016/j.chaos.2019.109583

Liang, Y. N., & Zhang, X. P. (2018). Battery swap pricing and charging strategy for electric taxis in China. *ENERGY, 147*, 561-577. doi:https://doi.org/10.1016/j.energy.2018.01.082

Lin, C. (2020). The State Council executive meeting passed the "New Energy Automobile Industry Development Plan". Retrieved from https://www.cenews.com.cn/company/202010/t20201016_960407.html

Lin, M. D., Liu, P. Y., Yang, M. D., & Lin, Y. H. (2021). Optimized allocation of scooter battery swapping station under demand uncertainty. *Sustainable Cities and Society, 71*, 102963. doi:https://doi.org/10.1016/j.scs.2021.102963

Liu, N. A., Lin, X. H., Chen, Q. F., Zou, F. Q., & Chen, Z. (2017). Optimal Configuration for Batteries and Chargers in Battery Switch Station Considering Extra Waiting Time of Electric Vehicles. *JOURNAL OF ENERGY ENGINEERING, 143*(1). doi:https://doi.org/10.1061/(ASCE)EY.1943-7897.0000389

Lora, K. (2021). Ample is trying to make battery swapping for EVs a reality, starting with Uber drivers in the Bay Area. Retrieved from https://www.cnbc.com/2021/03/03/ample-opens-5-ev-battery-swapping-stations-for-bay-area-uber-drivers.html

Luo, J. J., & Moschini, G. C. (2019). Pass-through of the policy-induced E85 subsidy: Insights from Hotelling's model. *Energy Economics, 84*, 104478. doi:https://doi.org/10.1016/j.eneco.2019.104478

Mark, K. (2021). China: NIO Reports 4 Millionth EV Battery Swap. Retrieved from https://insideevs.com/news/537644/nio-4-million-battery-swaps/

Nie, Y., Chung, C. Y., Chen, L., Wang, X., & Qin, M. (2014, 27-31 July 2014). *Inventory management of DSCC system via improved (s, S) model.* Paper presented at the 2014 IEEE PES General

Meeting | Conference & Exposition, National Harbor, MD, USA.

Nora. (2021). Nio presents next-gen battery swap station with Sinopec. Retrieved from https://www.electrive.com/2021/04/15/nio-presents-next-gen-battery-swap-station-with-sinopec/

Phate, Z. (2021). China's Battery Swap National Standard Set to Go into Effect on November 1, 2021. Retrieved from https://equalocean.com/news/2021051116233

Prnewswire. (2021). YKC Charging Promotes 3-in-1 SaaS Platforms For the Charging Station Industry. Retrieved from https://www.prnewswire.com/news-releases/ykc-charging-promotes-3-in-1-saas-platforms-for-the-charging-station-industry-301385410.html

Promeet. (2020). SUN Mobility To Set Up 100 Battery Swap Points In Bengaluru: Read More About It. Retrieved from https://www.drivespark.com/four-wheelers/2020/sun-mobility-to-set-up-100-battery-swap-points-in-bengaluru-read-more-about-it-033182.html

Qian, L. X., & Yin, J. L. (2017). Linking Chinese cultural values and the adoption of electric vehicles: The mediating role of ethical evaluation. *Transportation Research Part D: Transport and Environment, 56*, 175-188. doi:https://doi.org/10.1016/j.trd.2017.07.029

Raustad, R. (2017). *Electric vehicle life cycle cost analysis*. Retrieved from https://rosap.ntl.bts.gov/view/dot/31875

Revankar, S. R., & Kalkhambkar, V. N. (2021). Grid integration of battery swapping station: A review. *JOURNAL OF ENERGY STORAGE, 41*. doi:https://doi.org/10.1016/j.est.2021.102937

Schneider, F., Thonemann, U. W., & Klabjan, D. (2018). Optimization of Battery Charging and Purchasing at Electric Vehicle Battery Swap Stations. *TRANSPORTATION SCIENCE, 52*(5), 1211-1234. doi:https://doi.org/10.1287/trsc.2017.0781

Sepetanc, K., & Pandzic, H. (2020). A Cluster-Based Operation Model of Aggregated Battery Swapping Stations. *IEEE TRANSACTIONS ON POWER SYSTEMS, 35*(1), 249-260. doi:https://doi.org/10.1109/TPWRS.2019.2934017

Singh, N., & Vives, X. (1984). Price and Quantity Competition in a Differentiated Duopoly. *RAND Journal of Economics, 15*(4), 546-554. doi:https://doi.org/10.2307/2555525

Sun, B., Sun, X., Tsang, D. H. K., & Whitt, W. (2019). Optimal battery purchasing and charging strategy at electric vehicle battery swap stations. *European Journal Of Operational Reserch, 279*(2), 524-539. doi:https://doi.org/10.1016/j.ejor.2019.06.019

Sun, B., Tan, X. Q., & Tsang, D. H. K. (2018). Optimal Charging Operation of Battery Swapping and Charging Stations With QoS Guarantee. *IEEE TRANSACTIONS ON SMART GRID, 9*(5), 4689-4701. doi:https://doi.org/10.1109/TSG.2017.2666815

Tan, X. Q., Sun, B., Wu, Y., & Tsang, D. H. K. (2018). Asymptotic performance evaluation of battery swapping and charging station for electric vehicles. *PERFORMANCE EVALUATION, 119*, 43-57. doi:https://doi.org/10.1016/j.peva.2017.12.004

Tesla. (2013). Battery Swap Event : Full Charge In 90 Seconds. Retrieved from https://www.tesla.com/videos/battery-swap-event

Tom. (2021). Geely's first model that supports battery swap in 60 seconds goes on sale. Retrieved from https://cnevpost.com/2021/03/10/geelys-first-model-that-supports-battery-swap-in-60-seconds-goes-on-sale/

Vallera, A. M., Nunes, P. M., & Brito, M. C. (2021). Why we need battery swapping technology. *Energy Policy, 157*. doi:https://doi.org/10.1016/j.enpol.2021.112481

W, T. H., P, G. K. H., C, K. L., & L, H. Y. (2015, 14-17 June 2015). *An optimization model for a battery* *swapping station in Hong Kong*. Paper presented at the 2015 IEEE Transportation Electrification Conference and Expo (ITEC), Dearborn, MI, USA.

Wang, R. T., Li, X. M., Xu, C. B., & Li, F. Y. (2020). Study on location decision framework of electric vehicle battery swapping station: Using a hybrid MCDM method. *Sustainable Cities and Society, 61*, 102149. doi:https://doi.org/10.1016/j.scs.2020.102149

Weidenbaum, M. (2005). Outsourcing: Pros and cons. *Business Horizons, 48*(4), 311-315. doi:https://doi.org/10.1016/j.bushor.2004.11.001

Widrick, R. S., Nurre, S. G., & Robbins, M. J. (2018). Optimal Policies for the Management of an Electric Vehicle Battery Swap Station. *TRANSPORTATION SCIENCE, 52*(1), 59-79. doi:https://doi.org/10.1287/trsc.2016.0676

Wu, H., Pang, G. K. H., Choy, K. L., & Lam, H. Y. (2018). An Optimization Model for Electric Vehicle Battery Charging at a Battery Swapping Station. *IEEE TRANSACTIONS ON VEHICULAR TECHNOLOGY, 67*(2), 881-895. doi:https://doi.org/10.1109/TVT.2017.2758404

Xi, X., & Zhang, J. X. (2020). Complexity analysis of a decision-making game concerning governments and heterogeneous agricultural enterprises with bounded rationality. *Chaos, Solitons & Fractals, 140*, 110220. doi:https://doi.org/10.1016/j.chaos.2020.110220

Xing, M. Q. (2014). On the optimal choices of R&D risk in a market with network externalities. *Economic Modelling, 38*, 71-74. doi:https://doi.org/10.1016/j.econmod.2013.12.024

Xpeng. (2021). Third-party Charging Networks. Retrieved from https://en.xiaopeng.com/charging.html

Yang, X., Shao, C. F., Zhuge, C. X., Sun, M. D., Wang, P. X., & Wang, S. Q. (2021). Deploying battery swap stations for shared electric vehicles using trajectory data. *Transportation Research Part D: Transport and Environment, 97*, 102943. doi:https://doi.org/10.1016/j.trd.2021.102943

Zeng, M., Pan, Y., Zhang, D., Lu, Z., & Li, Y. (2019). Data-Driven Location Selection for Battery Swapping Stations. *IEEE Access, 7*, 133760-133771. doi:http://doi.org/10.1109/ACCESS.2019.2941901

Zhang, F., Yao, S. J., Zeng, X. K., Yang, P., Zhao, Z. L., Lai, C. S., & Lai, L. L. (2021). Operation Strategy for Electric Vehicle Battery Swap Station Cluster Participating in Frequency Regulation Service. *PROCESSES, 9*(9). doi:https://doi.org/10.3390/pr9091513

Zhang, J., Wang, Z. Y., & Zhao, H. J. (2020). The Impact of Consumer Subsidy on Green Technology Innovations for Vehicles and Environmental Impact. *INTERNATIONAL JOURNAL OF ENVIRONMENTAL RESEARCH AND PUBLIC HEALTH, 17*, 7518. doi:https://doi.org/10.3390/ijerph17207518

Zhang, T. Y., Chen, X., Yu, Z., Zhu, X. Y., & Shi, D. (2018). A Monte Carlo Simulation Approach to Evaluate Service Capacities of EV Charging and Battery Swapping Stations. *IEEE TRANSACTIONS ON INDUSTRIAL INFORMATICS, 14*(9), 3914-3923. doi:https://doi.org/10.1109/TII.2018.2796498

Zhang, X. P., & Rao, R. (2016). A Benefit Analysis of Electric Vehicle Battery Swapping and Leasing Modes in China. *EMERGING MARKETS FINANCE AND TRADE, 52*(6), 1414-1426. doi:https://doi.org/10.1080/1540496X.2016.1152798

Zhang, Y. M., Chen, W. D., & Li, Q. R. (2021). Third-party remanufacturing mode selection for a capital-constrained closed-loop supply chain under financing portfolio. *Computers & Industrial Engineering, 157*. doi:https://doi.org/10.1016/j.cie.2021.107315

Zhao, G., Guo, J., & Qiang, H. (2017). Research on SFLA-Based Bidirectional Coordinated Control Strategy for EV Battery Swapping Station. *CMC-Computers, Materials & Continua, 53*(4), 343-356.

Zhou, B. H., & Tan, F. (2018). Electric vehicle handling routing and battery swap station location optimisation for automotive assembly lines. *INTERNATIONAL JOURNAL OF COMPUTER INTEGRATED MANUFACTURING, 31*(10), 978-991. doi:https://doi.org/10.1080/0951192X.2018.1493229

Zhou, Q., Meng, C., & Yuen, K. F. (2021). Remanufacturing authorization strategy for competition among OEM, authorized remanufacturer, and unauthorized remanufacturer. *INTERNATIONAL JOURNAL OF PRODUCTION ECONOMICS, 242*. doi:https://doi.org/10.1016/j.ijpe.2021.108295

Zou, Z. B., Wang, J. J., Deng, G. S., & Chen, H. Z. (2016). Third-party remanufacturing mode selection: Outsourcing or authorization? *Transportation Research Part E: Logistics and Transportation Review, 87*, 1-19. doi:https://doi.org/10.1016/j.tre.2015.12.008