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Battery as a Service versus Complete Vehicle Sales: A Perspective of Consumer Resale Anxiety

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Abstract

Battery-as-a-Service (BaaS) strategy is viewed as a promising solution to alleviate consumer anxiety about the future depreciation of electric vehicles (EVs). This sales strategy involves leasing batteries rather than selling them outright, thereby mitigating the negative impact of rapid battery depreciation on vehicle value. This paper develops a game-theoretic model to investigate the impact of BaaS on competition between electric and fuel vehicles. The profit-maximizing EV manufacturer chooses between the Complete-Vehicle-Sales (CVS) strategy and the BaaS strategy. Our analysis yields three main findings. First, to enhance profits through BaaS over CVS, an EV manufacturer must ensure that the EV depreciation rate with BaaS is at least slightly lower than with CVS. Achieving higher EV sales under BaaS compared to CVS requires a further reduction in depreciation. Second, a win-win situation for both vehicle manufacturers occurs if the EV depreciation rate under BaaS is reduced to a moderate level. Considering additional battery acquisitions in BaaS can result in a mutually beneficial outcome for the three parties, including the battery supplier. Third, a lower depreciation rate can increase consumer surplus, but it does not always benefit the environment, as it may lead to higher overall vehicle purchases and usage in the market.

Index Terms

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Supply chain management, BaaS, CVS, Resale anxiety, Battery swapping.

Managerial Relevance Statement: An innovative sales strategy, BaaS, which relies on battery-swapping technology and a battery leasing model, can effectively mitigate EVs' competitive disadvantages in terms of market value retention; however, it imposes high costs on EV manufacturers. This paper provides strategic support for BaaS's viability by examining it from the perspective of consumers' resale anxiety and identifying the circumstances under which this arises. In addition, since BaaS can shift energy replenishment to non-peak hours, its adoption also has positive implications for grid energy storage, potentially further optimizing carbon efficiency. To realize the BaaS model's full potential, a combined effort from industry and policymakers is crucial to jointly address and overcome its cost challenges. Policymakers can promote broader market participation by fostering an open industry environment or by providing direct investment and subsidies for companies adopting the BaaS model, thereby easing their financial challenges. These insights serve to guide sales practices in the electric vehicle industry. This paper also contributes to SDG 13.

I. Introduction

A. *Background and Motivation*

The global electric vehicle (EV) market has experienced rapid growth in recent years, establishing itself as a formidable competitor to traditional fuel vehicles (FVs). According to the Global EV Outlook 2024 released by the International Energy Agency (IEA), between 2018 and 2023, EV sales increased from 2% to 18% of the global vehicle market, with China exceeding 30% and projected to surpass 50% soon [1]. Market competition between EV and FV will continue for some time in the foreseeable future [2], [3]. The FV market in China decreased by 8% in 2023, while the overall market grew by 5%, driven by EV growth [1]. China's new energy vehicle retail penetration rate reached 47.6% in 2024, nearly matching that of FVs.[1]

Despite rapid market growth, two key consumer concerns, known as *range anxiety* and *resale anxiety*, constrain the broader adoption of EVs [4]. Existing studies primarily focus on range

[1] https://www.199it.com/archives/1743685.html (Accessed on March 4, 2025)

anxiety for EVs [5]–[7], while resale anxiety, although widely recognized, remains insufficiently explored. Resale anxiety refers to consumers' concern about the rapid depreciation rate of their EVs [4]. For durable goods such as cars, consumers consider their future value when making a purchase decision, and the loss in value is a crucial component of the total cost over the vehicle's lifetime [8]. Data from a British second-hand car service indicate that from 2020 to 2023, the average depreciation rate of FVs was 37%, while that of EVs was as high as 51% [9]. EVs typically depreciate faster than FVs, which in turn makes resale anxiety more pronounced in this context [1]. The primary factor contributing to the disparate depreciation rates observed between EVs and FVs is the battery, one of the most expensive components in an EV [10]. Performance concerns about EV batteries have reduced the resale value of EVs in the second-hand market [11]. Although some manufacturers offer replacement services, the high cost —currently exceeding 30% of the price of a new vehicle —makes few people choose to replace their batteries.[2] The mismatch between battery life and vehicle lifespan [12], along with potential high replacement costs, results in a higher depreciation rate for the entire vehicle. For durable goods, it is a common practice to separate ownership of the product [13]. Consequently, several battery-based operational strategies have emerged that can significantly impact the attractiveness of EVs. Among these, the Battery-as-a-Service (BaaS) strategy is arguably the most prominent.

Battery-as-a-Service combines battery-swapping technology with a subscription-based model of battery ownership [14]. In 2020, NIO, a leading Chinese EV manufacturer, introduced BaaS in the Chinese market to reshape the EV sales model. Under BaaS, consumers can purchase EVs without batteries and lease batteries from the battery supplier. Separation of ownership can help maintain vehicle performance and residual value, alleviating widespread consumer concerns about battery degradation [15]. NIO's statement suggests that BaaS will assist EVs in maintaining their value more effectively,[3] thereby resolving the long-standing challenges for EV penetration [16]. According to a McKinsey report, EVs with battery-swapping technology can retain up to

[2]https://www.recurrentauto.com/research/costs-ev-battery-replacement (Accessed on February 1, 2025).

[3]Statistical data indicate that the residual values of NIO vehicles have risen following the introduction of BaaS, consistently surpassing EV industry averages. For instance, the ES8 model's residual value improved by 6.51% in 2021, following the launch of BaaS in 2020, and maintained a 16.76% lead above the industry average by 2024. See Appendix D for detailed information.

78.2% of their value after 1 year, while those without such technology retain only 70.9%.[4]

However, battery swapping is an expensive mode, which has raised concerns about the sustainability of BaaS. Compared to the charging station operated by automakers under a Complete-Vehicle-Sales (CVS) strategy, the swapping station involves the deployment of automation technology and maintenance of battery inventory. Thus, setting and maintenance costs would be significantly higher than those of regular charging stations. In fact, other companies have attempted to implement analogous battery leasing business models based on battery-swapping technology. However, these efforts were ultimately abandoned due to technological immaturity at the time, consumer acceptance issues, and significant cost pressures, similar to those faced by Silicon Valley startup Better Place and EV giant Tesla.

NIO is the first EV manufacturer to successfully operate its battery-swapping service [17], primarily due to an innovative partnership with its battery supplier for battery leasing. Weineng Battery Asset Company, a joint venture between NIO and CATL, the world's largest power battery producer, is dedicated to delivering user-oriented BaaS services. In this cooperation, the swapping stations will be operated by NIO, and the battery lease rates collected will be used to pay CATL.[5] This model has achieved significant market recognition, with more than 80% of consumers adopting BaaS for their NIO vehicle purchases in 2024.[6] An increasing number of enterprises in China have become aware of the potential of this model and have started to engage in battery swapping and BaaS, as illustrated in Figure 1. Besides China, several companies in other countries have also ventured into the field, such as California-based startup Ample and India's SUN Mobility.

So far, BaaS is still in the early stages of development [14]. Empirical studies show that consumers' choices between traditional vehicles and EVs are highly influenced by the business model. Offering battery leasing can enhance the attractiveness of EVs and serve as an effective method to boost sales [18]. Although NIO's BaaS appears promising, the impact of its pros and cons on this model's success remains uncertain and under-researched. Therefore, this paper

[4]https://www.mckinsey.com.cn (Accessed on February 1, 2025)
[5]https://www.nio.cn/smart-technology/20241127001
[6]https://xueqiu.com/1333903283/292948804 (Accessed on February 1, 2025)

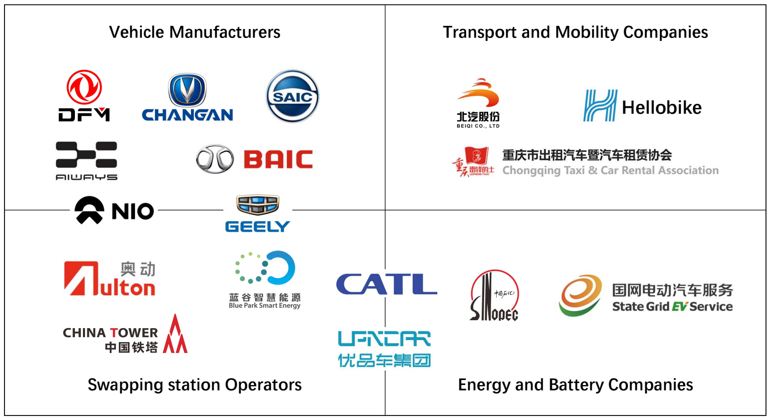


Fig. 1: Companies engaged in battery-swapping and BaaS in China
Source: GIZ. Overview of Battery Swapping and Battery-as-a-Service (BaaS) in China.

explicitly examines the competitive market in which EVs and FVs coexist, considering differences in EV depreciation rates across various strategies. From the perspective of consumer resale anxiety, it evaluates the feasibility of BaaS. Furthermore, we analyze the impact of this strategy on both the market and the environment, aiming to provide a deeper understanding of the value of BaaS in the context of market competition.

B. Research Questions and Major Findings

This study focuses on the sales strategy choice of EV manufacturers when BaaS can mitigate the high depreciation rate of EVs. Under BaaS, the reduction in depreciation loss of EVs can enhance their market competitiveness. In addition to increasing EV value retention, BaaS also reduces the initial purchase cost, which benefits consumers. Generally, EV manufacturers are required to participate in the construction and maintenance of charging stations to ensure the convenience of EV charging. However, the setup cost of operating a battery swapping station is higher than that of a charging station due to significantly higher setup and equipment maintenance costs.[7] Additionally, as part of the emission reduction plan, promoting EVs is usually considered a potential solution to help improve the environment. In light of the considerations mentioned above, the three questions posed in this study are as follows.

[7]Excluding the cost of batteries and land rent, the setup cost of a swapping station is approximately 1.25 million yuan, the setup cost of a supercharging station is approximately 1.12 million yuan, while the setup cost of an ordinary charging station is about several hundred thousand yuan in China. https://www.nio.cn/app-articles/517430 (Accessed on August 18, 2024)

1) Can a BaaS strategy be more profitable than a CVS strategy for EV manufacturers?
2) How does BaaS influence both FV manufacturers and battery suppliers?
3) Does BaaS contribute to environmental benefits and improve consumer surplus?

To address these questions, we develop a game-theoretic model of an automobile sales market comprising an EV manufacturer, an FV manufacturer, and a battery supplier. The EV manufacturer can choose between two sales strategies: the traditional Complete-Vehicle-Sales (CVS) and the emerging Battery-as-a-Service (BaaS). To focus on the EV manufacturer's sales model choice in a competitive environment, we use vehicle depreciation rates to implicitly capture transactions in the secondary market. Additionally, we consider the asymmetric operational costs associated with charging and battery-swapping stations. We thoroughly compare and analyze the two sales strategies, yielding three meaningful insights. First, we find that if the EV manufacturer aims to improve profit performance with BaaS, the depreciation rate of EVs under BaaS should be at least slightly lower than under CVS. Furthermore, increasing sales requires an even greater reduction in the depreciation rate. Second, with BaaS, both EV and FV manufacturers benefit when the EV depreciation rate under BaaS is moderately low. Considering the additional battery acquisition in BaaS, a win-win-win situation can be achieved, including benefits for the battery supplier. Since battery swapping generally remains faster than charging, the advantage in energy replenishment efficiency widens the range of ways EV manufacturers can further increase profits under BaaS. Third, our results indicate that BaaS does not consistently improve environmental outcomes and consumer surplus. When BaaS results in a notable reduction in the depreciation rate of EVs, the total consumer surplus will always be enhanced, while the improvement in total environmental performance will further require that the environmental benefits of EVs are substantial enough. Our findings serve as a reference for EV manufacturers considering adopting the BaaS strategy.

C. Contribution Statements and Paper Organization

This paper delivers three major contributions. First, it develops a game-theoretic model that incorporates the depreciation rate —an essential element in vehicle buyers' decision-making—

into the consumer's payoff. This study explores the operational decisions of EV manufacturers in response to consumers' concerns about resale value, thereby expanding academic insights into the competitive dynamics between EVs and FVs within this framework. Second, this paper conducts a thorough analysis of the fundamental mechanism behind the emerging BaaS model in the EV supply chain. By weighing its relative strengths and weaknesses against the CVS model, this study offers insights for the EV industry to navigate existing challenges and explore more effective development opportunities. Finally, this paper examines how the BaaS sales model affects the environmental performance and consumer benefits of the vehicle market, identifies areas for improvement in the competitive landscape between EVs and FVs, and offers academic insights for practical application.

The rest of this paper is organized as follows. Three streams of relevant literature are summarized in Section II, and then we introduce the problem description and model setting in Section III. Section IV compares the two strategies, conducting an in-depth analysis of the available strategy choices for the EV manufacturer and their potential implications. Section V considers two extensions: scenarios necessitating supplementary battery reserves under BaaS and scenarios involving environmentally conscious consumers. Section VI presents a summary of the paper and suggests avenues for future research. Notation table, proofs, market data, and additional analysis are available in the appendices.

II. Literature Review

The literature on the subject is reviewed in three streams: (1) operations management under BaaS, (2) impact of resale anxiety on EV adoption, and (3) competition between EVs and FVs.

A. *Operations Management under BaaS*

An increasing number of studies have focused on BaaS strategies in the EV industry. Early research on BaaS primarily analyzed the impact of battery-swapping services on EV adoption, highlighting that such service systems could play a positive role in this process [4], [19]. With the widespread rise of this model in recent years, the existing literature has examined it from various perspectives, including optimization of battery-swapping station operations [7], [20]–[23], pricing and financing strategies [24]–[26], and performance comparisons of different business models [15], [17], [27]–[29]. Among these, one of the most relevant studies to our work also focused on the issue of sales model selection. Zhou et al. [15] examined the impact of the secondary market by comparing two models: selling and providing battery-related services. They demonstrated that BaaS could yield higher profits for companies when battery costs or degradation rates are too high. They primarily analyzed the battery supply model, focusing on monopolistic scenarios. In contrast, this paper also examines the selection of sales models for EVs within a competitive environment that includes both EVs and FVs. Consequently, we do not delve into the specifics of second-hand market transactions for electric vehicles; instead, we address this aspect through variations in their depreciation rates, expand the scope to include the competitive coexistence of EVs and FVs, and examine the environmental impact.

Compared with the existing literature, this research explicitly examines changes in vehicle depreciation rates resulting from the separation of battery and vehicle ownership under BaaS. We introduce resale anxiety in consumer EV purchases and reveal a range of impacts stemming from the improved EV retention performance of BaaS versus CVS.

*B. **Impact of Resale Anxiety on EV Adoption***

Our research is related to the literature on the impact of consumer resale anxiety on EV adoption. Resale anxiety is a psychological concern that arises from consumers' lack of confidence in the future value of their vehicles [4]. Most studies employed empirical methods to examine the impact of consumer anxiety, finding that it is a negative factor that can hinder purchasing behavior [11], [30], [31]. Existing modeling studies that focused on resale anxiety were relatively limited. Lim et al. [4] considered a monopoly company and, using a two-stage modeling framework, compared different business practices. The results indicated that when consumer resale anxiety is high, offering battery leasing would increase EV adoption. Li and Wang [32] adopted a game-theoretic model to investigate EV anxiety, including resale anxiety, and found that consumer anxiety can hinder EV purchase. Zhang and Zhao [33] considered the guaranteed resale value strategy to alleviate consumer resale anxiety and demonstrated that it can increase supply chain profits in a monopoly context. The applicability of existing findings on resale anxiety to a competitive market remains uncertain. We address this issue by examining competition between EVs and FVs, building upon established research.

Numerous empirical studies suggest that resale anxiety has a negative impact on consumer purchasing decisions. To our knowledge, model-based articles are limited and largely consider monopoly settings. This paper models consumers' behavior regarding depreciation costs and uses a modeling approach to discuss how resale anxiety poses a competitive challenge to EV adoption compared to FVs.

C. ***Competition between EVs and FVs***

Our work is also related to the literature focusing on the competition between the two vehicles, as EV technology has long been competing with traditional vehicle technology [2]. Among the literature on competition between two manufacturers, several papers focused on price competition. For example, Ma et al. [34] considered the Stackelberg and simultaneous pricing game models to study the effects of government subsidies and interventions on carbon emissions constraints. Rasti-Barzoki and Moon [35] and Srivastava et al. [36] studied the pricing game under different government subsidies and tax policies. Kumar et al. [37] analyzed three market structures arising from manufacturers' power asymmetry and explored optimal pricing strategies. While the above literature focused on pricing, another stream of research focused on production decisions. Cheng and Fan [38] examined how the dual-credit policy impacts the optimal production strategies of new energy vehicle manufacturers and fuel vehicle manufacturers. Huang and Zhu [39] investigated the impact of ZEV credit regulations on EV production, finding that stricter regulations decrease EV production volume and market share. In addition, unlike the above literature, which considered competition between two manufacturers, several studies examined the production strategies of a traditional manufacturer that produces both EVs and FVs, while accounting for competition between the two vehicle types [40], [41].

Previous literature has mainly focused on policy aspects to examine price and production competition between EVs and FVs. In contrast, our research examines manufacturers' sales strategies by incorporating the depreciation factor that influences consumer purchasing decisions. We characterize the different usage and depreciation costs for the two vehicle types from the consumer's perspective and then examine manufacturers' production decisions in this competitive scenario.

The key differences between the most relevant literature and this paper are summarized in Table I in Appendix A, providing a visual comparison of our work with existing studies.

III. Model and Equilibrium Results

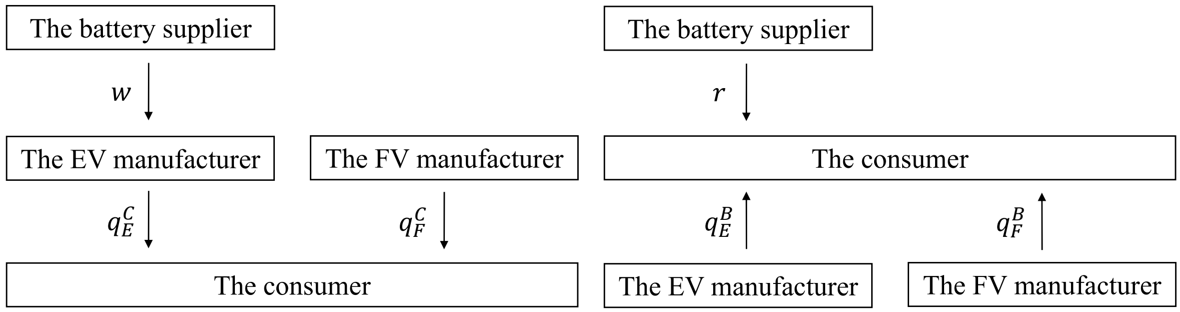
A. *Problem Description and Model Setting*

Consider a duopoly vehicle market comprising an EV manufacturer and an FV manufacturer. The EV manufacturer makes the choice between two main sales models: the Complete-Vehicle-Sales (CVS) model and the Battery-as-a-Service (BaaS) model. Under CVS, the EV manufacturer sources batteries from its supplier and sells complete vehicles, batteries included, to customers, as seen with Tesla and BYD. In contrast, the BaaS model involves a partnership between the EV manufacturer and the battery supplier to provide a battery leasing service. Here, consumers initially purchase the vehicle from the EV producer without the battery cost, as seen with NIO. To emphasize the effects of BaaS on the depreciation rates of EVs and to more clearly compare BaaS and CVS sales strategies, we simplify BaaS to a pure vehicle-battery-separated sales mechanism.

This paper employs a game-theoretic model to characterize competition between EV and FV manufacturers. The game sequence of events in this paper is as follows. In the initial stage, the EV manufacturer has to choose between the above two strategies. In a given strategy, the battery supplier first decides the wholesale price or the lease rate of the battery.[8] Then, both EV and FV manufacturers make quantity decisions, after which the consumer makes the purchasing decision. To simplify notation, subscripts E, F and B represent the EV manufacturer, the FV manufacturer, and the battery supplier, respectively. Additionally, the CVS strategy and BaaS strategy are denoted by the superscripts C and B, respectively. Figure 2 illustrates the market structure under the two strategies.

Due to the high degree of functional substitutability between EVs and FVs, we employ the representative consumer model proposed by Singh and Vives [42] to describe market choices.

[8]Due to the significant bargaining power of battery suppliers in their collaborations with EV manufacturers (See https://www.vzkoo.com/document/2024031100399f1ecfcfcdab00457544.html), this paper treats the two as independent entities to capture the actual pricing agents in the game.



(a) CVS Strategy (b) BaaS Strategy

Fig. 2: Market Structure under CVS and BaaS Strategies

This model has been widely used in the field of operations management, particularly in scenarios where competition exists between products or services [43]–[45]. The consumer seeks to maximize his payoff when purchasing two types of vehicles. Let q_i denote the quantity of product i purchased by the consumer under a given strategy, where $i \in \{E, F\}$. Based on the literature, the utility that the consumer gets from consuming the two goods is quadratic and strictly concave, expressed as follows:

$$U_{(q_E,q_F)} = \sum_{i=E,F} (\alpha q_i - \frac{1}{2} q_i^2) - \gamma q_E q_F, \tag{1}$$

where $\alpha > 0$ represents the utility that the consumer gains from consuming each product, and $\gamma \in (0, 1)$ denotes the degree of substitutability between the two products.

When deciding to purchase a vehicle, consumers evaluate both long-term usage costs and depreciation loss. We represent the usage cost for each vehicle type i as c_i per period ($i \in \{E, F\}$).[9] Let T be the duration of usage periods. For simplification, this study excludes cases where a battery replacement is necessary due to battery life expiration. Accordingly, the total usage cost of a vehicle is given by Tc_i.

Both types of vehicles will experience physical and economic deterioration throughout their service life, with a depreciation rate λ_i ($i \in \{E, F\}$). Based on real-world observations, we consider $\lambda_F < \lambda_E^C$ to signify that FVs retain their value better than complete EVs. The depreciation

[9] The cost dynamics between electric vehicles (EVs) and fuel vehicles (FVs) may differ. Generally speaking, EVs might incur lower energy costs but higher insurance premiums than FVs. Here, we do not enforce that c_E is less than c_F. In fact, we can prove that the comparative size of these costs does not influence the main results.

rates of an EV with and without the battery are denoted by λ_E^C and λ_E^B, respectively. The setting of $\lambda_E^B \leq \lambda_E^C$ implies that the depreciation rate of an EV with a battery is not lower than that without.

Under the CVS strategy, consumers purchase FVs and EVs (with batteries installed). Thus, the consumer's payoff can be formulated as:

$$\pi_c^C = U_{(q_E^C, q_F^C)} - \sum_{i=E,F} \left(Tc_i + \lambda_i^C p_i^C\right) q_i^C, \tag{2}$$

where $U_{(q_E^C, q_F^C)}$ refers to the utility that the consumer gains from consuming two vehicles and the cost paid by the consumer throughout the usage cycle is $\sum_{i=E,F} \left(Tc_i + \lambda_i^C p_i^C\right) q_i^C$, including usage cost and depreciation cost. By taking the partial derivatives of the payoff in Equation (2) with respect to q_i^C and solving the system of equations, the market clearance price for each vehicle can be derived as:

$$\begin{cases} p_E^C = \frac{\alpha - q_E^C - Tc_E - \gamma q_F^C}{\lambda_E^C}, \\ p_F^C = \frac{\alpha - q_F^C - Tc_F - \gamma q_E^C}{\lambda_F^C}. \end{cases} \tag{3}$$

Under the BaaS strategy, the consumer purchases FVs and EVs without batteries, then leases them from the battery supplier. We use r to represent the fixed unit battery lease rate per period.[10] For brevity, we assume that the common discount factor for the battery supplier and the consumer is δ, $\delta \in (0, 1)$. The consumer's payoff can be written as:

$$\pi_c^B = U_{(q_E^B, q_F^B)} - \sum_{i=E,F} (Tc_i + \lambda_i^B p_i^B) q_i^B - q_E^B \int_0^T \delta^t r dt, \tag{4}$$

where $q_E^B \int_0^T \delta^t r dt$ represents the total battery lease rate that the consumer needs to pay throughout the whole usage period. Similarly, the market clearance prices of the two types of vehicles are summarized as follows:

$$\begin{cases} p_E^B = \frac{(\alpha - q_E^B - Tc_E - \gamma q_F^B) \ln \delta + r(1-\delta^T)}{\lambda_E^B \ln \delta}, \\ p_F^B = \frac{\alpha - q_F^B - Tc_F - \gamma q_E^B}{\lambda_F}. \end{cases} \tag{5}$$

[10]In reality, the pricing of battery lease rates is generally agreed upon at the time of purchasing the vehicle and remains stable over the long term; therefore, we adopt a one-time decision setup in our model.

B. ***Equilibrium Results under CVS***

In order to streamline the sales strategy, the distinction in production costs between EVs and FVs is ignored, and we standardize the unit production costs of the EV body, battery, and FV to zero. Under CVS, both types of vehicles are sold as complete vehicles. The profit of the FV manufacturer comes from the sale of cars, its profit function can be simplified as:

$$\pi_F^C(q_F^C) = p_F^C q_F^C. \tag{6}$$

The EV manufacturer first needs to purchase batteries from the battery supplier and then sell the battery and vehicle body together to the consumer. We use w to represent the wholesale price of a battery. In practice, unlike FV gas stations, which are typically operated by third parties, the power replenishment infrastructure for EVs is widely provided or jointly operated by the EV manufacturer [27]. The cost disparity between charging stations and battery-swapping stations for EV manufacturers is significant, resulting in a greater financial burden compared to FV manufacturers. To simplify the analysis, we assume that the FV manufacturer incurs zero cost and exogenously defines the costs of the two types of EV energy replenishment stations separately.[11] Under CVS, let s_1 denote the marginal cost of developing the charging capacity required to ensure convenient charging for each vehicle. Furthermore, we assume that the costs of constructing and maintaining the charging equipment are directly proportional to the number of EVs on the market. For instance, in China's EV market, the EV-to-charging-post ratio is typically mandated to be 1:1.[12] The profit function of the EV manufacturer can be expressed as follows:

$$\pi_E^C(q_E^C) = (p_E^C - w - s_1)q_E^C. \tag{7}$$

The battery supplier's profit is derived from the revenue obtained by charging the EV manu-

[11]Despite the presence of public charging stations in the market, participation in the operation and construction of charging stations by EV manufacturers remains a common phenomenon. We surveyed the top 10 companies with the largest global EV market shares in 2024, as released by TrendForce, among which 9 own or are currently constructing their own charging stations. For example, Tesla owns and operates the world's largest fast-charging network, with over 50,000 Supercharger stations as of March 2024. Meanwhile, BYD jointly operates charging stations through partnerships with large corporations, including State Grid and Shell.

[12]https://www.gov.cn/zhengce/zhengceku/2015-10/09/content_10214.htm. (Accessed on August 18, 2024)

facturer for wholesale batteries, and it sets the wholesale price to maximize the following profit function:

$$\pi_B^C(w) = wq_E^C. \tag{8}$$

Lemma 1 characterizes the equilibrium results of the battery supplier and the two competitive manufacturers. All proofs are included in Appendix A.

Lemma 1. *The optimal decisions and corresponding profits under the CVS strategy are presented below.*

(i) *The optimal wholesale price of the battery is*

$$w^* = \frac{\alpha(2-\gamma) - 2Tc_E - 2s_1\lambda_E^C + \gamma Tc_F}{4\lambda_E^C};$$

(ii) *The optimal quantities of EVs and FVs are*

$$\begin{cases} q_E^{C*} = \frac{\alpha(2-\gamma)-2Tc_E-2s_1\lambda_E^C+\gamma Tc_F}{2(4-\gamma^2)}, \\ q_F^{C*} = \frac{\alpha(2-\gamma)(4+\gamma)-(8-\gamma^2)Tc_F+2\gamma(Tc_E+s_1\lambda_E^C)}{4(4-\gamma^2)}; \end{cases}$$

(iii) *The optimal profits of the EV manufacturer, the FV manufacturer, and the battery supplier are*

$$\begin{cases} \pi_E^{C*} = \frac{(\alpha(2-\gamma)-2Tc_E-2s_1\lambda_E^C+\gamma Tc_F)^2}{4(4-\gamma^2)^2\lambda_E^C}, \\ \pi_F^{C*} = \frac{(\alpha(2-\gamma)(4+\gamma)-(8-\gamma^2)Tc_F+2\gamma(Tc_E+s_1\lambda_E^C))^2}{16(4-\gamma^2)^2\lambda_F}, \\ \pi_B^{C*} = \frac{(\alpha(2-\gamma)-2Tc_E-2s_1\lambda_E^C+\gamma Tc_F)^2}{8(4-\gamma^2)\lambda_E^C}. \end{cases}$$

After examining the equilibrium results under the traditional CVS strategy, we next explore the decisions and payoffs of various market participants under the emerging BaaS strategy.

C. Equilibrium Results under BaaS

Under BaaS, EVs are designed with a modular structure that separates the vehicle from the battery. The EV manufacturer provides the vehicle without a battery, while the battery supplier offers consumers battery leasing schemes. Similarly, the FV manufacturer determines the product quantity to maximize the following profit function:

$$\pi_F^B(q_F^B) = p_F^B q_F^B. \tag{9}$$

We assume that $p_E^B < p_E^C$ because the retail price of an EV without a battery would be lower than that of a complete vehicle that includes a battery. For example, in the case of NIO's standard battery pack, the retail price of a vehicle under BaaS is 70,000 CNY lower than under CVS.[13] Empirical observations indicate that many EV manufacturers are responsible for operating the battery-swapping station. Accordingly, we use s_2 to represent the marginal cost of developing the swapping capacity needed to ensure convenient battery swapping for each EV. We further assume $s_1 < s_2$ to reflect the higher operating cost of a battery-swapping station than a charging station. The EV manufacturer determines the product quantity to maximize the following profit function:

$$\pi_E^B(q_E^B) = (p_E^B - s_2)q_E^B. \tag{10}$$

For the battery supplier, profit comes from the lease fees paid by the consumer during the battery's use, and the supplier sets the lease rate to maximize the following profit function:

$$\pi_B^B(r) = q_E^B \int_0^T \delta^t r dt. \tag{11}$$

In the extension, we also consider the additional batteries needed to be stored at the swapping station, and our key conclusions still hold. Lemma 2 characterizes the equilibrium results. All proofs are included in Appendix A.

Lemma 2. *The optimal decisions and corresponding profits under the BaaS strategy are presented below.*

(i) *The optimal lease rate for the battery is*

$$r^* = \frac{(\alpha(2-\gamma) - 2Tc_E - 2s_2\lambda_E^B + \gamma T c_F)\ln\delta}{4(\delta^T - 1)};$$

[13]More detailed supporting data can be found in Appendix D.

(ii) *The optimal quantities of EVs and FVs are*

$$\begin{cases} q_E^{B*} = \frac{\alpha(2-\gamma)-2Tc_E-2s_2\lambda_E^B+\gamma Tc_F}{2(4-\gamma^2)}, \\ q_F^{B*} = \frac{\alpha(2-\gamma)(4+\gamma)-(8-\gamma^2)Tc_F+2\gamma(Tc_E+s_2\lambda_E^B)}{4(4-\gamma^2)}; \end{cases}$$

(iii) *The optimal profits of the EV manufacturer, the FV manufacturer, and the battery supplier are*

$$\begin{cases} \pi_E^{B*} = \frac{(\alpha(2-\gamma)-2Tc_E-2s_2\lambda_E^B+\gamma Tc_F)^2}{4(4-\gamma^2)^2\lambda_E^B}, \\ \pi_F^{B*} = \frac{(\alpha(2-\gamma)(4+\gamma)-(8-\gamma^2)Tc_F+2\gamma(Tc_E+s_2\lambda_E^B))^2}{16(4-\gamma^2)^2\lambda_F}, \\ \pi_B^{B*} = \frac{(\alpha(2-\gamma)-2Tc_E-2s_2\lambda_E^B+\gamma Tc_F)^2}{8(4-\gamma^2)}. \end{cases}$$

We impose the following constraints to exclude trivial cases: $\lambda_E^B > \frac{2}{6-\gamma^2}\lambda_E^C$ and $\alpha > \max\{0, \alpha_1, \alpha_2, \alpha_3\}$. The expressions are all provided in Appendix A. These assumptions constrain vehicle prices within a reasonable range and ensure that our subsequent analysis takes place in a competitive environment where both types of vehicles can coexist.

D. Analysis of Equilibrium Results

To better understand the equilibrium outcomes, we analyze the impact of changes in depreciation-related parameters on the results. First, we explore the effects stemming from changes in the duration of consumer usage.

For FVs, due to their high fuel costs, an increase in usage duration consistently has a negative impact on FV manufacturers. However, for the EV supply chain, the effect of usage duration depends on whether it has a cost advantage and the magnitude of that advantage, as demonstrated in Corollary 1.

Corollary 1. *The sensitivity analysis regarding the equilibrium outcomes of the EV supply chain and the overall market size, with respect to usage duration, is shown in Table I.*

Our results can be analyzed in relation to various real-world scenarios. If the cost advantage of EVs is significant (i.e., $c_E < \frac{\gamma}{2}c_F$), an increase in consumer usage duration is more likely to promote the development of the EV supply chain (i.e., $\frac{\partial q_E^{j*}}{\partial T} > 0$, $\frac{\partial p_E^{j*}}{\partial T} > 0$, $\frac{\partial \pi_E^{j*}}{\partial T} > 0$, and $\frac{\partial \pi_B^{j*}}{\partial T} > 0$). In contrast, if the cost advantage is less pronounced or nonexistent (i.e., $c_E \geq \frac{\gamma}{2}c_F$),

TABLE I: Sensitivity analysis of consumer usage duration

		p_E^{j*}	q_E^{j*}	$q_E^{j*}+q_F^{j*}$	w^*	r^*	π_E^{j*}	π_B^{j*}
	$c_E < c_E'$	$\uparrow$	$\uparrow$	$\downarrow$	$\uparrow$	$\uparrow$	$\uparrow$	$\uparrow$
$T\uparrow$	$c_E' \le c_E < \frac{\gamma}{2}c_F$	$\uparrow$	$\uparrow$	$\downarrow$	$\uparrow$	$\downarrow$	$\uparrow$	$\uparrow$
	$\frac{\gamma}{2}c_F \le c_E$	$\downarrow$	$\downarrow$	$\downarrow$	$\downarrow$	$\downarrow$	$\downarrow$	$\downarrow$

an increase in the duration of consumer use could negatively impact the EV supply chain. We also find that the price and quantity of EVs vary in the same direction as T. When the usage cost of EVs is low, EV manufacturers strategically increase production; however, the shift in consumer preference from FVs to EVs still drives up the price. In contrast, when the usage cost is high, EV manufacturers reduce production. However, the overall increase in usage cost lowers consumers' willingness to pay, which in turn leads to a decrease in the price of EVs. Moreover, the rate of change in EV price is always slower under BaaS (i.e., if $c_E < \frac{\gamma}{2}c_F$, $0 < \frac{\partial p_E^{B*}}{\partial T} < \frac{\partial p_E^{C*}}{\partial T}$; if $c_E \ge \frac{\gamma}{2}c_F$, $\frac{\partial p_E^{C*}}{\partial T} < \frac{\partial p_E^{B*}}{\partial T} < 0$), which indicates that the price of EVs remains more stable under BaaS. Since the vehicle-battery separation design allows for independent pricing of the vehicle body and battery, it helps stabilize the initial purchase price for consumers.

Interestingly, we find that when the EV usage cost is moderate (i.e., $c_E' \le c_E < \frac{\gamma}{2}c_F$), the wholesale price of the battery and the lease rate exhibit opposite trends under the two strategies. The expression for c_E' is provided in Appendix B. Under the traditional CVS strategy, the supplier charges a one-time wholesale price for the battery, leading the supplier to maximize his revenue by setting a higher price in transactions with the EV manufacturer (i.e., $\frac{\partial w^*}{\partial T} > 0$). In contrast, under the BaaS strategy, the battery lease rate generates long-term revenue. Since longer consumer usage translates into greater potential profits, the battery supplier is more likely to strategically lower the periodic lease rate (i.e., $\frac{\partial r^*}{\partial T} < 0$). Our results highlight the strategic interaction between firms and consumers under different business models. The sales model enables firms to charge higher prices by leveraging longer product usage durations, whereas the leasing model aims to promote long-term relationships between firms and consumers.

Next, we conduct a sensitivity analysis regarding the operating cost of the energy replenishment station, with the results presented in Corollary 2.

Corollary 2. *The sensitivity analysis of the equilibrium outcomes of the EV supply chain and the overall market size with respect to the operating cost is shown in Table II.*

TABLE II: Sensitivity analysis of the operating cost

	p_E^{j*}	q_E^{j*}	$q_E^{j*} + q_F^{j*}$	w^*	r^*	π_E^{j*}	π_B^{j*}
$s_1 \downarrow$	$\downarrow$	$\uparrow$	$\uparrow$	$\uparrow$	$-$	$\uparrow$	$\uparrow$
$s_2 \downarrow$	$\downarrow$	$\uparrow$	$\uparrow$	$-$	$\uparrow$	$\uparrow$	$\uparrow$

A decline in the marginal cost of the charging (or swapping) station leads to a lower EV price and an increase in the quantity of EVs. The revenue generated by this increase in quantity drives the overall profit trend, resulting in higher profits for all members of the EV supply chain. At the same time, the increase in the number of EVs also expands the overall size of the vehicle market. In practice, technological advances and government subsidies help alleviate the burden of charging and swapping infrastructure costs for EV manufacturers. This trend is expected to foster the growth of the EV industry.

IV. Equilibrium Strategy And Analysis

In this section, we compare the outcomes of the two strategies, examine the EV manufacturer's strategic preferences, and assess the impact of BaaS on the market. For brevity, further details of the closed-form expressions of the thresholds defined in our results are provided in Appendix B.

A. Comparison of CVS and BaaS

We compare the changes in the market share of two competing vehicle manufacturers. The results are summarized in Proposition 1.

Proposition 1. *(Comparison of sale quantity in equilibrium between two strategies)*

Under BaaS,

(i) *if* $\frac{\lambda_E^B}{\lambda_E^C} < \frac{s_1}{s_2}$*, the quantity of EVs is higher (i.e.,* $q_E^{B*} > q_E^{C*}$*) and the quantity of FVs is lower (i.e.,* $q_F^{B*} < q_F^{C*}$*) than that under CVS; and*

(ii) *if* $\frac{\lambda_E^B}{\lambda_E^C} \geq \frac{s_1}{s_2}$*, the quantity of EVs is lower (i.e.,* $q_E^{B*} \leq q_E^{C*}$*) and the quantity of FVs is higher (i.e.,* $q_F^{B*} \geq q_F^{C*}$*) than that under CVS.*

As $\frac{\lambda_E^B}{\lambda_E^C}$ decreases, reflecting the fact that the relative advantage of the depreciation performance of EV under BaaS over CVS is more significant, while as $\frac{s_1}{s_2}$ decreases, the marginal cost disadvantage of BaaS relative to CVS becomes more pronounced. Proposition 1 reveals that when the depreciation rate performance of EVs under BaaS has a significant advantage over CVS, i.e., $\frac{\lambda_E^B}{\lambda_E^C} < \frac{s_1}{s_2}$, compared with CVS, the quantity of EVs in the market is boosted while the amount of FVs decreases. For consumers, the depreciation rate of EVs is lower under BaaS, resulting in lower ownership costs. Therefore, they will give priority to EVs when making purchasing decisions. However, if the relative advantage of depreciation under BaaS is less than its marginal cost disadvantage, i.e., $\frac{\lambda_E^B}{\lambda_E^C} \geq \frac{s_1}{s_2}$, BaaS will lead to a decrease in the number of EVs. Although the price of EVs without a battery has dropped under BaaS, consumers still need to lease the battery long-term in order to drive the vehicle. They do not own the batteries but pay for their use. A low residual value makes the cost of owning an EV relatively high for the consumer under BaaS. Therefore, the consumer will consider purchasing FVs instead.

In addition, the depreciation rate threshold, $\frac{s_1}{s_2}\lambda_E^C$, increases in s_1 and decreases in s_2. In other words, the threshold is related to the relative cost of the refueling facilities operated by the EV manufacturer. The smaller the cost gap between the swapping station and the charging station, the greater the possibility of expansion of the market share of EVs under BaaS. Our analysis offers an explanation for NIO's approach. Since implementing BaaS, NIO has consistently conveyed to consumers that this strategy mitigates the issue of high EV depreciation rates, actively guiding them to better recognize its products in the market. Additionally, NIO has actively formed partnerships to operate battery swapping stations, aiming to reduce costs. Empirical evidence shows that NIO sales have consistently grown, securing the leading position in its market segment with a market share of over 40% in 2023.[14]

[14]https://www.jiemian.com/article/10879243.html (Accessed on August 18, 2024)

Next, we further examine the changes in the overall market size under different strategies, which are illustrated in Corollary 3.

Corollary 3. *(Impact of BaaS on the overall market size)*

(i) *If* $\frac{\lambda_E^B}{\lambda_E^C} < \frac{s_1}{s_2}$, *BaaS will enlarge the overall vehicle market size;*

(ii) *if* $\frac{\lambda_E^B}{\lambda_E^C} = \frac{s_1}{s_2}$, *the overall vehicle market size is the same under both strategies;*

(iii) *if* $\frac{\lambda_E^B}{\lambda_E^C} > \frac{s_1}{s_2}$, *BaaS will shrink the overall vehicle market size.*

Corollary 3 summarizes the conditions for changes in the overall size of the market. As Proposition 1 indicates, the factors influencing the market expansion or contraction coincide with those affecting the rise or decline in the number of EVs. As demonstrated in Figure 3, the increasing homogeneity of the two products intensifies competition between them. At this stage, the changes primarily result from seizing each other's market share, leading to a reduction in the difference in their relative quantity changes. When the quantity of EVs increases, it primarily comes at the expense of FVs. Currently, vehicle intelligence is emerging as a new development trend, and many EV manufacturers are differentiating themselves from traditional automakers by offering smart driving experiences, thereby creating new consumer demand, as exemplified by Tesla's Sentry Mode.[15]

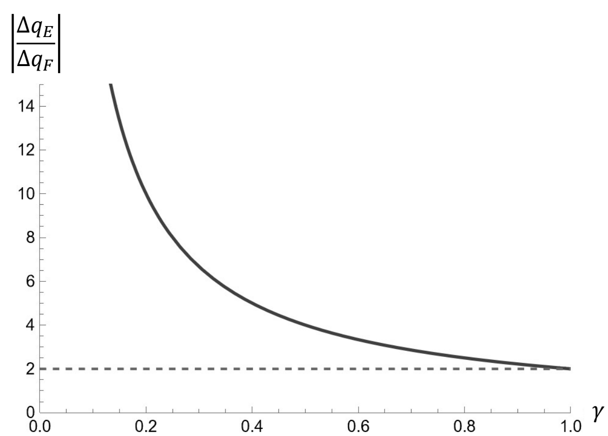


Fig. 3: The relative sales change of EVs and FVs

Note. $\Delta q_E = q_E^{B*} - q_E^{C*}, \Delta q_F = q_F^{B*} - q_F^{C*}$.

To study the impact of two strategies on the EV manufacturer, we compare the EV manufac-

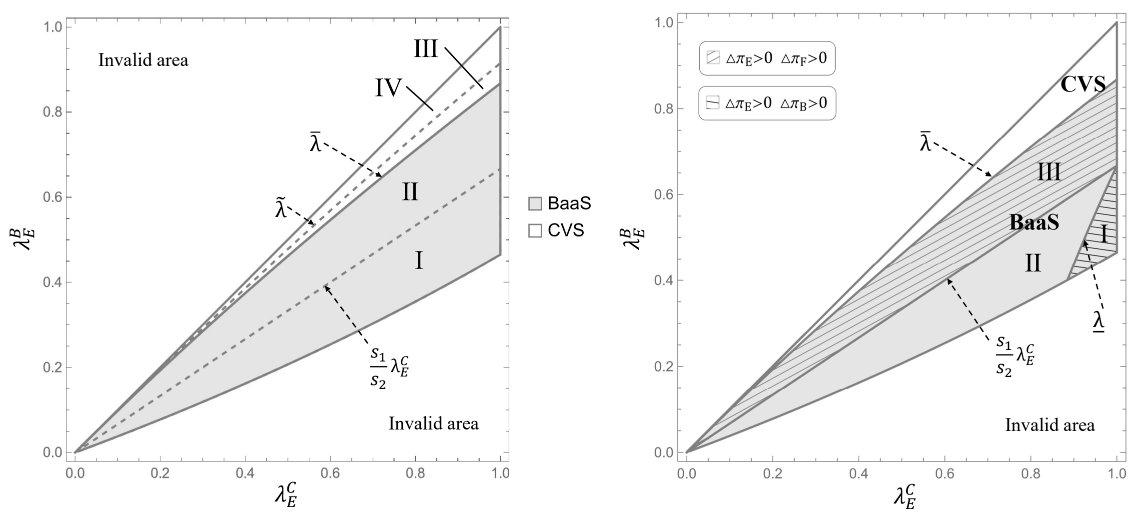
[15]https://www.dongchedi.com/article/7270148521737962039 (Accessed on August 18, 2024)

turer's marginal profit under the two strategies. The results are shown in Lemma 3.

Lemma 3. *(Comparison of marginal profit of the EV manufacturer)*

If $\lambda_E^B < \widetilde{\lambda}$*, the marginal profit of the EV manufacturer under BaaS is higher than that under CVS (i.e.,* $p_E^{B*} - s_2 > p_E^{C*} - w^* - s_1$*), where* $\widetilde{\lambda} = \frac{(\alpha(2-\gamma)-2Tc_E+\gamma Tc_F)\lambda_E^C}{\alpha(2-\gamma)-2Tc_E+\gamma Tc_F+2\lambda_E^C(s_2-s_1)}$.

Lemma 3 shows that when the depreciation rate of EVs is low, i.e., $\lambda_E^B < \widetilde{\lambda}$, the EV manufacturer can achieve a higher marginal profit under the BaaS strategy. On the one hand, under BaaS, the EV manufacturer avoids the cost of batteries wholesaled from the supplier. On the other hand, while the price of EVs without batteries is lower than that of CVS, the enhanced value retention subsequently increases consumers' willingness to pay, allowing EV manufacturers to achieve greater profitability per unit sold. By comparing the profits of the EV manufacturer under different strategies, we can summarize the EV manufacturer's strategy preference in Proposition 2.



(a) Equilibrium strategy of the EV manufacturer

(b) The win-win area under BaaS

Fig. 4: Equilibrium Strategies

Note. $\Delta\pi_i = \pi_i^{B*} - \pi_i^{C*}, i \in \{E, F, B\}$. In both panels, $\alpha = 1$, $c_E = 0.1$, $c_F = 0.2$, $s_1 = 0.1$, $s_2 = 0.15$, $T = 3$, $\lambda_F = 0.37$ and $\gamma = 0.8$.

Proposition 2. *(Strategy preference of the EV manufacturer)*

(i) *When* $\lambda_E^B < \overline{\lambda}$*, BaaS is more profitable for the EV manufacturer (i.e.,* $\pi_E^{B*} > \pi_E^{C*}$*); and*

(ii) *When* $\lambda_E^B \geq \overline{\lambda}$*, CVS is more profitable for the EV manufacturer (i.e.,* $\pi_E^{B*} \leq \pi_E^{C*}$*).*

Moreover, the conditions for BaaS to facilitate the attainment of higher profits by EVs are less onerous than those necessary for the achievement of higher sales volumes (i.e., $\frac{s_1}{s_2}\lambda_E^C < \overline{\lambda}$).

The closed-form expression for the threshold $\overline{\lambda}$ is provided in Appendix B. To better understand Proposition 2, we present the result in Figure 4(a). In region I of Figure 4(a), both the marginal profit and vehicle quantity of the EV manufacturer increase; in region II, despite a decline in vehicle quantity, the increase in marginal profits serves to offset the sales losses incurred, thereby ensuring that BaaS continues to yield higher profits. In region III, the increase in marginal profit cannot compensate for the loss caused by the decrease in quantity. In region IV, both the marginal profit and the product quantity of manufacturers will decrease. Therefore, the CVS strategy would be more profitable for EV manufacturers in III and IV.

Proposition 2 and Figure 4(a) illustrate that if the issue of rapid EV depreciation is substantially mitigated under the BaaS strategy (i.e., $\lambda_E^B < \overline{\lambda}$), BaaS will be more profitable. In other words, EV manufacturers must effectively reduce the depreciation rate of EVs to capitalize on the BaaS strategy. Notably, an EV manufacturer is more likely to enhance profitability through a BaaS sales strategy than to achieve a significant increase in sales volume. In practice, as charging infrastructure becomes more widespread and charging technology advances, the limitations posed by an EV's range are gradually diminishing for consumers. This shift, however, brings the rapid degradation of EV batteries into increasingly sharper focus as a primary concern for consumers. When manufacturers aim to boost profitability, the residual value advantage offered by BaaS can effectively contribute to this objective. If the strategic priority shifts to competing for market share with FVs, manufacturers are required to exert greater effort.

Similarly, we next explore the impacts of BaaS on the profitability of the FV manufacturer and the battery supplier. First, we compare the prices of FVs under two strategies. The results are summarized in Lemma 4.

Lemma 4. *(Comparison of FV's prices under two strategies)*

(i) *If $\frac{\lambda_E^B}{\lambda_E^C} < \frac{s_1}{s_2}$, the price of FVs under BaaS is lower than that under CVS (i.e., $p_F^{B*} < p_F^{C*}$); and*

(ii) *if $\frac{\lambda_E^B}{\lambda_E^C} \geq \frac{s_1}{s_2}$, the price of FVs under BaaS is higher than that under CVS (i.e., $p_F^{B*} \geq p_F^{C*}$).*

Lemma 4 illustrates the price changes of FVs. FV prices will decrease when the depreciation rate of EVs under BaaS is low. However, when the depreciation rate of EVs is still high, the cost for consumers to own an EV becomes more expensive compared to CVS, and the existence of market competition will enhance consumers' willingness to pay for FVs.

We then compare the profits of the FV manufacturer and the battery supplier under two strategies to analyze their preferred strategies. These results are shown in Corollary 4.

Corollary 4. *(Comparison of the profits of the FV manufacturer and battery supplier under two strategies)*

(i) *If* $\lambda_E^B < \frac{s_1}{s_2}\lambda_E^C$*, the FV manufacturer's profit is higher under BaaS than that under CVS (i.e.,* $\pi_F^{B*} < \pi_F^{C*}$*).*

(ii) *If* $\lambda_E^B < \underline{\lambda}$*, the battery supplier's profit is higher under BaaS than that under CVS (i.e.,*$\pi_B^{B*} > \pi_B^{C*}$*), where* $\underline{\lambda} = \frac{(\alpha(2-\gamma)-2Tc_E+\gamma Tc_F)\left(\sqrt{\lambda_E^C}-1\right)+2s_1\lambda_E^C}{2s_2\sqrt{\lambda_E^C}}$.

Corollary 4 reveals the impact of BaaS on the profitability of the FV manufacturer and battery supplier. When the depreciation rate of EVs under BaaS is low (i.e., $\lambda_E^B < \frac{s_1}{s_2}\lambda_E^C$), the quantity and price of FVs will decrease, thereby leading to a decrease in the total profit of the FV manufacturer. The total profit of the battery supplier with BaaS will be higher only if the depreciation rate of EVs is sufficiently low (i.e., $\lambda_E^B < \underline{\lambda}$). This is because, on the one hand, a lower depreciation rate of EVs leads to an increase in sales, which in turn increases the demand for batteries; on the other hand, under BaaS, the profit of the battery supplier comes from the regular battery lease rate paid by consumers, and his marginal profit is difficult to reach the same level as CVS. Therefore, the battery supplier will benefit from transitioning to BaaS only if the revenue growth derived from increased sales volume outweighs the reduction in profit margins.

Combining Proposition 2 and Corollary 4, we summarize the conditions under which BaaS can create win-win areas in Proposition 3.

Proposition 3. *(Conditions of win-win situations)*

(i) *If* $\lambda_E^B < \underline{\lambda}$*, BaaS will achieve a win-win situation for the EV manufacturer and the battery supplier.*

(ii) *If* $\frac{s_1}{s_2}\lambda_E^C \leq \lambda_E^B < \overline{\lambda}$*, BaaS will achieve a win-win situation for the EV manufacturer and the FV manufacturer.*

Please see the details of $\underline{\lambda}$ and $\overline{\lambda}$ in Appendix B, and we can prove $\underline{\lambda} \leq \frac{s_1}{s_2}\lambda_E^C < \overline{\lambda}$. To better illustrate Proposition 3, Figure 4(b) graphically shows these results. Proposition 3 indicates that in region I, both the EV manufacturer and the battery supplier achieve higher profits when the depreciation rate of EVs under BaaS is low (i.e., $\lambda_E^B < \underline{\lambda}$). In this region, the production volumes of both EVs and batteries increase significantly, fostering a mutually beneficial outcome for the EV supply chain. In region III, the profits of both manufacturers are higher when the depreciation rate of EVs under BaaS is moderate (i.e., $\frac{s_1}{s_2}\lambda_E^C \leq \lambda_E^B < \overline{\lambda}$). In this case, while the total cost of owning an EV remains relatively high, there is an increase in the purchase of FVs. BaaS enables the EV manufacturer to improve profit margins despite reduced product volumes, ensuring overall profitability. This result indicates that under BaaS, the manufacturer's profit enhancement does not necessarily come at the expense of its competitor. Instead, it creates a strategic environment where both competing manufacturers can simultaneously improve their total profits. In our base model, no region exists where all three participants simultaneously achieve profit increases under the BaaS strategy.

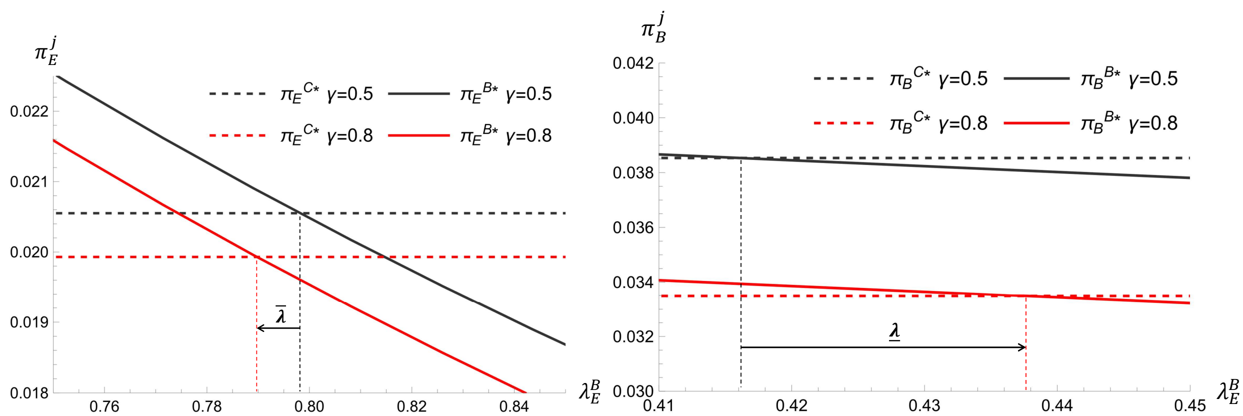
For EV manufacturers running swapping stations, maintaining a sufficient battery inventory is crucial for efficient service operation. As battery demand increases, battery suppliers have the potential to experience profitable growth within a BaaS framework, benefiting all three stakeholders. This scenario is discussed in Section V-A. Next, we examine the impact of competition, with the conclusion summarized in Corollary 5.

Corollary 5. *(Impact of competition on strategy choice)*

The increase in the degree of substitutability reduces the feasibility of the BaaS strategy for the EV manufacturer (i.e., $\frac{\partial\overline{\lambda}}{\partial\gamma} < 0$*), while enhancing its feasibility for the battery supplier (i.e.,* $\frac{\partial\underline{\lambda}}{\partial\gamma} > 0$*), without affecting the feasibility for the FV manufacturer (i.e.,* $\frac{s_1}{s_2}\lambda_E^C$ *is not affected by* γ*).*

A larger γ indicates that the market competition is more intense. Corollary 5 seems to show a conflict between the strategic preferences of the EV supply chain, but they are actually consistent. Recall that $\underline{\lambda} \leq \frac{s_1}{s_2}\lambda_E^C < \overline{\lambda}$. When $\lambda_E^B \geq \frac{s_1}{s_2}\lambda_E^C$, compared to CVS, intensified competition leads to a greater decline in the number of EVs under BaaS (i.e., $\frac{\partial(q_E^{B*}-q_E^{C*})}{\partial\gamma} \leq 0$). At the same time, the potential to increase the marginal profits of the EV manufacturer under BaaS decreases (the conditions to increase the marginal profit are more stringent, i.e., $\frac{\partial\widetilde{\lambda}}{\partial\gamma} \leq 0$). As a result, the feasibility of BaaS for the EV manufacturer is ultimately diminished, as shown in Figure 5(a).

When $\lambda_E^B < \frac{s_1}{s_2}\lambda_E^C$, BaaS is the optimal choice for EV manufacturers. At this point, intensified competition amplifies the advantages of BaaS for EVs, leading to a greater increase in the number of EVs compared to CVS (i.e., $\frac{\partial(q_E^{B*}-q_E^{C*})}{\partial\gamma} > 0$), and consequently driving up battery demand. Moreover, the potential for increasing the supplier's marginal profit will be enhanced. Therefore, the more intense the market competition, the greater the potential for the supplier to realize higher profits, as shown in Figure 5(b). In other words, when the BaaS strategy's advantage in mitigating depreciation outweighs its cost disadvantage, intensified market competition can promote alignment between EV manufacturers and battery suppliers to adopt the BaaS model.



(a) The EV manufacturer's profit

(b) The battery supplier's profit

Fig. 5: The changes in EV manufacturer and battery supplier profits under different levels of competition

Note. In both panels, $\alpha = 1$, $c_E = 0.1$, $c_F = 0.2$, $s_1 = 0.1$, $s_2 = 0.15$, $T = 3$, $\lambda_E^C = 0.9$, $\lambda_F = 0.37$ and $\gamma = 0.8$.

B. *Impact of BaaS on Environmental Performance and Consumer Surplus*

In the current context of green and low-carbon transition, as one of the five key clean energy technologies, EVs are considered effective in helping to mitigate carbon emissions [46]–[49].[16] In what follows, we analyze whether and when BaaS would be more friendly to the environment and consumers.

Following the depiction of environmental impacts in the durable goods literature [36], [51], we use e_E and e_F represent the average emissions per EV and FV, respectively, during their usage phases.[17] From 2019 to 2023, the deployment of EVs led to an annual reduction of approximately 60 metric tons of CO_2 emissions [52]. Therefore, we further consider $e_E < e_F$ to reflect the fact that EVs have fewer carbon emissions in use than FVs, which is consistent with the modeling assumptions in the current literature [37], [41], [51], [53]. The total carbon emissions E^j under a given strategy j ($j \in \{C, B\}$) is:

$$E^j = \sum_{i=E,F} e_i q_i^j. \tag{12}$$

Proposition 4. *(Impact of BaaS on environmental performance)*

The total carbon emissions under BaaS are lower than those under CVS (i.e., $E^{B*} < E^{C*}$) if

(i) $\frac{e_E}{e_F} \geq \frac{\gamma}{2}$ *and* $\frac{\lambda_E^B}{\lambda_E^C} \geq \frac{s_1}{s_2}$*; or*

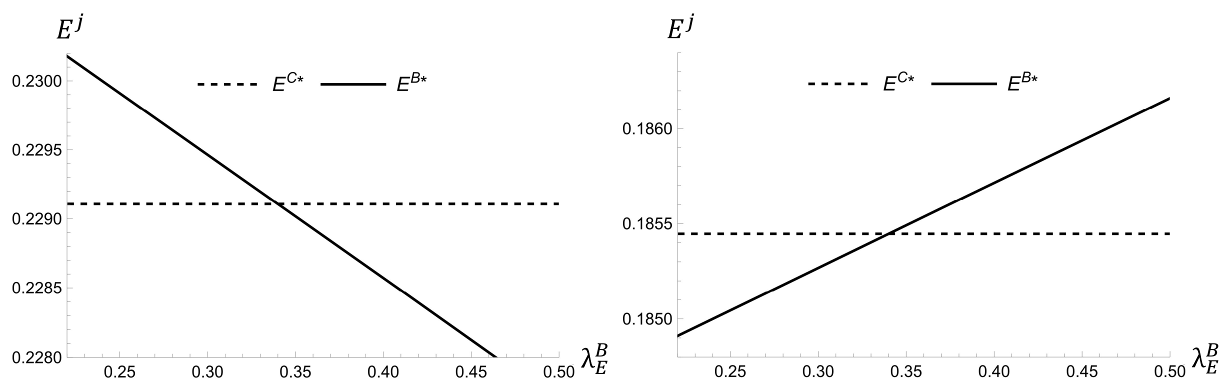
(ii) $\frac{e_E}{e_F} < \frac{\gamma}{2}$ *and* $\frac{\lambda_E^B}{\lambda_E^C} < \frac{s_1}{s_2}$.

Proposition 4 reveals the conditions under which the BaaS strategy can bring better environmental performance, and the results are shown in Figure 6. The parameter $\frac{e_E}{e_F}$ denotes the relative environmental efficiency of EVs in comparison to FVs. A lower value of $\frac{e_E}{e_F}$ implies greater environmental advantages associated with EVs. When the environmental performance advantages of EVs are not significant (i.e., $\frac{e_E}{e_F} \geq \frac{\gamma}{2}$), the still high depreciation rate (i.e., $\frac{\lambda_E^B}{\lambda_E^C} \geq \frac{s_1}{s_2}$) will shrink the size of the vehicle market, and the overall shrinkage in the vehicle market size will dominate the reduction in total carbon emissions.

[16]Without the growing deployment of five key clean energy technologies since 2019, including EVs, wind, solar PV, nuclear and heat pumps, the emissions growth would have been three times larger [50].

[17]Given the ongoing debate surrounding the carbon performance of EVs, particularly in relation to battery production, this paper focuses on the low carbon performance of the two vehicles in use.

Conversely, when implementing BaaS significantly reduces the depreciation rate of EVs (i.e., $\frac{\lambda_E^B}{\lambda_E^C} < \frac{s_1}{s_2}$), it can lead to an expansion of the overall vehicle market. At this point, if the environmental performance advantages of EVs are sufficiently pronounced (i.e., $\frac{e_E}{e_F} < \frac{\gamma}{2}$), the resulting increase in carbon emissions caused by increased EV sales will still be outweighed by the emission reduction caused by the decrease in FV sales. Consequently, aggregate emissions from the vehicle market are expected to decline. In conclusion, the implementation of BaaS can only serve as a more environmentally friendly approach under limited conditions. This finding highlights the importance of jointly considering both the environmental performance of EVs and their sales volume in product design and policy incentives. In practice, EVs are considered a significant new electric load [54]. BaaS helps balance power grid load by shifting more energy replenishment to off-peak hours, thereby further reducing the carbon intensity of EV usage. To fully realize the environmental benefits, the depreciation advantage of EVs must also be further strengthened. Without this, the full synergy between environmental and economic benefits cannot be realized.



(a) $\frac{e_E}{e_F} \geq \frac{\gamma}{2}$ (b) $\frac{e_E}{e_F} < \frac{\gamma}{2}$

Fig. 6: Total carbon emissions quantity

Note. In both panels, $\alpha = 1$, $c_E = 0.1$, $c_F = 0.2$, $s_1 = 0.1$, $s_2 = 0.15$, $T = 3$, $\lambda_E^C = 0.51$, $\lambda_F = 0.37$ and $e_F = 1$. In the left panel, $e_E = 0.6$. In the right panel, $e_E = 0.3$.

Next, we examine whether and when the BaaS strategy can generate a higher consumer surplus. By substituting the equilibrium results into Equation (2) and (4), the consumer surplus can be calculated [55]. The results are presented in Proposition 5.

Proposition 5. *(Impact of BaaS on consumer surplus)*

The total consumer surplus under BaaS is higher than under CVS if and only if $\frac{\lambda_E^B}{\lambda_E^C} < \frac{s_1}{s_2}$.

The condition $\frac{\lambda_E^B}{\lambda_E^C} < \frac{s_1}{s_2}$ implies that consumers will experience less value depreciation when purchasing EVs and lower prices when buying FVs (see Lemma 4), thus benefiting consumers in both instances. Intuitively, BaaS appears to improve the residual value of EVs and enables consumers to purchase vehicles at a lower initial price, potentially driving down the price of FVs due to competition; however, the results are not always as anticipated. The total cost of ownership for an EV under BaaS is actually higher if $\frac{\lambda_E^B}{\lambda_E^C} > \frac{s_1}{s_2}$. Our findings thus offer an alternative perspective on the debate regarding which model makes EV purchase more cost-effective. In this scenario, the residual value advantage of BaaS is minimal, leading FVs to raise prices due to competition, ultimately reducing consumer surplus.

V. Extensions

In this section, we examine two extensions: (1) additional battery acquisition in BaaS, and (2) environmentally conscious consumer, to check the robustness of the base model's results and gain further insights. In addition, we further consider the recharge time gap between BaaS and CVS and an agent-based modeling approach as supplementary extensions, which are provided in Appendix C.

A. Additional Battery Acquisition in BaaS

In the base model, we default to matching one battery per EV for both strategies. However, under BaaS, to provide sustainable, practical battery-swapping services to consumers, a certain number of batteries must be reserved at the swapping station to ensure its continuous operation. For example, in NIO's fourth-generation swap station, each station accommodates 23 batteries [56]. In this section, we consider an extension in which the EV manufacturer is required to maintain additional battery inventory to ensure the continuous and efficient operation of the swapping station.

To be specific, let ρ (where $\rho \in [0,1)$) denote the proportion of batteries stocked at the swapping station. Note that $\rho = 0$ is equivalent to the base model. Therefore, the profit functions of the EV manufacturer and the battery supplier are, respectively:

$$\pi_E^B(q_E^B) = (p_E^B - s_2 - \rho \int_0^T \delta^t r dt) q_E^B, \tag{13}$$

$$\pi_B^B(r) = (1+\rho) q_E^B \int_0^T \delta^t r dt. \tag{14}$$

Lemma 5. *The lease rate of batteries decreases in the proportion of additional batteries (i.e., ($\frac{\partial r'^*}{\partial \rho} \leq 0$), and the battery supplier's profit increases in the proportion of additional batteries (i.e., $\frac{\partial \pi_B^{B\prime *}}{\partial \rho} \geq 0$).*

Lemma 5 shows that the additional demand for batteries increases the battery supplier's potential to gain higher profits under BaaS. Moreover, unlike the results in our base model, we find that under certain conditions, the EV manufacturer, the FV manufacturer, and the battery supplier can simultaneously obtain higher profits under BaaS when the EV manufacturer needs to reserve batteries. The results are summarized in Proposition 6, and the closed-form expressions for the threshold values are provided in Appendix C.

Proposition 6. *(Conditions of a win-win-win situation)*

BaaS can lead to higher profits for the EV manufacturer, the FV manufacturer, and the battery supplier if and only if $\frac{s_1}{s_2}\lambda_E^C \leq \lambda_E^B < \underline{\lambda}'$.

Proposition 6 illustrates the condition under which the BaaS strategy can achieve a win-win-win outcome for all three parties. Recall that in our base model, BaaS can only bring higher profits to the EV supply chain when the depreciation rate of EVs under BaaS is sufficiently low (see Proposition 3). When the EV manufacturer is required to reserve batteries at swap stations, the demand for the battery increases, increasing opportunities for profit growth for the battery supplier. Therefore, if the BaaS model effectively mitigates the issue of rapid EV depreciation and leads to increased battery demand by the EV manufacturer, the FV manufacturer can benefit from a rise in both product quantity and price, the EV manufacturer can achieve higher marginal profits, and the battery supplier can gain from elevated battery demand. This creates a mutually beneficial outcome for all three stakeholders, as illustrated in Figure 7.

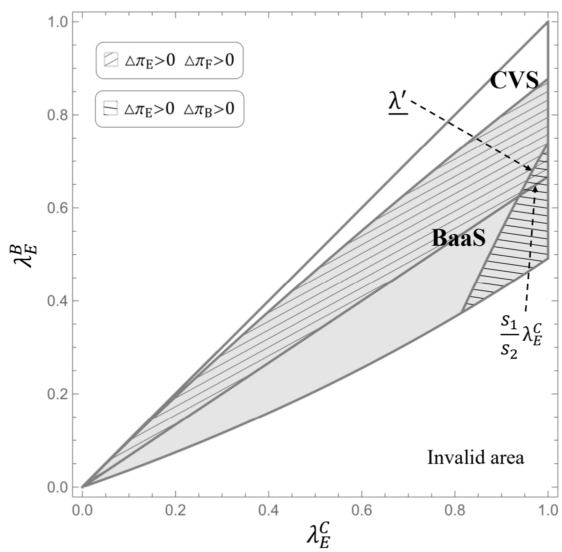


Fig. 7: The common area preference of strategy BaaS

Note. In this panel, $\alpha = 1$, $c_E = 0.1$, $c_F = 0.2$, $s_1 = 0.1$, $s_2 = 0.15$, $T = 3$, $\lambda_F = 0.37$, $\gamma = 0.5$, $\delta = 0.9$ and $\rho = 0.2$.

*B. **Environmentally Conscious Consumer***

In our base model, consumers do not consider the various environmental impacts of two types of vehicles when making the purchase decision. In fact, modern consumers are becoming increasingly socially responsible [29], especially when it comes to environmental impact [57]–[59]. For example, according to a survey by ClimatePartner, 51% of the respondents stated that carbon-neutral or climate-friendly products would influence their purchasing decisions [60]. In this section, we extend the base model to a general case where the consumer is environmentally conscious. In this context, we consider the consumer to suffer a loss in utility, which is proportional to the average carbon emissions of two types of vehicles. Following Wen et al. [61], we denote the level of environmental awareness of the consumer as θ, where $\theta \in [0, 1]$ also reflects the consumer's aversion to carbon emissions. The closer the value of θ is to 1, the more preferable a product with a lower level of carbon emissions to the consumer (note that $\theta = 0$ in the base model). In the two strategies, the consumer's payoff is, respectively:

$$\pi_c^C = U_{(q_E^C, q_F^C)} - \sum_{i=E,F} \left(Tc_i + \lambda_i^C p_i^C\right) q_i^C - \theta \sum_{i=E,F} e_i q_i^C, \tag{15}$$

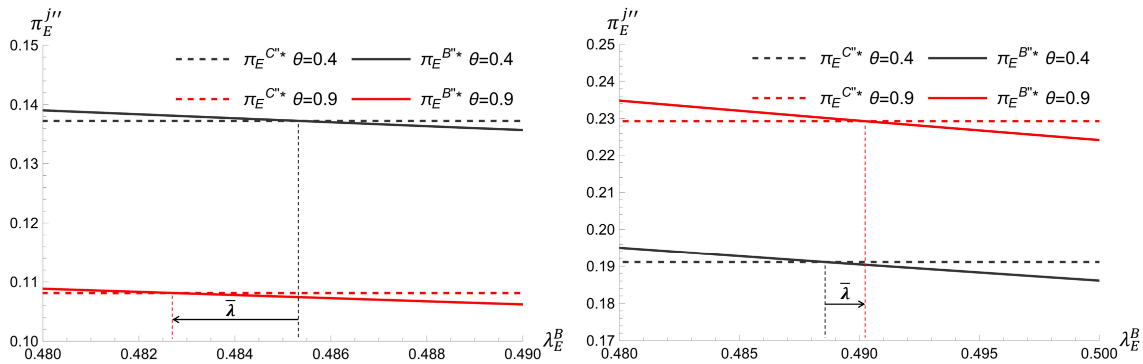
$$\pi_c^B = U_{(q_E^B, q_F^B)} - \sum_{i=E,F} \left(Tc_i + \lambda_i^B p_i^B\right) q_i^B - q_E^B \int_0^T \delta^t r dt - \theta \sum_{i=E,F} e_i q_i^B. \tag{16}$$

Similarly to previous analyses, we show that the main results are derived from the above model. Furthermore, we examine how consumer environmental awareness influences the decisions and profits of two manufacturers and their battery supplier, as illustrated in Lemma 6.

Lemma 6. *(Impact of consumer environmental awareness on the market)*

Given a sales strategy $j \in \{C, B\}$, an increase in consumer environmental awareness always weakens the market performance of FVs (including their price, quantity, and profit). It enhances the market performance of the EV supply chain - including the price, quantity of EVs, the wholesale price or lease rate of batteries, and the profits of supply chain members - when $\frac{e_E}{e_F} < \frac{\gamma}{2}$ and diminishes it if $\frac{e_E}{e_F} \geq \frac{\gamma}{2}$.

All proofs are included in Appendix C. The negative impact of increasing consumer environmental awareness on FVs is relatively straightforward. We also find that this awareness does not always benefit the development of the EV supply chain. Its positive impact depends not only on the fact that EVs are more environmentally friendly than EVs, but also on the extent of this advantage. When the environmental benefits of EVs are not significant, the consumers' willingness to pay for both types of vehicles will decrease. Hence, the quantities and prices of both products decline as consumers' environmental awareness increases, resulting in lower profits for all three parties. Nowadays, the transition from FVs to EVs aims to address the climate change and environmental challenges humanity faces. However, there has been an ongoing debate on whether EVs truly offer significant environmental benefits as initially anticipated. In this context, EV manufacturers must not only claim environmental friendliness but also actively develop more eco-friendly and sustainable EVs, maximizing their advantages to position themselves favorably. Otherwise, they may instead be harmed by the very green mobility principles they advocate.



(a) $\frac{e_E}{e_F} \geq \frac{\gamma}{2}$ (b) $\frac{e_E}{e_F} < \frac{\gamma}{2}$

Fig. 8: Profit of EV manufacturer under consumer environmental consciousness

Note. In both panels, $\alpha = 1.8$, $c_E = 0.1$, $c_F = 0.2$, $s_1 = 0.1$, $s_2 = 0.15$, $T = 3$, $\lambda_E^C = 0.51$, $\lambda_F = 0.37$, $\delta = 0.9$, $\gamma = 0.8$ and $e_F = 1$. In the left panel, $e_E = 0.6$. In the right panel, $e_E = 0.2$.

Next, we explore how the EV manufacturer's strategic choice is influenced when consumers are environmentally conscious.

Proposition 7. *(Impact of environmentally conscious consumer on the choice of the sales strategy)*

Consumer environmental awareness makes BaaS more feasible for EV manufacturers if and only if $\frac{e_E}{e_F} < \frac{\gamma}{2}$.

Proposition 7 indicates that if EVs have a significant relative environmental advantage, consumers' environmental awareness will facilitate EV manufacturers' shift from CVS to BaaS (with looser depreciation-rate requirements; see Figure 8). This suggests that, as societal emphasis on green principles rises, BaaS has the potential to become a more widely adopted strategy.

VI. Conclusion and Discussion

A. *Theoretical Contributions*

The advent of EVs has been accompanied by a notable shift in the automotive landscape, with these vehicles gaining considerable traction in recent years and posing a growing challenge to the dominance of FVs. The emergence of BaaS has prompted a shift in consumer behavior, moving away from the traditional "buy-and-own" paradigm towards a usage-based payment model for

EV batteries. This transition has helped alleviate concerns related to battery availability and the residual value of electric vehicles. This strategy appears to have long-term promise. However, the battery-swapping technology at the core of the BaaS strategy significantly increases operating costs for EV companies, posing an obstacle to adoption for many EV manufacturers.

In this paper, we develop and compare models of the BaaS and CVS from the perspective of consumer resale anxiety, aiming to answer under what conditions BaaS becomes a better choice for EV manufacturers and to examine its resulting impact on the market. First, we find that EV manufacturers can increase their profits with a slight reduction in the EV's depreciation rate under BaaS, while gaining a larger market share requires a more substantial decrease. This is because, even with lower sales volumes, BaaS enables EV manufacturers to earn higher marginal profit per unit sold, thereby enhancing overall profitability. Second, we identify two distinct win-win regions when the EV manufacturer adopts BaaS: one that benefits both manufacturers and another that benefits the EV manufacturer and the battery supplier. The former arises at moderate EV depreciation rates, where the FV manufacturer can increase price and sales due to competition; the latter occurs at low depreciation rates, where higher EV sales boost battery demand. Moreover, when additional battery inventory is considered, all three parties may benefit simultaneously. Third, when the advantage of a low depreciation rate under BaaS outweighs its higher cost, it compels the FV manufacturer to lower prices to remain competitive, thereby reducing the ownership costs of both products and benefiting consumers. In this case, the increase in EV adoption leads to an overall expansion of the market. However, environmental friendliness can only be ensured if the per-unit carbon emissions of EVs are sufficiently low. Our results suggest that BaaS can be a promising and sustainable sales strategy and inform when this is the case. These insights offer theoretical support for promoting BaaS in the EV industry and provide practical guidance for its implementation.

*B. **Managerial Implications***

Following our paper's analysis, we offer managerial implications to guide market stakeholders effectively.

EV manufacturers: From the perspective of consumer concerns about resale value, the depreciation rate of EVs and the cost pressure of battery-swapping stations are two key factors that affect the feasibility of BaaS. On the one hand, manufacturers can enhance consumer confidence by improving after-sales services and establishing a robust system for evaluating second-hand vehicles. Specifically, by facilitating seamless ownership transfer and renewal of battery lease contracts, BaaS can boost vehicle market acceptance. On the other hand, EV manufacturers should prioritize reducing operational costs, including optimizing battery maintenance for longevity and teaming up with other firms to build and manage battery swap stations effectively.

FV manufacturers: With the development of battery-swapping technology and the increase in consumer confidence, the depreciation advantage of FVs is gradually eroded; however, it is expected that both types of vehicles will coexist in the market for the foreseeable future. FV manufacturers can adjust prices and production volumes in a timely manner by monitoring specific market responses, thereby achieving profit growth. In addition, FV manufacturers must actively seek different competitive advantages to mitigate the impact of the growth of the EV market on their operations, particularly as they advance towards smart vehicle technologies.

Battery suppliers: The adoption of BaaS in the EV industry presents an opportunity for battery suppliers. Although the profits of these suppliers may initially decline, as market acceptance increases, the depreciation rate of vehicles under BaaS is expected to decrease further, ultimately leading to higher profits in the long run. Additionally, the widespread deployment of battery-swapping stations, along with increased average battery reserves at each station, can boost demand for batteries, thereby enhancing the profitability potential of battery suppliers. However, this requires strong cooperation between suppliers and EV manufacturers to ensure consumer rights under BaaS, such as the transfer of battery lease contracts during vehicle resale.

*C. **Future Research***

This paper acknowledges limitations that suggest paths for future research. First, although a game-theoretic model is used to explore two sales strategies, future studies could verify and expand these results using empirical or experimental methods. Second, the paper assumes EV manufacturers manage charging and battery-swapping stations, but in reality, these roles might be fulfilled by third-party service providers or battery suppliers. Investigating different partnership models in the EV supply chain could offer valuable insights. Lastly, the study considers a fixed battery lease rate and an exogenous vehicle depreciation rate. Examining transaction dynamics in the second-hand electric vehicle market and the variability in battery rental pricing could provide valuable insights.

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