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Strategic investment in electric vehicle charging service: Fast charging or battery swapping

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ABSTRACT

With the increasing adoption of electric vehicles (EVs), there is a growing need for public charging infrastructure. As a result, significant investments have been made in charging services, particularly, fast-charging (FC) and battery-swapping (BS) services. This paper examines the impact of technical and operational factors, as well as market conditions, on the pricing and profitability of each service to explore whether and how EV charging service providers should invest in these emerging charging services. The analysis with benchmark to private-use slow-charging (SC) services reveals that if the valley electricity price is high and the potential market size is small, lowering service costs does not make BS services a viable option. When the valley electricity price is low, reducing battery loss will not give FC services an advantage. However, in such scenarios, BS services can gain an edge by decreasing service costs. Interestingly, even if both SC and BS services are negatively affected by higher valley electricity prices, the impact on the profitability of BS services is more severe. Our results provide implications for the development of public EV charging service infrastructure. We recommend that implementing energy storage solutions can help alleviate the negative consequences of escalating valley electricity prices and wider peak–valley electricity price differences on BS services and FC services, respectively.

1. Introduction

1.1. Background and objective

Electric vehicles (EVs) are gaining momentum as a substitute for fossil fuels-dependent, internal-combustion vehicles to reduce the greenhouse gas emissions from transportation (Ren et al., 2019; Quddus et al., 2021). The adoption of EVs around the world has accelerated with the rapid improvement in battery capacity and cruising range. Despite the supply chain disruption by the Covid-19 pandemic, EV sales surged to 2.6 million units in 2021, an increase of 168% compared to the previous year, with growth in all major markets including China, the United States, and Europe. Due to this increasing popularity, public charging infrastructure has become the primary constraint on the uptake of EVs in many countries. According to the International Energy Agency, by the end of 2030, EV charging demand will exceed 400 TWh even in the most conservative case (Valogianni et al., 2020).

Currently, slow charging (SC) remains the most common charging way for many EV users. Although customers can benefit from low electricity prices by charging at home during the valley period, the excessively long charging time (i.e., up to 10 h) limits its expediency (Feng and Lu, 2021). Moreover, installing a charging point at private driveway or garage may not be a feasible option for many EV users, especially in metropolitan cities. The recharging speed has overtaken the mileage range as the most important factor influencing the adoption of EVs (Abouee-Mehrizi et al., 2021). An obvious alternative to SC is fast-charging (FC) service, which can reduce the charging time to 20–30 min, according to Pod Point (2021). Major EV makers like Tesla have invested significantly in developing faster charging technologies and improving charging speeds. However, there is a concern, as reported by Financial Times and Forbes, that frequent FC may have detrimental consequences on the batteries of some EV models, such as Nissan (Winton, 2022). Specifically, to ensure faster charging speeds, FC utilizes direct current as the recharging technology, which negatively affects battery performance and durability.[1] Therefore, FC is more detrimental to battery life compared to SC, implying a trade-off between the charging speed and the loss of battery life (Shi et al., 2017; Chaudhari et al., 2018; Zhang et al., 2018). This shortcoming brings some concern to EV owners in choosing FC services.

Another alternative option is battery-swapping (BS). An EV battery can be swapped by technicians in a few minutes (Gu et al., 2021). In

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[1] See https://www.myev.com/research/interesting-finds/is-dc-fast-charging-bad-for-your-electric-car. Accessed October 30, 2023.

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addition to the speed advantage, BS differs from FC services. While FC offers relatively high recharging speed, it achieves at the expense of battery loss. In contrast, BS allows spare batteries to be recharged at lower voltages and professionally maintained, preserving battery performance (Sun et al., 2019). However, the setup cost of a typical BS station is about twice the cost of an FC station, according to NIO, a leading EV manufacturer in China. Customers may choose to lease batteries (i.e., battery-as-a-service offerings), which requires BS service providers to maintain ample battery supply and ensure efficient dispatch. Additionally, unlike the self-charging service of SC and FC, batteries must be swapped or maintained by professionally trained staff, resulting in additional operational costs. For instance, according to Marius Hayler, the CEO of NIO Norway, each BS station requires three to six technicians to perform battery swapping and maintenance tasks. While the first BS program was launched by Tesla in 2013, Tesla strategically abandoned the BS program and began to focus on developing FC technologies (The Tesla Team, 2014). Does Tesla's strategic move to FC indicate a dead-end for BS? NIO provides an opposing answer. In April 2021, NIO officially announced a partnership with Sinopec with a plan to build 5000 smart charging and BS stations by 2025 (NIO, 2021). NIO believes BS can capture a large market share because of the immediate results obtained by swapping a used EV battery for a fully recharged battery.

1.2. Research questions and key findings

Although FC and BS programs have been studied against the backdrop of the rapid growth in the EV industry (Avci et al., 2014; Lim et al., 2014; Abouee-Mehrizi et al., 2021), the existing literature has not yet comprehensively compared the two emerging EV charging services by considering their unique attributes and the associated benefits and drawbacks of each service. These practical observations and the literature gap prompted us to investigate the following questions:

- Should EV charging service providers opt for FC or BS? And what are the key factors restricting the adoption of FC or BS respectively?
- What are the optimal pricing policies for the chosen EV charging services?
- How will technological improvement affect the selection of EV charging services?

To address these questions, we introduce a game-theoretical model where new FC or BS service providers, offering partially substituted charging services, initially benchmark with incumbent SC services and subsequently compete with each other in the EV charging market. Our model analyzes the interaction between battery loss, unit service cost, peak or valley electricity prices, potential market size, and fixed setup cost, and their impacts on the pricing and profitability of FC and BS services. We then investigate scenarios where technological advancements in FC or BS services can simultaneously enhance battery charging/swapping speed and reduce battery loss/unit service cost, and their impacts on the profitability of the charging services.

Our research offers several interesting findings. First, we reveal that if the valley electricity price is low, efficiently reducing battery loss cannot make FC services economically advantageous. When the valley electricity price is high and the market size is small, improving unit service cost efficiency is insufficient to make BS services more profitable than SC services. Second, we show that valley electricity prices mitigate the adverse effects of battery loss on FC services while intensifying the negative effects of unit service costs on BS services. Conventional wisdom would suggest that both BS and SC services are electricity-cost efficient as both of them can take advantage of valley electricity prices. However, we show that when valley electricity prices increase, the profitability of BS services reduces more than SC services. The above findings present a dilemma for FC and BS services during periods of energy crisis and suggest that energy storage could become a solution. In the public EV charging market, the adoption of FC or BS services primarily depends on potential market size. Even with sufficiently low unit service cost, BS service cannot achieve an economic advantage if the potential market is limited. This result highlights that the main priority for BS services competing with FC services should be on expanding the market. We also analyze the pricing strategy for each service. The pricing of FC services depends primarily on valley electricity prices, while the pricing of BS services mainly relies on the market size. High fixed costs of SC and FC services can moderate the effect of battery loss on the pricing of FC services. High fixed setup costs of BS services tend to mitigate the impact of unit service cost on the price of BS services. In the public EV charging market, the effect of unit service cost efficiency on the price difference between FC and BS services is moderated by the fixed setup cost of BS services while remaining unaffected by FC services.

1.3. Contributions and organization of the study

Our research makes several key contributions. First, although the existing literature has explored individual charging services (Wang et al., 2010; Avci et al., 2014; Anjos et al., 2020; He et al., 2021), few studies have conducted a pairwise comparison of the alternative charging services. Our research study is the first to systematically compare the two emerging EV charging services with benchmark to the private-use SC service, positioning itself as the first to fill an important gap in the literature. This exploration enhances the understanding of the strengths and weaknesses concerning different EV charging services, and the impact of relevant technological improvements on the widespread adoption of those respective charging services. Second, by incorporating both internal operational and technical factors (i.e, battery charging/swapping speed, battery loss, and unit service cost efficiency) and external market factors (i.e., peak–valley electricity price difference and market potential), our work provides a more extensive analysis compared to previous studies, which have only taken some of these factors into account (Mak et al., 2013; Lim et al., 2014; Abouee-Mehrizi et al., 2021; He et al., 2021). Finally, our research offers practical implications. During the energy crisis period, energy storage can help to reduce the negative impact of valley electricity prices on BS services and peak–valley electricity price differences on FC services. We also show that in a public EV charging market, BS services should prioritize expanding the market through infrastructure development and government subsidies, followed by improving battery acquisition, dispatching, and maintenance cost efficiency. Technical advancements and fixed cost reductions effectively enhance FC and BS services' competitiveness, with the former being more effective for FC services and the latter being more effective for BS services.

For the remainder of the paper, the related literature is reviewed in Section 2, and the model setup and assumptions are presented in Section 3. Next, the equilibrium of FC and BS services are compared to SC services in Section 4 to identify critical factors influencing the implementation of different EV charging services. Section 5 extends the analysis to the effects of various technological developments on the implementation of the two evolving EV charging services. Afterward, Section 6 presents a pairwise comparison of FC and BS services. Section 7 provides a numerical analysis of the effects of fixed-cost reduction and technological improvement on charging service selection. Finally, the study concludes by discussing the key findings, managerial insights, and future research directions. All proofs are presented in the appendix.

2. Literature review

The literature on EV charging service infrastructure planning and development has grown substantially in the past decade reflecting the rapid growth of EVs in the automotive sector. The relevant literature on battery charging services primarily concentrates on the issues of queuing and the location of FC stations. For instance, while considering the technological improvement in charging speeds and unit service cost savings, He et al. (2021) develop a queuing network model that integrates charging infrastructure planning and vehicle repositioning operations for FC service. They find that concentrating limited charging resources at select locations can enhance the viability of EV sharing. As for the location of charging stations, Anjos et al. (2020) introduce a multi-period optimization framework that not only effectively covers the current charging demand, but also increases EV adoption over a given time horizon. Focusing on demand uncertainty and the constraint of investment budgets, Kadri et al. (2020) investigate the FC stations' location problem by proposing a multi-stage stochastic integer programming approach to meet the EV charging need. Abouee-Mehrizi et al. (2021) investigate the adoption of EVs compared to traditional internal-combustion vehicles in the car-sharing market and find that charging speed, the number of charging stations, and the range of EVs are the top three determinants. Interestingly, considering technological improvements in charging speed and battery improvement, they show that EVs may lead to even higher emissions.

In the research trend on BS, along with infrastructure development like BS station location, battery-related issues such as battery inventory and standardization have also received increasing attention. Among them, Lim et al. (2014) study the station-location problem of BS by incorporating the impact of consumer anxiety concerning battery capacity, charging speed, and resale value. By comparing EV adoption, emission savings, profitability, and consumer surplus for alternative business models, their results indicate that the optimal infrastructure deployment policy requires a combination of battery owning or leasing and an enhanced charging service. Considering the spare battery inventory issue and demand uncertainty, Mak et al. (2013) develop robust optimization models to analyze the effects of battery standardization and technological advances, such as charging speed, battery capacity, and battery loss on the optimal infrastructure deployment strategy for BS stations. Sun et al. (2019) propose a two-stage optimization framework with the aim of finding an optimal battery-purchasing and charging policy, taking into account the difference in peak–valley electricity prices. They show that when the demand function is not synchronized with the price function, charging at full capacity during the valley price period can reduce both the costs of waiting and charging simultaneously. Avci et al. (2014) explore the key mechanisms driving the adoption of EVs by comparing BS-based EVs with conventional EVs. They find that BS-based EVs can improve user adoption but can be environmentally harmful in the long run.

Although both FC and BS have been studied by considering internal technological and operational capabilities or external market conditions, thus far, no research has systematically evaluated alternative EV charging services, including SC, FC, and BS, that is being pursued by different EV makers and charging service providers. Alternative EV charging services necessitate downstream competition in the EV market. Competition between two downstream market players is often depicted by studies focusing on the selection of alternative business strategies and services. For instance, Shen et al. (2019) and Tian et al. (2018) study the optimal channel strategy for a manufacturer who engages with a platform retailer and a traditional reseller. Chen et al. (2019) consider the competition between upstream manufacturers and explore the optimal production coopetition strategies for competing manufacturers. Their study examines the impacts of external, relationship-specific, and internal factors on firms' selection among wholesale coopetition, licensing coopetition, and competition. The substitution effect between alternative charging services is an important market factor that must be captured in the evaluation. We adopt a similar modeling framework proposed by McGuire and Staelin (1983) that investigates the impact of product substitutability on Nash equilibrium distribution structures in a duopoly.

Despite an increasing number of studies on the EV charging service related topics as summarized in Table 1, there are several gaps in the existing literature. First, there is lack of comparative analysis among the different EV charging services although extensive research has been carried focusing on various issues regarding specific battery recharging service (i.e., SC or FC) or BS programs. Second, few studies have incorporated both the internal technological and operations capabilities and external market condition in evaluating the performance of different charging services. Filling these literature gaps, our research explores the strategic selection of EV charging services by examining the comprehensive impacts of both internal technological and operational factors (i.e., charging and swapping speeds and battery-related capabilities) and external market factor (i.e., difference in peak–valley electricity prices and market expansion).

3. Model setup

We examine a setting where an EV charging service provider chooses between two different EV charging services: FC and BS. These two new services can significantly reduce charging time but require a significant investment. We assume EV charging service providers are economically rational and perform strategically to maximize their profits. The variables and parameters used in this paper are outlined in Table 2, with charging service prices as decision variables and the peak and valley electricity prices as exogenous parameters. This is because trading decisions of the EV charging service providers do not affect peak–valley electricity prices, due to the unique nature of the electricity market[2] (Zhou et al., 2016). Following Shen et al. (2019) and Han et al. (2022), we assume that the market size for FC (denoted by a_f) and BS (denoted by a_b) is distinct from that for SC (denoted by a_s) and can be greater than, equal to, or less than 1. This suggests that the FC and BS services represent public EV charging solutions, while SC stands for the private EV charging method and may cater to different customer groups. In a sense, the three charging services: SC, FC and BS are competitive yet not mutually exclusive. These indicate that the customer segments may vary for each of the three charging methods, in which case separate market sizes would be appropriate.

3.1. Slow-charging services

SC services are treated as a benchmark to examine the effects of different internal and external factors on the performance of the two new EV charging services. Consistent with prior research (Shen et al., 2019), the market share for SC services, denoted by a_s, is standardized to be 1. We define a superscript $j \in \{fs, bs\}$, where fs represents the model comparison between FC and SC services and bs denotes the model comparison between BS and SC services. The demand for SC service is directly affected by its service price p_s^j, among which, the subscript s represents SC services. Since the charging speed of SC services is slow, its relative waiting cost compared with other charging services $h_j, j \in \{fs, bs\}$ also affects the demand, among which, subscript f and b represent FC and BS services respectively. For simplicity, the waiting costs for FC and BS services are normalized to zero. In alignment with prior research (e.g., Ingene and Parry, 1995; Shen et al., 2019), the demand is also affected by the prices of alternative EV charging services $p_i^j, i \in \{f, b\}$ and the substitution level $\theta \in [0, 1]$ between alternative services. When $\theta = 0$, the service is unique and the demand is independent of the substitute charging service. In contrast, a high degree of θ leads to an intense market competition (Chen et al., 2019; Qing et al., 2017; Wang et al., 2013). The demand function for SC services can be represented as follows:

$$d_s^j = \begin{cases} 1 - p_s^j - h_j + \theta p_f^j, & j = fs, \\ 1 - p_s^j - h_j + \theta p_b^j, & j = bs. \end{cases} \tag{1}$$

[2] According to the power market regulations, upstream electricity prices are set based on the bidding strategies, which are independent of the downstream retailers (CNESA, 2021).

Table 1
Comparison of contribution of the existing literature.

Literature	SC	FC	BS	Charging speed	Battery loss	Charging service cost	Difference in peak-valley electricity price
Mak et al. (2013)			√	√	√		
Avci et al. (2014)			√				√
Lim et al. (2014)			√	√	√		
Sun et al. (2019)			√				
Anjos et al. (2020)		√					
Kadri et al. (2020)		√					
Abouee-Mehrizi et al. (2021)	√	√		√	√		
He et al. (2021)		√		√		√	
Shi and Hu (2022)			√			√	
Our research	√	√	√	√	√	√	√

Table 2
Notations.

$p_i^{fs}, i \in \{s, f\}$	Charging service price for SC and FC services for the comparison between FC and SC services
$p_i^{bs}, i \in \{s, b\}$	Charging service price for SC and BS services for the comparison between BS and SC services
$p_i^{bf}, i \in \{f, b\}$	Charging service price for FC and BS services for the comparison between BS and FC services
c	Battery loss for FC services
m	Unit service cost for BS services
$h_{is}, i \in \{f, b\}$	Waiting cost for SC services when normalizing that of FC or BS services to be zero, given SC services are in the market
h_{bf}	Waiting cost for FC services when normalizing that of BS services to be zero, given SC services are out of the market
$F_i, i \in \{s, f, b\}$	Fixed setup costs for SC, FC, and BS services; $F_s \leq F_f \leq F_b$
a_s	Potential market size for SC services; $a_s = 1$
a_f	Potential market size for FC services
a_b	Potential market size for BS services
θ	Substitution effect between alternative charging services; $\theta \in [0, 1]$
w_v	Valley electricity price
w_p	Peak electricity price; $w_p > w_v$
Δw	Difference of the peak–valley electricity price; $\Delta w = w_p - w_v$
ΔF_{fs}	Difference in the fixed setup costs of FC and SC services; $\Delta F_{fs} = F_f - F_s$, where $F_f > F_s$
ΔF_{bs}	Difference in the fixed setup costs of BS and SC services; $\Delta F_{bs} = F_b - F_s$, where $F_b > F_s$
ΔF_{bf}	Difference in the fixed setup costs of BS and FC service; $\Delta F_{bf} = F_b - F_f$, where $F_b > F_f$

Due to the long charging period, SC services often run during off-peak hours and are charged at the valley electricity price w_v. Correspondingly, the profit function for SC services can be described as

$$\pi_s^j = d_s^j (p_s^j - w_v) - F_s,\ j \in \{fs, bs\}, \tag{2}$$

where $p_s^j - w_v$ is the marginal profit and F_s is the fixed setup cost.

3.2. Fast-charging services

Compared with SC services, the charging speed of FC services is faster, but still slower than BS services (i.e., $h_{bf} > 0$). A superscript bf is used to denote the model comparison between FC and BS services. Then we have the demand function as follows:

$$d_f^j = \begin{cases} a_f - p_f^j - c + \theta p_s^j,\ j = fs, \\ a_f - p_f^j - c - h_j + \theta p_b^j,\ j = bf, \end{cases} \tag{3}$$

where a_f represents the potential market size of FC services, which can be greater than, equal to, or less than 1 and c represents the battery loss. Recall that SC utilizes alternating current and operates at a lower recharging speed, which causes less damage to the battery life. In contrast, the use of direct current in FC negatively affects battery performance and durability, which reduces customer demand for FC. We use c to represent the negative influence of battery loss on the demand for FC. Considering the instant request for the demand of FC services, the flexibility of charging EVs during the off-peak period would be significantly limited. Therefore, the peak electricity price w_p is applied to FC services. The profit function of FC services can be expressed as follows:

$$\pi_f^j = d_f^j (p_f^j - w_p) - F_f,\ j \in \{fs, bf\}, \tag{4}$$

where $p_f^j - w_p$ is the marginal profit and F_f is the fixed setup cost.

3.3. Battery-swapping services

BS services have drawn great attention in recent years because EV batteries can be swapped in seconds by technicians. Since the speed associated to BS services is drastically cut to a few seconds, its relative waiting cost can be normalized to zero. In addition, the low recharging speed of spare batteries and battery maintenance reduce battery loss considerably. Accordingly, battery loss costs associated with the BS services are normalized to zero. The demand function for BS services is presented as

$$d_b^j = \begin{cases} a_b - p_b^j + \theta p_s^j,\ j = bs, \\ a_b - p_b^j + \theta p_f^j,\ j = bf. \end{cases} \tag{5}$$

Here, a_b represents the potential market size of BS services. Similar to FC services, a_b can be greater than, equal to, or less than 1. Since the spare batteries are recharged using the SC technology, the BS service provider can minimize its battery charging costs by leveraging the valley electricity price w_v. In addition, the spare batteries are recharged at a slower speed to minimize battery loss. Consequently, in the BS model, battery loss is standardized to 0. However, customers may opt to lease batteries as a service, requiring BS service providers to obtain an adequate number of batteries and dynamically allocate them to meet service demands. Furthermore, to accomplish efficient battery-swapping and maintenance operations, skilled technicians need to be employed, resulting in additional labor costs. We define these associated costs as a unit service cost, denoted by m, which mainly includes three parts: per-service amortized battery cost, dispatching cost, and battery swapping and maintenance cost. Following Shi and Hu (2022), m can be directly compared with the service price. Therefore, the profit function of BS services is described as:

$$\pi_b^j = d_b^j (p_b^j - w_v - m) - F_b,\ j \in \{bs, bf\}, \tag{6}$$

where $p_b^j - w_v - m$ represents the marginal profit and F_b is the fixed setup cost for BS stations.

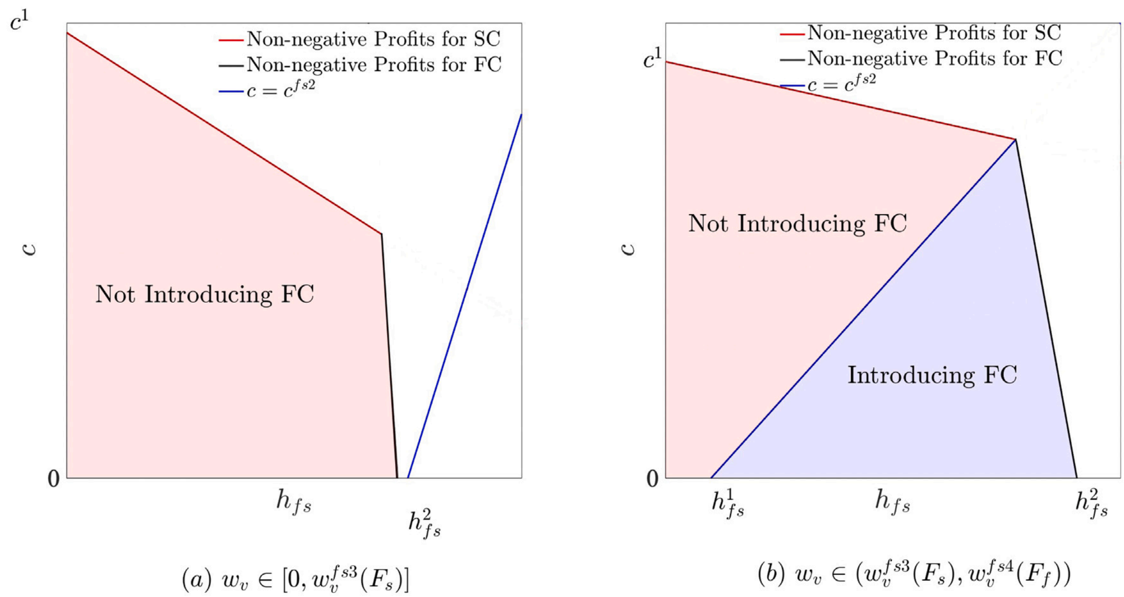

Fig. 1. Selection between FC and SC: Interaction between h_{fs} and c.[4] (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 3
Equilibrium solutions for FC and SC services.

	SC service $(i = s)$	FC service $(i = f)$
p_i^{fs*}	$\frac{2+\theta a_f-2h_{fs}+2w_v-\theta c+\theta w_p}{4-\theta^2}$	$\frac{2a_f-2c+2w_p-\theta h_{fs}+\theta w_v+\theta}{4-\theta^2}$
d_i^{fs*}	$\frac{2+\theta a_f-2h_{fs}-2w_v-\theta c+\theta w_p+\theta^2 w_v}{4-\theta^2}$	$\frac{2a_f-2c-2w_p-\theta h_{fs}+\theta w_v+\theta^2 w_p+\theta}{4-\theta^2}$
π_i^{fs*}	$\frac{(2+\theta a_f-2h_{fs}-2w_v-\theta c+\theta w_p+\theta^2 w_v)^2}{(4-\theta^2)^2} - F_s$	$\frac{(2a_f-2c-2w_p-\theta h_{fs}+\theta w_v+\theta^2 w_p+\theta)^2}{(4-\theta^2)^2} - F_f$

4. Equilibrium analysis

4.1. Opt for fast-charging?

We first investigate the case where EV charging service providers decide whether to provide FC services along with the existing SC services. In such case, the EV charging service providers determine the optimal service prices that maximize π_s^{fs} and π_f^{fs}. In order to avoid trivial cases, c satisfies $c \in [0, c_{max}]$[3] to make both π_s^{fs} and π_f^{fs} non-negative. Table 3 describes the equilibrium prices, demands, and profits for SC and FC services. Now, we examine the effects of various factors on the profit of each charging service. From the equilibrium results in Table 3, we obtain that π_s^{fs*} decreases in w_v but increases in w_p; whereas π_f^{fs*} increases in w_v but decreases in w_p. Surprisingly, both π_s^{fs*} and π_f^{fs*} decrease in h_{fs} and c. Intuitively, a FC service provider is more motivated to enter the market with a smaller cost disadvantage compared to its competitors (i.e., a lower w_p or a higher w_v). However, it is counterintuitive that an increase in the waiting time for SC services (h_{fs}) also reduces the profit of FC services. This occurs because an increase in the waiting cost savings amplifies the superiority of FC services, compelling SC services to lower their service price in order to stimulate demand. Consequently, this intensifies competition and negatively impacts the demand and profit of FC services. A similar principle can also elucidate the negative effect of battery loss (c) on the profit of SC services.

Next, we analyze the effects of introducing FC services on the price of SC and FC services and derive the following lemma.

Lemma 1. *There exist two thresholds, $w_v^{fs1}(F_f) < w_v^{fs2}(F_s)$, such that the service prices charged by the EV charging service provider in equilibrium satisfy:*

(i) $p_f^{fs*} > p_s^{fs*}$ *if* $w_v \in [0,\ w_v^{fs1}(F_f)]$, *or* $w_v \in (w_v^{fs1}(F_f),\ w_v^{fs2}(F_s))$ *and* $c < c^{fs1}$;
(ii) $p_f^{fs*} \le p_s^{fs*}$ *if* $w_v \in [w_v^{fs2}(F_s),\ w_p]$, *or* $w_v \in (w_v^{fs1}(F_f),\ w_v^{fs2}(F_s))$ *and* $c \ge c^{fs1}$;

where $w_v^{fs1}(F_f) = (2-\theta)(w_p + \sqrt{F_f}) - 1$, $w_v^{fs2}(F_s) = \frac{w_p + a_f}{2-\theta} - \sqrt{F_s}$ *and* $c^{fs1} = h_{fs} + \Delta w + (a_f - 1)$.

According to Lemma 1, the price difference between FC and SC services depends directly on the valley electricity price. When the valley electricity price is low ($w_v \in [0,\ w_v^{fs1}(F_f)]$), SC services can charge lower prices. However, a high valley electricity price increases the cost of SC services, leading to a higher price. Interestingly, when the valley electricity price is moderate ($w_v \in (w_v^{fs1}(F_f),\ w_v^{fs2}(F_s))$), the price difference between the two services is influenced by battery loss. When battery loss is high, FC services charge a lower price to compensate for the customer's utility loss, while low battery loss gives FC services more pricing power to charge a higher price. However, when both fixed investment costs for FC and SC are high, the moderating effect of the battery loss may disappear ($w_v^{fs1}(F_f) \approx w_v^{fs2}(F_s)$), making the price difference between SC and FC services solely dependent on the valley electricity price. This result has practical implications: when the fixed cost for both SC and FC is low, FC services should focus on updating its technology to reduce battery loss and gain a pricing advantage in the EV market.

We then examine the effects of introducing FC services on the profitability of SC and FC services and derive the following proposition:

Proposition 1. *There exist two thresholds, $w_v^{fs3}(F_s) < w_v^{fs4}(F_f)$, such that the profits in equilibrium satisfy:*

(i) $\pi_f^{fs*} < \pi_s^{fs*}$ *if* $w_v \in [0,\ w_v^{fs3}(F_s)]$, *or* $w_v \in (w_v^{fs3}(F_s),\ w_v^{fs4}(F_f))$ *and* $c > c^{fs2}$;

[3] $c_{max} = min\{ \frac{-2h_{fs}+2+\theta a_f-2w_v+\theta w_p+\theta^2 w_v-\sqrt{F_s}(4-\theta^2)}{\theta}, \frac{-\theta h_{fs}+2a_f-2w_p+\theta w_v+\theta^2 w_p+\theta-\sqrt{F_f}(4-\theta^2)}{2} \}$.

[4] For brevity and ease of exposition, we assume an ideal case for the FC service that $\Delta F_{fs} = 0$. $h^1_{fs} = (\theta+1)\Delta w - \left(a_f - 1\right)$, $h^2_{fs} = \frac{\theta}{2} w_p - \left(1 - \frac{\theta^2}{2}\right) w_v + \frac{\theta}{2} a_f + 1 - \frac{\sqrt{F_s}}{2}\left(4-\theta^2\right)$ and $c^1 = \frac{\theta}{2} w_v - \left(1 - \frac{\theta^2}{2}\right) w_p + a_f + \frac{\theta}{2} - \frac{\sqrt{F_f}}{2}\left(4-\theta^2\right)$.

(ii) $\pi_f^{fs*} \geq \pi_s^{fs*}$ *if* $\Delta F_{fs} \in [0,\ F_{fs}^1]$ *and* $c \leq c^{fs3}$;

where $w_v^{fs3}(F_s) = \frac{w_p - a_f + (2-\theta)\sqrt{F_s}}{\theta}$, $w_v^{fs4}(F_f) = \theta w_p - (2-\theta)\sqrt{F_f} + 1$, $c^{fs2} = h_{fs} - (\theta+1)\Delta w + (a_f - 1)$, $\Delta F_{fs}^1 = \frac{(a_f - w_p + \theta w_v)^2 - (1 - h_{fs} + \theta w_p - w_v)^2}{(4-\theta)^2}$ *and* $c^{fs3} = a_f - w_p + \theta w_v - \sqrt{(1 - h_{fs} + \theta w_p - w_v)^2 + (4-\theta)^2 \Delta F_{fs}}$; c^{fs3} *increases in* a_f, w_v, h_{fs} *whereas decreases in* w_p *and* ΔF_{fs}.

Proposition 1(i) suggests that the profitability of FC services depends primarily on the valley electricity price (w_v), as shown in Fig. 1(a). If the valley electricity price is sufficiently low ($w_v \in [0,\ w_v^{fs3}(F_s)]$), FC services will not be economically advantageous, even if the battery loss is minimal. When the valley electricity price is in the medium range ($w_v \in (w_v^{fs3}(F_s),\ w_v^{fs4}(F_f))$) FC can outperform SC services if the battery loss is below a threshold (See the blue line in Fig. 1(b)). This threshold is moderated by the difference of peak–valley electricity price (Δw). If the difference is larger, FC must reduce battery loss to gain a competitive edge in the charging market. Note that as the substitution effect between the two services is strong (i.e., $\theta > 0$), the negative impact of the difference of peak–valley electricity price on FC services can be amplified.

Proposition 1(ii) indicates that if the fixed setup costs of FC services can be managed at a certain level (ΔF_{fs} is below a threshold), the low battery loss can enable FC service to dominate SC services. However, this threshold is influenced by peak and valley electricity prices. Lower peak electricity prices or higher valley electricity prices can increase the threshold, making it less urgent for FC service to reduce battery loss. These findings complement previous studies that underestimate the impact of the electricity market and emphasize the importance of battery charging speed and battery damage in the EV charging service (Abouee-Mehrizi et al., 2021; Zhang et al., 2018). Additionally, we demonstrate that electricity prices can moderate the impact of charging speed and battery loss on the advantage of charging service. This finding has practical implications, especially during the energy crisis. For example, in 2022, the energy crisis led to a sharp rise in electricity prices in Europe, with the peak prices rising faster than valley prices, prompting EV drivers to charge their vehicles at home overnight to take advantage of cheaper valley electricity prices (Hickey, 2022). With rising electricity prices, particularly peak electricity prices, EV users usually find SC services to be the most cost-efficient option, creating a dilemma for FC services. This could be the reason why Tesla, a leading FC service provider, continues to focus on cultivating the energy storage market to avoid the negative impact of high peak electricity prices.[5]

4.2. Opt for battery-swapping?

Next, we investigate the case where the EV charging service provider decides whether to provide BS service along with SC services. The SC and BS service providers determine the optimal service prices that maximize π_s^{bs} and π_b^{bs}, respectively. In order to avoid trivial cases, we focus on the case that satisfies the condition of π_s^{bs} and π_b^{bs} are non-negative. That is, unit service costs m satisfies $m \in [m_{\min}^{bs}, m_{\max}^{bs}]$.[6]

Based on the equilibrium solutions in Table 4, we derive that both π_s^{bs*} and π_b^{bs*} decrease in w_v and h_{bs}; π_s^{bs*} increases in m whereas π_b^{bs*} decreases in m. Similar to the previous analysis, the long charging time of SC services (h_{bs}) exerts a knock-on negative effect on the demand and profit of the alternative service. In contrast, compared with battery loss

Table 4
Equilibrium solutions for BS and SC services.

	SC service ($i = s$)	BS service ($i = b$)
p_i^{bs*}	$\frac{2+\theta a_b - 2h_{bs} + 2w_v + \theta m + \theta w_v}{4-\theta^2}$	$\frac{2a_b + 2\ m + 2w_v - \theta h_{bs} + \theta w_v + \theta}{4-\theta^2}$
d_i^{bs*}	$\frac{2+\theta a_b - 2h_{bs} - 2w_v + \theta m + \theta w_v + \theta^2 w_v}{4-\theta^2}$	$\frac{2a_b + \theta - 2\ m - 2w_v - \theta h_{bs} + \theta w_v + \theta^2\ m + \theta^2 w_v}{4-\theta^2}$
π_i^{bs*}	$\frac{(2+\theta a_b - 2h_{bs} - 2w_v + \theta m + \theta w_v + \theta^2 w_v)^2}{(4-\theta^2)^2} - F_s$	$\frac{(2a_b + \theta - 2\ m - 2w_v - \theta h_{bs} + \theta w_v + \theta^2\ m + \theta^2 w_v)^2}{(4-\theta^2)^2} - F_b$

(c) in FC services, unit service costs (m) have a negative effect on the profit of BS services, but a positive effect on the profit of SC services. This is because an increase in unit service costs forces the BS service provider to raise the service price to cover the extra operational costs, which allows the alternative service to gain price competitiveness. We further analyze the effects of introducing the BS service on the prices and the profits of SC and BS services and derive the following lemma and proposition.

Lemma 2. *There exists a threshold,* $w_v^{bs1}(F_b)$*, such that the service prices charged by the EV charging service provider in equilibrium satisfy:*

(i) *given* $a_b \geq 1, p_b^{bs*} \geq p_s^{bs*}$;

(ii) *given* $a_b < 1, p_b^{bs*} < p_s^{bs*}$ *if* $w_v \in (w_v^{bs1}(F_b),\ w_p]$, *or* $w_v \in (0,\ w_v^{bs1}(F_b))$ *and* $m < m^{bs1}$; $p_b^{bs*} \geq p_s^{bs*}$ *if* $w_v \in [0, w_v^{bs1}(F_b)]$ *and* $m \geq m^{bs1}$;

where $w_v^{bs1}(F_b) = \frac{-1+(1+2\theta)a_b+\theta^2-\theta(4-\theta^2)\sqrt{F_b}}{\theta(2+\theta)(1-\theta)}$ *and* $m^{bs1} = 1 - a_b - h_{bs}$.

Lemma 2 suggests that the price difference between BS and SC services is initially influenced by the potential market size. BS services always charge higher prices when their market is larger than the SC services. Conversely, if their market is smaller than the SC services, the price of BS services is first affected by the valley electricity price. A high valley electricity price ($w_v \in [w_v^{bs1}(F_b), w_p]$) would increase the price for both SC and BS services. However, BS services charge a lower price. When the valley electricity price is low ($w_v \in (0,\ w_v^{bs1}(F_b))$), the price difference between two services is further influenced by the unit service cost of BS services. Specifically, when m exceeds a threshold level (m^{bs1}), the BS service charges a higher price due to the operational cost disadvantage compared to the competitors. However, when the fixed setup cost for BS services is high, the impacts of the unit service cost may dissipate ($w_v^{bs1}(F_b) \approx 0$), rendering market size and valley electricity price as the only influential factors. This result highlights that, when the fixed setup costs of BS services are low, the role of service cost efficiency in boosting BS services' pricing competitiveness is significant.

Proposition 2. *There exist two thresholds,* $w_v^{bs1}(F_b) < w_v^{bs2}(F_b)$*, such that the profits in equilibrium satisfy:*

(i) *given* $a_b \geq 1, \pi_b^{bs*} < \pi_s^{bs*}$ *if* $w_v \in [0,\ w_v^{bs2}(F_b)]$ *and* $m > m^{bs2}$; *given* $a_b < 1, \pi_b^{bs*} < \pi_s^{bs*}$ *if* $w_v \in [w_v^{bs1}(F_b),\ w_p]$, *or* $w_v \in [0,\ w_v^{bs1}(F_b))$ *and* $m > m^{bs2}$;

(ii) $\pi_b^{bs*} \geq \pi_s^{bs*}$ *if* $\Delta F_{bs} \in [0,\ \Delta F_{bs}^1]$ *and* $m \leq m^{bs3}$;

where $w_v^{bs1}(F_b) = \frac{-1+(1+2\theta)a_b+\theta^2-\theta(4-\theta^2)\sqrt{F_b}}{\theta(2+\theta)(1-\theta)}$, $w_v^{bs2}(F_b) = \frac{1}{4-\theta^2}[2a_b + \theta - (4-\theta^2)\sqrt{F_b} - \frac{(1-a_b)(2-\theta^2)}{1+\theta}]$, $m^{bs2} = \frac{h_{bs}-(1-a_b)}{1+\theta}$, $\Delta F_{bs}^1 = \frac{[a_b-(1-\theta^2)w_v+\theta(1-h_{bs})]^2-[1-(1-\theta^2)w_v+\theta a_b-h_{bs}]^2}{(1-\theta^2)(4-\theta)^2}$ *and* $m^{bs3} = \frac{1}{1-\theta^2}[a_b - (1-\theta^2)w_v + \theta(1-h_{bs}) - \sqrt{(1-(1-\theta^2)w_v + \theta a_b - h_{bs})^2 + (1-\theta^2)(4-\theta^2)\Delta F_{bs}}]$; m^{bs3} *increases in* a_b, h_{bs} *whereas decreases in* w_v *and* ΔF_{bs}.

Proposition 2(i) demonstrates that the profitability of BS services primarily depends on the valley electricity price, which is consistent with the cases of FC services in Proposition 1(i). The impact of valley electricity price on BS services' profitability is further influenced by either the potential market size, the unit service cost efficiency, or a combination of both factors. Specifically, when the valley electricity

[5] Tesla's energy storage arm caps 2022 with 'highest level' of deployments ever, https://www.reuters.com/business/sustainable-business/tesla-opens-first-charging-station-china-with-energy-storage-facilities-2021-06-23/, assessed on 24th March.

[6] $m_{\min}^{bs} = \frac{2}{\theta}h_{bs} + \frac{2-\theta-\theta^2}{\theta}w_v - a_b - \frac{2}{\theta} + \frac{\sqrt{F_s}}{\theta}(4-\theta^2)$ and $m_{\max}^{bs} = -\frac{\theta}{2-\theta^2}h_{bs} - \frac{2-\theta-\theta^2}{2-\theta^2}w_v + \frac{2}{2-\theta^2}a_b + \frac{\theta}{2-\theta^2} - \frac{\sqrt{F_b}}{2-\theta^2}(4-\theta^2)$.

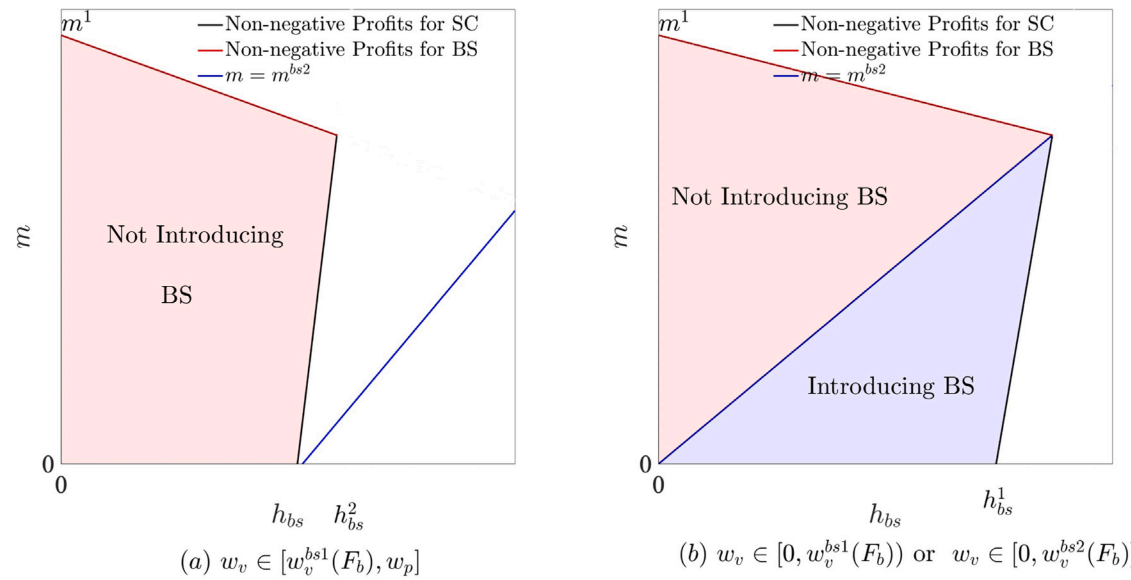

Fig. 2. Service selection between BS and SC: interaction between h_{bs} and m.[7]

price is high ($w_v \in [w_v^{bs1}(F_b), w_p]$), and the potential market of BS services is smaller than its competitor, it will not be economically advantageous, even if the corresponding service efficiency is high, as shown in Fig. 2(a). Conversely, if the valley electricity price is low ($w_v \in [0, \min\{w_v^{bs1}(F_b), w_v^{bs2}(F_b)\}] \Rightarrow w_v \in [0, w_v^{bs1}(F_b)]$), the profitability of BS services depends entirely on the unit service efficiency, rendering the potential market size less important. If the valley electricity price falls within the medium range ($w_v \in (w_v^{bs1}(F_b), w_v^{bs2}(F_b)]$), both market size and unit service cost should be taken into account. The latter two scenarios are illustrated in Fig. 2(b).

Proposition 2(ii) illustrates that controlling the fixed setup cost to a low level can allow BS services to achieve economic viability if the unit service cost falls below a certain threshold ($m \leq m^{fs3}$). The negative effect of a unit service cost on the profitability of BS services is intensified by valley electricity prices. It implies that high valley electricity prices make it more urgent for BS services to decrease the service cost. Additionally, high valley electricity prices will reduce the profitability of BS services more than SC services. This finding is counterintuitive, as conventional wisdom would underestimate this effect, given that both SC and BS services can benefit from low valley electricity prices. Our results indicate that BS services face difficulties in taking advantage of valley electricity prices to recharge their spare batteries during energy crisis periods, making energy storage a potential solution.

5. Effects of technological improvement

In this section, we examine the impacts of advancements in FC and BS technologies on the selection of EV charging services. We focus on technological improvements that reduce battery loss in FC services and improve unit service cost efficiency for BS services while enhancing charging and swapping speeds for both.

5.1. Technological effect on FC adoption

Recall that without technological advancements, faster charging often sacrifices battery lifespan. Replacing lithium-ion batteries with graphene batteries can enhance both battery life and charging speed. We use x^{fs} to represent battery loss reduction for FC services, while γ captures the extent of increased waiting cost savings, with $\gamma \in [0, 1]$. Following prior studies (Li and Zhao, 2022; Gupta, 2008), a negative quadratic term represents diminishing returns to R&D expenditure. The updated demand functions for SC and FC services are reformulated as:

$$d_s^{fs} = 1 - p_s^{fs} - \left(h_{fs} + \gamma x^{fs}\right) + \theta p_f^{fs}, \tag{7}$$

$$d_f^{fs} = a_f - p_f^{fs} - \left(c - x^{fs}\right) + \theta p_s^{fs}. \tag{8}$$

Technological advancements reduce battery loss for FC services by x^{fs}, boosting customer utility and total demand. As charging speed is enhanced in FC services, the relative waiting cost for SC services increases by γx^{fs} when normalizing FC waiting costs to 0. b_f signifies the cost efficiency of technological efforts. Consequently, the updated profit functions are:

$$\pi_s^{fs} = \left(p_s^{fs} - w_v\right) d_s^{fs} - F_s, \tag{9}$$

$$\pi_f^{fs} = \left(p_f^{fs} - w_p\right) d_f^{fs} - \frac{1}{2} b_f {x^{fs}}^2 - F_f. \tag{10}$$

In line with existing research (Gupta, 2008), we assume a lower limit for b_f to guarantee the existence and uniqueness of effort-level equilibria: $b_f > b_{fmin}$, where $b_{fmin} = \frac{2(2-\theta\gamma)^2}{\left(4-\theta^2\right)^2}$. This assumption reflects high unit costs of technological improvement and aligns with the EV market practice where substantial expenditure is required for FC service development (Zhang et al., 2018).

Optimal solutions are derived via a two-stage game. First, the FC service provider determines the effort level (x^{fs}) for technological improvement. Subsequently, both FC and SC providers simultaneously set service prices. Table 5 outlines the equilibrium results, with analytical outcomes based on this comparison denoted by the superscript fsT.

A comparison of equilibrium results leads to the following proposition:

Proposition 3.

(i) $\pi_f^{fsT*} > \pi_f^{fs*}$;

(ii) *if* $\theta > 2\gamma$, $\pi_s^{fsT*} > \pi_s^{fs*}$; *if* $\theta \leq 2\gamma$, $\pi_s^{fsT*} \leq \pi_s^{fs*}$;

[7] For brevity and ease of exposition, we assume an ideal case for the BS service that $\Delta F_{bs} = 0$. $h_{bs}^1 = -\frac{2-\theta-\theta^2}{2} w_v + \frac{\theta}{2} a_b + 1 - \frac{\sqrt{F_s}}{2}\left(4-\theta^2\right), m^1 = -\frac{2-\theta-\theta^2}{2} w_v + \frac{2}{2-\theta^2} a_b + \frac{2}{2-\theta^2} - \frac{\sqrt{F_b}}{2-\theta^2}\left(4-\theta^2\right)$ and $h_{bs}^2 = 1 - a_b$.

Table 5
Equilibrium solutions for FC and SC services with technological improvement.

	SC service ($i = s$)	FC service ($i = f$)
p_i^{fsT*}	$\frac{2+\theta a_f-2h_{fs}+2w_v-\theta c+\theta w_p+\theta x^{fs*}-2\gamma x^{fs*}}{4-\theta^2}$	$\frac{2a_f-2c+2w_p-\theta h_{fs}+\theta w_v+\theta+2x^{fs*}-\theta\gamma x^{fs*}}{4-\theta^2}$
d_i^{fsT*}	$\frac{2+\theta a_f-2h_{fs}-2w_v-\theta c+\theta w_p+\theta^2 w_v+\theta x^{fs*}-2\gamma x^{fs*}}{4-\theta^2}$	$\frac{2a_f-2c-2w_p-\theta h_{fs}+\theta w_v+\theta^2 w_p+\theta+2x^{fs*}-\theta\gamma x^{fs*}}{4-\theta^2}$
π_i^{fsT*}	$\frac{\left(2+\theta a_f-2h_{fs}-2w_v-\theta c+\theta w_p+\theta^2 w_v+\theta x^{fs*}-2\gamma x^{fs*}\right)^2}{\left(4-\theta^2\right)^2} - F_s$	$\frac{\left(2a_f-2c-2w_p-\theta h_{fs}+\theta w_v+\theta^2 w_p+\theta+2x^{fs*}-\theta\gamma x^{fs*}\right)^2}{\left(4-\theta^2\right)^2} - \frac{b_f}{2} x^{fs*2} - F_f$
x^{fs*}	\	$\frac{2\left(2a_f-2c-2w_p-\theta h_{fs}+\theta w_v+\theta^2 w_p+\theta\right)(2-\theta\gamma)}{b_f\left(4-\theta^2\right)^2-2(2-\theta\gamma)^2}$

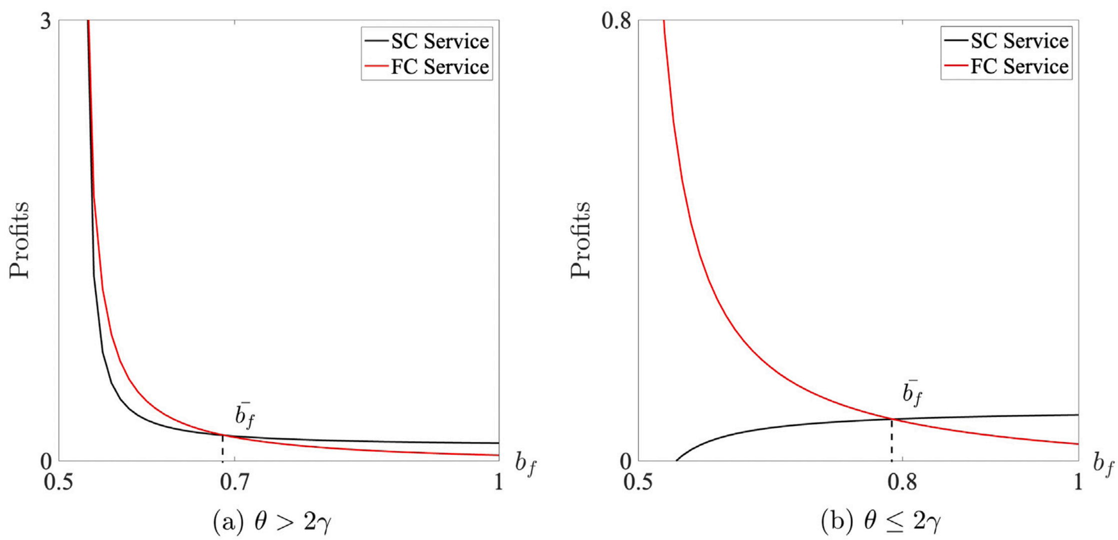

Fig. 3. Effect of b_f on service selection between FC and SC with technological improvement.

(iii) *if* $\pi_f^{fsT*}\Big|_{b_f=b_{fmin}} > \pi_s^{fsT*}\Big|_{b_f=b_{fmin}}$ *and* $b_f < \bar{b_f}$*, FC services are more profitable than SC services; otherwise, SC services generate more profit.*

Proposition 3(i) reveals that regardless of technological cost efficiency, FC service profits always rise after reaching the optimal investment in technological improvement ($\pi_s^{fsT*}\left(b_f\right) > \pi_s^{fs*}$), with the maximum profit occurring when cost efficiency approaches its maximum threshold ($b_f \approx b_{fmin}$). Proposition 3(ii) presents an interesting outcome: the impact of technological advancements in FC services on SC services can be both positive or negative, depending on the relationship between the service substitution effect θ and the increase in the relative waiting cost γ, as shown in Fig. 3. This is because on one hand, technological advancements can mitigate competition between two services and positively affect SC services. While on the other hand, it may limit the customer base for SC services, primarily appealing to those who are less concerned with charging speed and reducing its profits. Proposition 3(iii) shows that when technological cost efficiency exceeds its threshold ($b_f < \bar{b_f}$), FC services become more profitable, potentially driving SC services out the market. This encouraging observation highlights that even if rising electricity prices may pose challenges for FC services, continuous improvements in technological efficiency ensure their competitiveness in the foreseeable future.

5.2. Effect of battery-swapping adoption

We now investigate the impact of technological advancements on the adoption of BS services. Following Cui et al. (2022), we assume reducing unit service costs and enhancing BS speed concurrently can increase relative waiting costs for SC services. Specifically, by launching new BS stations featuring advanced technologies, BS speed is enhanced, and costs related to battery dispatching, swapping, and maintenance are reduced by increasing battery storage slots, enhancing battery transportation efficiency, and the development of automation technology (Cui et al., 2022). Additionally, ongoing advancements in battery technology, such as the adoption of solid-state batteries, can reduce the per-service amortized battery cost by up to 17% (Kimani, 2022).

We define x^{bs} as the reduction in unit service cost and γx^{bs} reflects the increase in additional waiting cost for SC services when normalizing waiting costs for BS services to 0, with $\gamma \in [0, 1]$. The demand functions for SC and BS services are reformulated as:

$$d_s^{bs} = 1 - p_s^{bs} - \left(h_{bs} + \gamma x^{bs}\right) + \theta p_b^{bs}, \tag{11}$$

$$d_b^{bs} = a_b - p_b^{bs} + \theta p_s^{bs}. \tag{12}$$

A negative quadratic term, $-\frac{1}{2} b_b x^{bs^2}$ is still employed to capture the diminishing returns on the R&D expenditure for technical effort. Consequently, the updated profit functions for both services are:

$$\pi_s^{bs} = \left(p_s^{bs} - w_v\right) d_s^{bs} - F_s, \tag{13}$$

$$\pi_b^{bs} = \left(p_b^{bs} - w_v - m + x^{bs}\right) d_b^{bs} - \frac{1}{2} b_b x^{bs^2} - F_b. \tag{14}$$

We assume $b_b > b_{bmin}$ and $b_{bmin} = \frac{2\left(2-\theta^2-\theta\gamma\right)^2}{\left(4-\theta^2\right)^2}$ to guarantee the existence and uniqueness of the effort-level equilibria. The BS service provider first determines the effort level (x^{fs}) for improving the BS process. Subsequently, the SC and BS service providers set their service prices. Equilibrium solutions are presented in Table 6, with analytical results denoted by the superscript bsT. A comparison of these results leads to Proposition 4.

Proposition 4.

(i) $\pi_b^{bsT*} > \pi_b^{bs*}$;
(ii) $\pi_s^{bsT*} < \pi_s^{bs*}$;

Table 6
Equilibrium solutions for BS and SC services with technological improvement.

	SC service ($i = s$)	BS service ($i = b$)
p_i^{bsT*}	$\frac{2+\theta a_b-2h_{bs}+2w_v+\theta m+\theta w_v-\theta x^{bs*}-2\gamma x^{bs*}}{4-\theta^2}$	$\frac{2a_b+2m+2w_v-\theta h_{bs}+\theta w_v+\theta+2x^{bs*}-\theta^2 x^{bs*}-\theta\gamma x^{bs*}}{4-\theta^2}$
d_i^{bsT*}	$\frac{2+\theta a_b-2h_{bs}-2w_v+\theta m+\theta w_v+\theta^2 w_v-\theta x^{bs*}-2\gamma x^{bs*}}{4-\theta^2}$	$\frac{2a_b-2m-2w_v-\theta(h_{bs}+w_v+1-\gamma x^{bs*})+\theta^2(m+w_v-x^{bs*}+2x^{bs*})}{4-\theta^2}$
π_i^{bsT*}	$\frac{(2+\theta a_b-2h_{bs}-2w_v+\theta m+\theta w_v+\theta^2 w_v-\theta x^{bs*}-2\gamma x^{bs*})^2}{(4-\theta^2)^2} - F_s$	$\frac{(2a_b+\theta-2m-2w_v-\theta h_{bs}+\theta w_v+\theta^2 m+\theta^2 w_v+2x^{bs*}-\theta^2 x^{bs*}-\theta\gamma x^{bs*})^2}{(4-\theta^2)^2} - \frac{b_b}{2} x^{bs*2} - F_b$
x^{bs*}	\	$\frac{2(2a_b+\theta-2m-2w_v-\theta h_{bs}+\theta w_v+\theta^2 m+\theta^2 w_v)(2-\theta^2-\theta\gamma)}{b_b(4-\theta^2)^2-2(2-\theta^2-\theta\gamma)^2}$

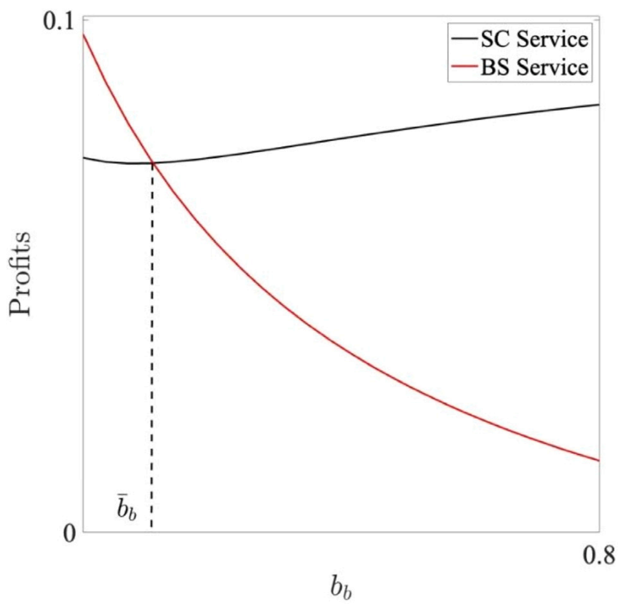

Fig. 4. Effect of b_b on service selection between BS and SC with technological improvement.

(iii) *if* $\pi_b^{bsT*}\big|_{b_b=b_{bmin}} > \pi_s^{bsT*}\big|_{b_f=b_{bmin}}$ *and* $b_b < \bar{b}_b$, *BS services are more profitable than SC services; otherwise, SC services generate more profits.*

In line with FC services, optimal investment level in technology consistently boosts BS service profitability, regardless of the technological cost efficiency. Intuitively, when technological cost efficiency approaches its highest level ($b_f \approx b_{bmin}$), the profitability of BS services is maximized. However, Fig. 4 illustrates that technological improvement in BS services decreases the profitability of SC services, which is in contrast to the effects of technological improvement in FC services. Proposition 4(iii) demonstrates that a high level of technological cost efficiency ($b_b < \bar{b}_b$) can help mitigate the negative impact of increasing valley electricity prices, potentially enabling continued market expansion for BS services and eventual dominance over SC services.

6. Choose between fast-charging and battery-swapping

According to IEA (2022), slow charging (SC) services dominate 80% of the current EV charging market. However, public and commercial charging infrastructure, including FC and BS, is growing more rapidly than private SC infrastructure. In 2021, public charging infrastructure experienced a 48% annual growth rate, significantly higher than the 33% for SC services. This section assumes that due to advancements in charging technology, SC services may eventually be displaced from the EV charging market. In this scenario, EV charging service providers would choose between FC and BS services. The potential market sizes for these two services are defined as a_f and a_b, with $a_b = a_f + \Delta a$. To maintain non-negative profit constraints, unit service costs must satisfy: $m \in \left[m_{\min}^{bf},\ m_{\max}^{bf}\right]$.[8] Table 7 presents the optimal prices and profits for FS and BS services.

Table 7
Equilibrium solutions for the FC and BS services.

	FC service ($i = f$)	BS service ($i = b$)
p_i^{fb*}	$\frac{2a_f-2c-2h_{bf}+2w_p+\theta a_b+\theta m+\theta w_v}{4-\theta^2}$	$\frac{2a_b+2m+2w_v+\theta a_f-\theta c-\theta h_{bf}+\theta w_p}{4-\theta^2}$
d_i^{fb*}	$\frac{2a_f-2c-2h_{bf}-2w_p+\theta a_b+\theta m+\theta w_v+\theta^2 w_p}{4-\theta^2}$	$\frac{2a_b-2m-2w_v+\theta a_f-\theta c-\theta h_{bf}+\theta w_p+\theta^2 m+\theta^2 w_v}{4-\theta^2}$
π_i^{fb*}	$\frac{(2a_f-2c-2h_{bf}-2w_p+\theta a_b+\theta m+\theta w_v+\theta^2 w_p)^2}{(4-\theta^2)^2} - F_f$	$\frac{(2a_b-2m-2w_v+\theta a_f-\theta c-\theta h_{bf}+\theta w_p+\theta^2 m+\theta^2 w_v)^2}{(4-\theta^2)^2} - F_b$

Based on Table 7, we derive that π_f^{bf*} increases in w_v but decreases in w_p; whereas π_b^{bf*} decreases in w_v but increases in w_p. Both π_f^{bf*} and π_b^{bf*} decrease in c and h_{bf}. π_f^{bf*} increases in m whereas π_b^{bf*} decreases in m. These findings first suggest that the superiority of FC services will persist if the peak–valley electricity price difference is small. Large unit service costs (m) of BS services help FC services gain a price advantage while high values of waiting time (h_{bf}) and battery loss (c) intensify competition between the two charging services, which erodes the profits of the two services. We derive the following lemma by comparing the equilibrium price decisions of the two services.

Lemma 3. *There exist two thresholds,* $a_b^{bf2}(F_b) < a_b^{bf1}$*, such that the service prices charged by the EV charging service provider in equilibrium satisfy:*

(i) $p_b^{bf*} > p_f^{bf*}$ *if* $a_b \geq a_b^{bf1}$*, or* $a_b \in (a_b^{bf2}(F_b),\ a_b^{bf1})$ *and* $m > m^{bf1}$*;*
(ii) $p_b^{bf*} \leq p_f^{bf*}$ *if* $a_b \in [0,\ a_b^{bf2}(F_b)]$*, or* $a_b \in (a_b^{bf2}(F_b),\ a_b^{bf1})$ *and* $m \leq m^{bf1}$*;*

where $a_b^{bf1} = a_f - h_{bf} + \Delta w$, $a_b^{bf2}(F_b) = (1-\theta)w_v + (2-\theta)\sqrt{F_b}$ *and* $m^{bf1} = -c - h_{bf} + \Delta w - \Delta a$.

Lemma 3 reveals that the price difference between FC and BS services is primarily dependent on their potential market sizes. BS services charge higher prices when their market size is large ($a_b \geq a_b^{bf1}$), even with high unit service cost efficiency, and vice versa ($a_b \in [0, a_b^{bf2}(F_b)]$). When the market size is moderate ($a_b \in (a_b^{bf2}(F_b),\ a_b^{bf1})$), the price difference between two services is influenced by the unit service cost. As the cost efficiency increases, the price disadvantage of BS services reduces. Interestingly, the effect of unit service cost efficiency on the price difference is influenced by BS services' fixed setup cost but remains unaffected by FC services' fixed setup cost (a_b^{bf1} and a_b^{bf2} is independent of F_f). When F_b is large (equivalently, $a_b^{bf2}(F_b) \approx a_b^{bf1}$), the impact of unit service cost efficiency diminishes.

We now examine the equilibrium profits of both services and present the following proposition.

Proposition 5. *There exist three thresholds,* a_b^3, a_b^4 *and* a_b^5*, such that the profits in equilibrium satisfy:*

[8] $m_{\min}^{bf} = \frac{2}{\theta}c + \frac{-2a_f-\theta a_b+2h_{bf}-\theta w_v+(2-\theta^2)w_p+\sqrt{F_f}(4-\theta^2)}{\theta}$ and $m_{\max}^{bf} = -\frac{\theta}{2-\theta^2}c + \frac{2a_b+\theta a_f-\theta h_{bf}+\theta w_p-(2-\theta^2)w_v-\sqrt{F_b}(4-\theta^2)}{2-\theta^2}$.

(i) $\pi_b^{bf*} < \pi_f^{bf*}$ *if* $a_b \in [0, min\{a_b^3,\ a_b^5\}]$, *or* $a_b^3 < a_b^5, a_b \in [a_b^3,\ a_b^5]$ *and* $m > m^{bf2}$, *or* $a_b > a_b^4$ *and* $m > m^{bf2}$;
(ii) $\pi_b^{bf*} \geq \pi_f^{bf*}$ *if* $\Delta F_{bf} \in [0, \Delta F_{bf}^1]$ *and* $m \leq m^{bf3}$;

where $a_b^3 = -\theta w_p + w_v + (2-\theta)\sqrt{F_b}$, $a_b^4 = \frac{-a_f+h_{bf}+\sqrt{F_b}(1+\theta)(2-\theta)}{\theta} + \frac{w_p(1+\theta)^2(2-\theta)}{\theta(2+\theta)}$, $a_b^5 = a_f - h_{bf} - (1+\theta)\Delta w$, $m^{bf2} = \frac{c+h_{bf}+(1+\theta)\Delta w+\Delta a}{1+\theta}$, $\Delta F_{bf}^1 = \frac{[a_b+\theta a_f-(1-\theta^2)w_v-\theta(c+h_{bf})]^2-[\theta a_b+a_f-(1-\theta^2)w_p-c-h_{bf}]^2}{(1-\theta^2)(4-\theta)^2}$ *and* $m^{bf3} = \frac{a_b+\theta a_f-(1-\theta^2)w_v-\theta c-\theta h_{bf}}{1-\theta^2} - \frac{\sqrt{(\theta a_b+a_f-c-h_{bf}-(1-\theta^2)w_p)^2+(1-\theta^2)(4-\theta^2)\Delta F_{bf}}}{1-\theta^2}$; m^{bf3} *increases in* a_b, h_{bf}, c, w_p *whereas decreases in* $a_f, w_v, \Delta F_{bf}$.

Proposition 5(i) suggests that the profitability of BS services relative to FC services primarily hinges on potential market sizes. BS services never achieve an economic advantage if the potential market is limited. If the market size is large, high unit service efficiency will enhance the economical advantage of BS services. The above findings contrast with Propositions 1 and 2(i), where SC services remain in the market, and electricity prices serve as key factors for the adoption of FC and BS services. This finding suggests that in the future public EV charging market, reducing unit service costs (i.e., battery acquisition, dispatching, and maintenance cost) will ensure an economical advantage for BS services only if their market size is substantial enough. This implies that since BS services are more resource-constrained than FC services, their main priority should be on expanding the market through infrastructure development and government subsidies. The corresponding market size thresholds are either moderated or intensified by the differences in peak–valley electricity prices (a_b^5) and fixed setup costs (a_b^3). Proposition 5(ii) indicates that high unit service cost efficiency enables BS services to dominate FC services if their fixed cost disadvantage is not substantial.

7. Numerical analysis

In this section, a numerical analysis is conducted to illustrate the extent to which reductions in fixed set up costs and technological improvements have influenced the economic performance of the charging services, thereby deriving insights and managerial implications on the strategic investment decisions for the service provider. We choose values meet the condition that $h_{fs} < h_{bs}$ and $w_v < w_p$, along with other non-negative constraints. Thus, we conduct our numerical analysis by setting $h_{fs} = 0.2$, $h_{bs} = 0.25$, $w_v = 0.1$, $w_p = 0.2$, $\theta = 0.4$, $c = 0.1$, $m = 0.1$, $\gamma = 0.1$, $b_f = 0.6$ and $b_b = 0.6$. In addition, given the evidence that the peak–valley electricity price difference is expected to exceed 40%, we set it to be 50% to reflect real-world scenarios.[9]

7.1. Effect of fixed setup cost reduction

Fig. 5 presents the effects of fixed setup cost reduction on the relationship between the potential market size of FC or BS services and their respective profitability. We show that when fixed setup costs for FC (or BS) services decrease (as indicated by the red arrow), the minimum thresholds of market size shift from a_{flarge}^{fs} to a_{fsmall}^{fs} and ultimately to a_{fmin}^{fs} (or from a_{blarge}^{bs} to a_{bsmall}^{bs} and then to a_{bmin}^{bs}). Above these thresholds, FC (or BS) services become more profitable compared to SC services. Even with minimal differences in fixed setup costs, the market size threshold for FC services must exceed a_{fmin}^{fs} to maintain their economic competitiveness. a_{fmin}^{fs} is likely to exceed 1, indicating that even with significant fixed setup cost reductions, FC services achieve greater profitability only if they secure a larger market than SC services. Conversely, when the fixed setup cost for FC and BS services are equal (i.e., $\Delta F_{fs} = \Delta F_{bs}$), BS services require a smaller market size than FC services to outperform SC services in terms of profitability (i.e., $a_{bsmall}^{bs} < a_{flarge}^{fs}$). Additionally, a substantial reduction in fixed setup costs for BS services may enable them to outperform SC services, even in a limited market (i.e., $a_{bmin}^{bs} < 1$). These findings suggest that reducing fixed setup costs is a more effective way for BS services than FC services, in order to achieve prominence as a widely adopted charging solution.

7.2. Effect of technological improvement

Fig. 6 demonstrates the impact of technological advancements on the profitability of alternative charging services across various market sizes. In contrast to $a_{fmin}^{fs} > 1$ in Figs. 5(a), 6(a) shows a_{fmin}^{fsT}, a_{fsmall}^{fsT}, and a_{flarge}^{fsT} all being less than 1. This suggests that technological advancements can enhance the profitability of FC services, even in a limited market (i.e., $a_{flarge}^{fsT} < 1$), and with relatively minor fixed setup cost reductions. Regarding BS services, given the same fixed setup costs as FC services (i.e., $\Delta F_{bs} = \Delta F_{fs} = 1$), they may still necessitate a larger market size than FC services (i.e., $a_{bsmall}^{bsT} > a_{flarge}^{fsT}$) to achieve economic competitiveness. In other words, if the market size of the new services is constrained and the fixed setup costs are equal, technological improvements will bolster the profitability of FC services more significantly, making them a more appealing choice over BS services.

From the management perspective, reducing fixed setup costs and technological improvement are two aspects that can be prioritized for EV charging service development. While the former is crucial for BS services, the latter is more effective for FC services. Our findings also offer theoretical explanations for the EV charging service business models chosen by Tesla and NIO. Tesla has strategically abandoned BS services, partially due to the obstacle of construction and equipment costs and limited subsidies from governments on fixed setup costs, despite the technological improvement in this area (Zhang et al., 2018; Feng and Lu, 2021). Conversely, as a Chinese company, NIO benefits from cheaper unit service costs and government subsidies on fixed setup costs, which have been critical to the success of its BS program.

8. Conclusion

EV charging service providers are investing in new charging services with the goal of providing customers with faster service speeds. This study systematically evaluates the economic performance of alternative EV charging services. Specifically, we derive the equilibrium solutions for SC, FC, BS services as well as the condition of making FC or BS services economically competitive. We analyze the effects of internal technological and operational factors (i.e., battery charging/swapping speeds, battery losses, unit service costs, and fixed setup costs) and external market factors (i.e., market size and peak and valley electricity prices) on the service prices and the profitability of the alternative EV charging services. The explorations are conducted in scenarios where SC services are prevalent in the existing EV charging market and can be squeezed out of the future public EV charging market, with technological advancements and/or reduction in the fixed setup costs of FC and BS services. Some interesting findings are summarized as:

First, we show that in competitive EV charging markets with low valley electricity prices, improving battery loss cannot increase the competitiveness of FC services. When valley electricity prices are high and the market is small, reducing unit service costs cannot make BS services more profitable than SC services. This finding contrasts with existing research on EV adoption (Avci et al., 2014; Anjos et al., 2020; Shi and Hu, 2022). Second, our results reveal that valley electricity prices mitigate the adverse effects of battery loss on FC services while intensifying the negative effects of unit service costs on BS services. Interestingly, although both SC and BS services can benefit from the

[9] See https://news.metal.com/newscontent/101613207/the-price-difference-between-peak-and-valley-electricity-is-expanded-and-energy-storage-subsidy-policies-are-issued-in-many-places-the-industry-is-expected-to-usher-in-large-scale-development. Accessed December 18, 2023.

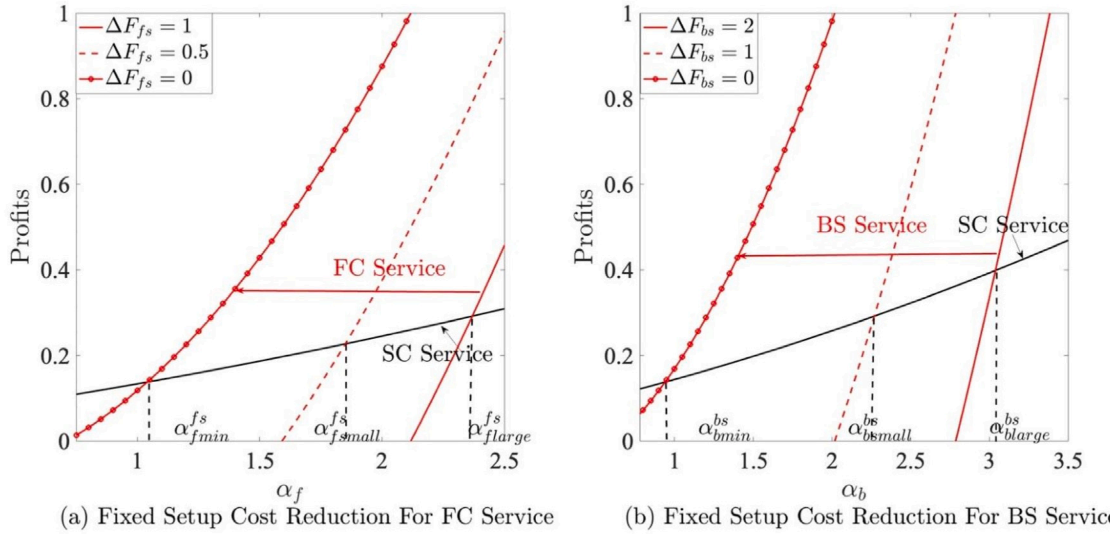

Fig. 5. Effect of fixed setup cost reduction on service selection.

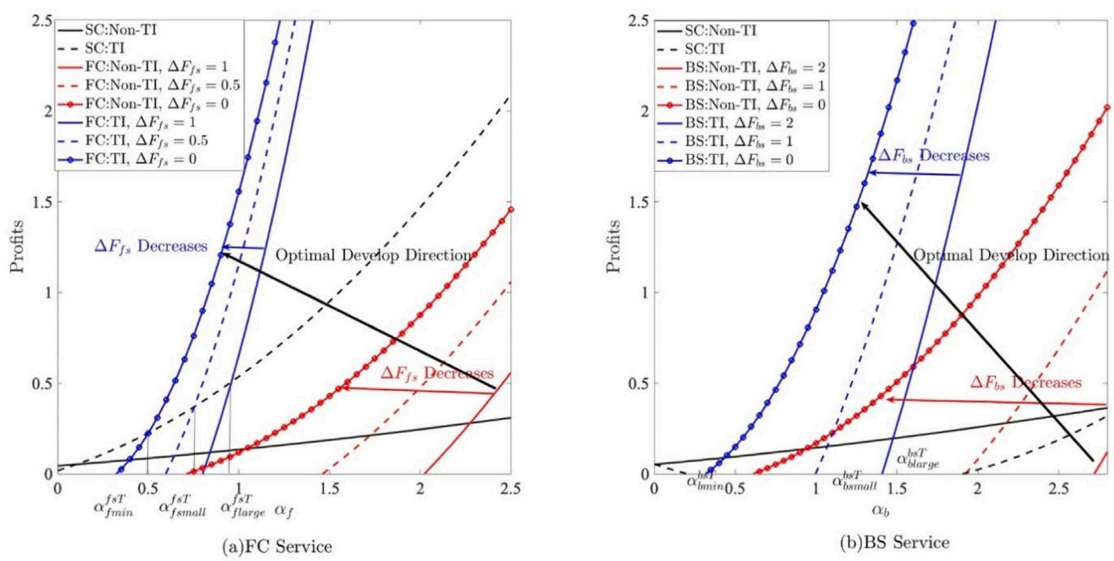

Fig. 6. Effect of technological improvement on service selection.

valley electricity prices, a rise in these prices will have a more negative effect on BS services. Third, technological advancements in FC and BS services, aimed at simultaneously enhancing charging/swapping speeds and reducing battery loss/unit service costs, may yield contrasting effects on SC services. Specifically, the impact of technological advancements in FC services on SC services can be either positive or negative, depending on the relationship between service competition mitigation and relative waiting cost increases. In contrast, technological improvements in BS services will decrease the profitability of SC services. Finally, in a public EV charging market where SC services are absent, the adoption of BS services over FC services primarily depends on their potential market sizes. As the market size surpasses a specific threshold, the BS service can reduce the service cost below a certain threshold, thereby gaining a competitive economic advantage.

We also analyze the pricing strategy for each service. The prices of FC services depend entirely on valley electricity prices, or the combined effect of valley electricity prices and battery loss. The prices of FC services are higher, if valley electricity prices are low, or valley electricity prices are moderate and battery loss is low. High fixed costs of FC and BS services tend to moderate the negative effects of battery loss on the pricing power (the ability to charge a higher price) for FC services. However, the pricing strategy of BS services depends primarily on their market size. If the market is larger than SC services, they will charge higher prices; or they may charge lower prices in a small market when facing high valley electricity prices. Fixed setup costs for BS services tend to mitigate the impacts of the unit service cost on the pricing strategy. For the public EV market, the price difference between FC and BS services depends primarily on the market sizes. Interestingly, the effect of unit service cost efficiency on the price difference tends to be moderated by BS services' fixed setup cost but remains unaffected by FC services' fixed setup cost.

Our study offers several managerial insights. First, the European energy crisis, which increases peak–valley electricity price differences, poses a challenge for FC services. Energy storage presents a solution to mitigate the negative impact of these price differences on FC services. (e.g., Tesla's solar charging program). Second, BS services may encounter more difficulties than SC services in leveraging valley electricity prices for their charging operations during periods of energy crisis where valley electricity prices rise. Thus, energy storage is a viable approach for BS services as well. Third, in the future public

EV charging market, BS services can gain an economic advantage by reducing battery acquisition, dispatching, and maintenance costs, only if their market size is substantial. This implies that since BS services are more resource-constrained than FC services, their primary focus should be on market expansion through infrastructure development and government subsidies. Finally, when developing new charging services, reducing fixed setup costs and technological improvement are two prioritized aspects, with the former being crucial for BS services and the latter being more effective for FC services.

This study has a few limitations that suggest directions for future research. Firstly, our analysis employs deterministic linear demand functions for different EV charging services. A potential research direction is to investigate how demand and battery inventory uncertainties impact the adoption of FC and BS services (Mak et al., 2013). Second, the standardization of battery pack design across various EV manufacturers may affect the adoption of BS services, which could be a possible subject for future research. Finally, although EV charging service providers are often price-takers and have limited influence on electricity prices, they can negotiate prices with the power grid when participating in the power regulation of smart grids. An additional research opportunity is to incorporate the negotiation of electricity prices with the power grid company into the analysis.

CRediT authorship contribution statement

Yudi Zhang: Conceptualization, Formal analysis, Investigation, Methodology, Writing – original draft, Visualization. **Xiaojun Wang:** Conceptualization, Supervision, Validation, Writing – review & editing. **Bangdong Zhi:** Supervision, Validation, Writing – review & editing.

Data availability

No data was used for the research described in the article.

Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.ijpe.2023.109136.

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