# Battery as a Service: Flexible Electric Vehicle Battery Leasing

Lingling Shi, Bin Hu
Naveen Jindal School of Management, University of Texas at Dallas, Richardson, TX 75080, USA
{Lingling.Shi, Bin.Hu}@utdallas.edu

Inspired by the electric vehicle (EV) startup NIO which adopts a Battery-as-a-Service (BaaS) model with a swappable battery design and experiments with flexible battery up/downgrading, we study a flexible EV battery lease program where customers lease batteries of their chosen capacities with the option to temporarily up/downgrade to batteries of different capacities during peak periods. Adopting a game-theoretical model, we find that the manufacturer may depend on acquiring additional batteries or reallocating customers' batteries to satisfy the peak up/downgrade demands, and that flexible battery leasing can lead to win-win outcomes (increased manufacturer profit and reduced customer total cost) compared with simple battery leasing. The results are found to be robust for different levels of customer sophistication, noncommittal battery acquisition, and correlated regular and peak needs for range. These findings inform EV manufacturers adopting the BaaS business model and highlight the value of flexible battery leasing.

*Key words*: EV, BaaS, servicization, battery lease, battery swapping

## 1. Introduction

Climate change, driven by greenhouse gas emissions due to human activities, is one of the greatest challenges faced by humanity. The transportation sector is an important source of carbon dioxide emissions, for example accounting for 36% of the total carbon emissions in the United States in 2020 (EIA 2021). To reduce transportation carbon emissions, the global auto industry is in a rapid transition toward battery-powered electric vehicles (EVs). EVs have zero tailpipe emissions, and allow the transportation sector to benefit from efficiency and emission improvements in fossil fuel power generation as well as zero-emission power generation including but not limited to nuclear, hydro, solar, wind, and geothermal power. The global EV industry has enjoyed a compound annual growth rate of 54% between 2015 and 2020 (IEA 2021). Multiple countries have set EV adoption targets, and more than 20 countries announced the full phase-out of conventional vehicles powered by internal combustion engines over the next 10-30 years (IEA 2021); for example, US President

Biden recently announced a target of 50% sales share of EVs by 2030 (The White House 2021). According to IEA (2021), by 2030, the global EV sales is expected to exceed 25 million units and the global EV stock will reach 145 million units.

Despite the rapid growth, EV adoption is still relatively slow. In 2020, EVs account for only 4.6% of global vehicle sales (IEA 2021). Two key barriers to EV adoption are range anxiety and purchase price (Egbue and Long 2012, Avci et al. 2015). Range anxiety refers to the concern of running out of power and becoming stranded in an EV (Eberle and Von Helmolt 2010, Garthwaite 2021). Limited battery capacity, sparse charging infrastructure, and slow charging speed all contribute to range anxiety. The EV industry attempts to mitigate range anxiety by increasing battery capacities and deploying charging infrastructure. Whereas a large battery capacity reduces the need for frequent charging, it also lengthens the charging time; even a Tesla Supercharger, the fastest charging system widely available, can still take upward of 30 minutes to charge a depleted battery (EnergySage 2021). Additionally, large battery capacities significantly increase EVs' production costs. In 2021, the average EV price is around $40,000, 25% higher than conventional vehicles (IEA 2021), and the battery pack is usually the most expensive component of an EV (Mruzek et al. 2016, Lacey et al. 2017). Pistoia (2010) estimates that over 80% of EVs' incremental costs compared to conventional vehicles can be attributed to the battery pack. One can see that the two key barriers to EV adoption—range anxiety and purchase price—are intrinsically conflicted and pose a challenging dilemma for EV manufacturers.

An EV startup in China, NIO, addresses this dilemma with a swappable-battery design and a battery-leasing business model. NIO designs its vehicles to be equipped with swappable batteries (including between models) that can be exchanged at a swapping station in under 3 minutes (NIO 2021a), and also invests heavily in swapping stations; for example, NIO had constructed 700 swapping stations in China by the end of 2021 (NIO 2021a), and plans to deploy 4,000 swapping stations worldwide by 2025 (NIO 2021b). Furthermore, a NIO customer may choose to buy a vehicle without a battery and pay a monthly fee to lease batteries from NIO. The customer may charge the battery by him/herself, or exchange a depleted battery with a charged one of the same capacity at a battery swapping station and pay for the charge level difference.[1] NIO describes this business model as Battery as a Service (BaaS) (NIO 2020). The time to exchange a battery is comparable to refueling a conventional vehicle at a gas station, which greatly helps alleviate

[1] NIO had offered early adopters lifetime free battery exchanges, and still offers up to six free (in terms of electricity) battery exchanges per month to current customers, but is expected to eventually phase out this perk. We ignore such perks for simplicity.

range anxiety. Not having to own a battery also significantly reduces purchase prices of EVs: NIO's BaaS customers enjoy CNY¥70,000-128,000 (USD$11,000-20,000) off the full-car purchase price depending on the battery capacity, bringing NIO EVs' entry price down to CNY¥300,000 (USD$47,000).[2] The battery-swapping business model was pioneered by Hartford Electric Light Company through the GeVeCo battery service for electric trucks between 1910 and 1924 (Reuters 2022), and later reignited in 2008 by the now-defunct Better Place; see Girotra et al. (2011) and Avci et al. (2015) for an analysis of this business model and its environmental impact. Different from these dedicated battery-swapping service providers, NIO is the first EV manufacturer to successfully operate its own battery-swapping service, having delivered 167,070 vehicles by the end of 2021 (NIO 2022). Another example is Gogoro, an electric scooter manufacturer offering a battery-swapping service that powers 97% of all electric scooters sold in Taiwan for more than 400,000 monthly subscribers (Gogoro 2021).

In addition to addressing range anxiety and reducing purchase prices, the BaaS model provides further flexibilities and opportunities. NIO currently offers two battery capacity options, 75kWh and 100kWh. At the time of purchasing the vehicle, a BaaS customer can lease batteries of either capacity based on his/her need and will exchange depleted batteries with charged ones of the same capacity. The leased battery capacity is a long-term decision that cannot be easily changed. (NIO currently does not allow customers to change the lease for a 100kWh battery down to a 75kWh one; the opposite is allowed, although there is a significant backlog.) Recently, NIO launched an experimental flexible battery lease program that allows a customer to temporarily upgrade a 75kWh battery to a 100kWh one or downgrade a 100kWh battery to a 75kWh one at set short-term rates (CnEVPost 2021). This program is intended for non-commute occasions (e.g., weekends and public holidays) during which some customers leasing low-capacity batteries go on road trips and have needs for high-capacity batteries, and some customers leasing high-capacity batteries may rest at home and can live with low-capacity batteries. NIO aims to reallocate customers' batteries during these occasions through this program and potentially improve overall customer experience as well as its own profitability. Such a flexible battery lease program poses interesting and challenging questions to the company. How should it price the temporary battery upgrade and downgrade options? How much does flexible battery leasing depend on battery reallocation versus acquisition to meet up/downgrade demands? How does flexible battery leasing impact the operations of the BaaS model? And can the manufacturer and its customers both benefit from flexible battery leasing?

[2] NIO EC6, `https://www.nio.cn/ec6`

To address these questions, we develop a game-theoretical model where a mass of BaaS EV customers have independent needs for range in two periods representing regular (e.g., daily commute) and peak (e.g., weekend and holiday road trips) EV usage, and driving an EV with an insufficient range incurs an inconvenience cost. The manufacturer offers two different battery capacities and determines the lease rates, peak up/downgrade rates, and additional battery acquisition quantity. Customers make their regular battery lease decisions after observing only their regular need for range, and have the option to up/downgrade the leased batteries during the peak period after learning their peak need for range.

We first analyze the problem assuming non-strategic customers who do not consider up/downgrading batteries for peak usage when making their regular battery lease decisions. We find that, in different scenarios, the manufacturer may acquire additional batteries or depend exclusively on reallocating customers' batteries to satisfy the peak up/downgrade demands. By comparing flexible battery leasing with simple battery leasing (without peak up/downgrade options), we find that the high-capacity battery lease rate may be larger or smaller for flexible than simple battery leasing; and more crucially, flexible battery leasing can reduce all customers' total cost in addition to improving the manufacturer's profit, leading to win-win outcomes. We then repeat the analysis for strategic customers who consider up/downgrading their leased batteries during the peak period when making battery lease decisions. We find the results to be generally consistent with those in the former case; particularly, flexible battery leasing can still lead to win-win outcomes (increased manufacturer profit and reduced total customer cost) with strategic customers, although less often than with non-strategic customers. We then investigate an alternative model with noncommittal battery acquisition (the manufacturer acquiring batteries after customers' battery lease decisions), and show that our results in the base model are largely preserved, although the manufacturer generally acquires more additional batteries with noncommittal battery acquisition. Finally, we find that correlated regular and peak needs for range generally reduce the win-win regions, with negative correlations having a more significant impact. Our findings provide instructive insights for EV manufacturers adopting the BaaS business model, and highlight the value of flexible battery leasing enabled by the BaaS model.

In the rest of this paper, we survey the relevant literature in Section 2 and introduce our model in Section 3. We analyze the model with non-strategic customers in Section 4 and with strategic customers in Section 5. Section 6 contains an analysis of noncommittal battery acquisition and numerical studies of a model extension with correlated regular and peak needs for range. Section 7 concludes the paper.

## 2. Literature review

There is a growing Operations Management literature on the management and impact of electric vehicles. Part of the literature takes an industry-level perspective and studies topics such as government incentives and policies (Cohen et al. 2016, Kök et al. 2020, Shi et al. 2021, Yu et al. 2022) and charging infrastructures (MirHassani and Ebrazi 2013, Widrick et al. 2018, Brandstätter et al. 2020, Zhang et al. 2021). Others consider firm-level operational decisions. Hu et al. (2017) study alternative-energy vehicle manufacturers' open-technology strategies for competing technologies (e.g., lithium-ion batteries versus hydrogen fuel cells). Given EV fleets as virtual power plants, Kahlen et al. (2018) propose a mixed rental-trading strategy to study potential benefits for the fleet owner and consumers. Cohen et al. (2015) characterize multiple green technology suppliers' pricing and production quantity decisions under various government subsidy mechanisms. More closely related to our work is the stream of literature on battery swapping/charging networks. Mak et al. (2013) develop optimization models for battery-swapping infrastructure deploying and conduct numerical examples to study the impacts of battery standardization and technology development. Considering both long-term infrastructure investments and short-term expenses, Schneider et al. (2018) study the optimization problem of operating battery-swapping stations in a network. Valogianni et al. (2020) design an adaptive pricing scheme for grid operators to induce the desired EV charging demand profile. Based on real-world data from car2go, He et al. (2021) propose a charging method that can increase EV sharing profit by 15%. By delaying charging until the cost is lower, Wu et al. (2021) show that substantial cost and emissions savings from smart charging.

Two recent papers are most closely related to our work. Avci et al. (2015) model a battery-swapping EV system, and compare it with a conventional system (no battery leasing and swapping option). They show that the battery-swapping system can lead to a higher EV adoption, but also encourage more driving than the conventional system. They further examine the environmental impact and find that it cannot always reduce emissions and oil dependence at the same time. In the presence of range and resale anxieties, Lim et al. (2015) evaluate four business practices in EV market based on battery ownership and battery charging options, and suggest that the combinations of battery leasing with enhanced charging service lead to more desirable outcomes when the level of resale anxiety is high. Although in a similar battery leasing context, our paper is different to theirs in several aspects. First, we focus on manufacturer's optimal decisions in a battery leasing business model, whereas they compare the effectiveness of battery selling and leasing models. Second, we focus on the flexibility of a battery-leasing model, namely the option to temporarily up/downgrade batteries—an element absent in their models. Therefore, our work complements and grows the literature on the battery-swapping and leasing model.

The battery-leasing model allows an EV manufacturer to become a service provider, and is thus related to the *servicization* literature which studies firm selling the use of a product as a service rather than the product itself (Vandermerwe and Rada 1988, Cohen 2012). The servicization trend is said to be driven by higher profit margin and stability of income (Wise and Baumgartner 2000), competitive opportunities and advantages (Bustinza et al. 2015), and increasing customer satisfaction and loyalty (Corrêa et al. 2007). Evaluating secondary data from 477 publicly traded manufacturing firms, Fang et al. (2008) state that firms with greater service sales achieve higher firm value in service transition strategies. Guajardo et al. (2012) show that the product reliability is improved as the component asset ownership is transferred to the firm. Considering profitability and environmental impact, Örsdemir et al. (2019) state that servicization can be a win-win strategy for products with a low use impact relative to their production and disposal impacts. Agrawal et al. (2022) study the business models of leasing and power purchase agreement under investment and generation subsidies in the solar panel industry. Compared with the existing literature, our study has a unique focus on the flexibility enabled by servicization and contributes to the growing stream of research on sustainable business model innovation (Girotra and Netessine 2013). Incidentally, Altmann and Chu (2001) discuss a new service plan where customers pay a flat rate for basic service and have access to higher quality service at usage-based rate on occasions when they need, and empirically show that this proposed service plan benefits both the internet service provider and customers.

## 3. Model

We adopt a game-theoretical model to study flexible battery leasing inspired by a similar program at NIO. Although NIO also sells EVs with batteries, we focus on the BaaS business model and only consider customers who buy EVs without batteries and lease their batteries from the manufacturer.

**Customer need for range.** We assume an EV manufacturer to have a unit mass of battery-leasing customers. For *regular* use of the EV (e.g., daily commute during week days), we assume that each customer's need for range $d$ is uniformly distributed between 0 and 1: $d \sim \mathcal{U}[0,1]$. In addition, each customer may also use the EV for occasions outside his/her regular usage; e.g., road trips during weekends and public holidays. The need for range during such occasions can potentially be much greater than the regular need for range. For example, based on GPS data covering 2,003 travel days, Wang et al. (2015) show that the the average daily traveling distance during weekends and public holidays is larger than that on weekdays. In addition, such need for range differs from trip to trip and cannot be known with certainty until a trip is planned. Therefore, we refer to the uncertain need for range outside the regular use as a customer's *peak* need for range and denote it by a random variable $D \sim \mathcal{U}[0,a]$ with $a > 1$. Note that although we use the term "peak need" and assume it to be statistically larger than the regular need, this is not necessarily the case for each customer and occasion. For example, a customer may make long daily commutes but do not go on road trips during weekends and public holidays. Therefore, we make a key assumption that *customers' regular and peak needs for range are independently distributed.* (Section 6 contains an extension with correlated regular and peak needs for range.) The observation that customers' regular and peak needs for range are not perfectly correlated is the main motivation for NIO's flexible battery lease program. Finally, we assume that the EV's overall usage consists of $\rho \in (a/(4+a), 1)$ proportion of regular usage time and $1-\rho$ proportion of peak usage time; $\rho \le a/(4+a)$ leads to uninteresting cases where no customer would lease low-capacity batteries. The regular and peak periods are assumed common for all customers because regular and peak usage is largely determined by the society's typical workday and holiday schedule.

**Customer cost.** The EV manufacturer offers two options for its existing EV battery-leasing customer base—$h$ for high-capacity batteries and $l$ for low-capacity batteries. The high- and low-capacity batteries offer respective ranges $r_h > r_l$ at respective lease rates $p_h > p_l$ per unit time. Customers have different regular need for range, e.g., depending on their daily commute distances. For a customer with regular need for range $d$, we model his/her total cost of leasing type-$i \in \{h, l\}$ batteries for regular usage as $(d - r_i)^+ + p_i$ per unit time. This model implies that if the range does not meet the customer's need ($r_i < d$), the customer incurs an inconvenience cost equal to the range deficiency ($d - r_i$), for example due to excessive battery exchanges. On the other hand, as long as the range meets the customer's need ($r_i \ge d$), s/he does not incur an inconvenience cost ($(d-r_i)^+ = 0$). Note that this customer cost model does not include the electricity cost, because the same electricity cost is incurred in all cases and does not affect any decision making or comparison. We assume $a/2 \le r_h \le a$ to rule out uninteresting cases; a shorter range $r_h$ would lead to trivial outcomes due to a lack of differentiation, and a longer range $r_h$ would exceed even the highest peak need for range (recall that $D \le a$). To simplify the analysis, we assume $r_l = 0$ and normalize $p_l = 0$. Assuming $r_l = 0$ implies that low-capacity batteries exactly meet the lowest regular need for range (recall that $d \ge 0$). We can normalize $p_l = 0$ because a customer must lease batteries for the vehicle to be useful, and thus $p_l$ is a baseline cost to which $p_h$ is compared. Under these simplifications, a customer's total cost of leasing low-capacity batteries for regular usage per unit time is simply his/her need for range $d$. His/her total cost of leasing high-capacity batteries for regular usage per unit time is $(d-r_h)^+ + p_h$.

The EV manufacturer also offers up/downgrade options for peak usage. We denote the upgrade rate by $\bar{p}_h$ per unit time, which means that a customer leasing low-capacity batteries can switch to high-capacity batteries for peak usage and pay $\bar{p}_h$ per unit time instead of the lease rate $p_l = 0$. Similarly, we denote the downgrade rate by $\bar{p}_l$ per unit time, which means that a customer leasing high-capacity batteries can switch to low-capacity batteries for peak usage and pay $\bar{p}_l$ per unit time instead of the lease rate $p_h$.[3] One can see that a customer's total cost of peak usage depends not only on his/her peak need for range $D$ and the type of installed battery $h$ or $l$, but also on his/her regular lease type $h$ or $l$. We list a customer's total cost of peak usage per unit time in Table 1. Note that we allow $\bar{p}_l < 0 (= p_l)$, namely a customer giving up his/her high-capacity batteries during peak usage may receive a discount for temporarily operating the EV with low-capacity batteries.

| | Peak battery | |
|---|---|---|
| Leased battery | $h$ | $l$ |
| $h$ | $(D-r_h)^+ + p_h$ | $D+\bar{p}_l$ |
| $l$ | $(D-r_h)^+ + \bar{p}_h$ | $D$ |

**Table 1 Customer costs of peak usage per unit time for varying leased and peak battery types**

**Manufacturer and customer decisions.** In practice, regular and peak usage occurs cyclically. To capture customers' long-term average EV usage costs, we consider a two-period model with a regular period followed by a peak period. In the regular period, the manufacturer chooses the lease rate for high-capacity batteries, $p_h$ (recall that the lease rate for low-capacity batteries is normalized to $p_l = 0$). We require $p_h < \min(1, r_h)$, otherwise no customer will lease high-capacity batteries. Each customer then realizes his/her regular need for range $d$ from distribution $\mathcal{U}[0,1]$ and chooses to lease high- or low-capacity batteries. In the peak period, the manufacturer chooses the up/downgrade rates $\bar{p}_h$ and $\bar{p}_l$. Each customer then realizes his/her peak need for range $D$ from distribution $\mathcal{U}[0,a]$, $a > 1$ (independent of his/her regular need for range $d$) and chooses to either keep the leased batteries or up/downgrade to batteries of the different capacity to minimize his/her total cost of peak usage (see Table 1).

[3] For expositional simplicity, we model the up/downgrade rates as absolute rates that replace the lease rates; NIO actually implements the up/downgrade rates as incremental rates on top of lease rates.

Aside from choosing $p_h$, $\bar{p}_h$ and $\bar{p}_l$, the manufacturer makes an additional decision of battery acquisition: there must be sufficient batteries to meet customer demand and fill pipeline and transit inventories for charging and relocation. For simplicity, in our analysis, we ignore the pipeline and transit battery inventories and only consider the battery requirement to directly satisfy customer needs. (We refer the reader interested in spare battery inventory management in the operation of a battery swapping network to Avci et al. 2015 who comprehensively study this subject.) We denote the acquisition cost of a type-$i \in \{h, l\}$ battery by $c_i$ and normalize $c_l = 0$. We further assume $c_h \leq (1-\rho)(2r_h - a)$, otherwise no customer will upgrade to high-capacity batteries in the peak period. Note that we allow $c_h$ to be a free parameter independent of the range offered by high-capacity batteries, $r_h$. This assumption captures the reality that both battery technologies and EV energy efficiencies are undergoing rapid developments, which means that the manufacturer may improve an EV's range without increasing the battery cost, or reduce the battery cost without affecting the range. For example, the promising solid-state batteries are expected to improve the EV range by 50-80% while reducing the battery cost by 17% compared with the current lithium-ion batteries (Kimani 2022).

In the current EV industry, batteries are generally in short supply (Motavalli 2021, Bove 2022), and thus the battery acquisition decision is usually planned well ahead and not easily adjustable. Therefore, in this base model, we assume that *the manufacturer commits to the battery acquisition decision*. Technically, this means that the battery acquisition decision is made in the regular period prior to any customer decisions. Note that in practice, regular and peak usage occurs cyclically. Therefore, this assumption should not be understood literally as about timing, but rather represents that the manufacturer commits to its battery acquisition decision and would not be swayed by any customer decisions. If the manufacturer can and is willing to adjust its battery acquisition decision based on customer decisions, then this decision should be modeled as occurring during the peak period, which we will study in Section 6.1. Figure 1 illustrates the timeline of our base model.

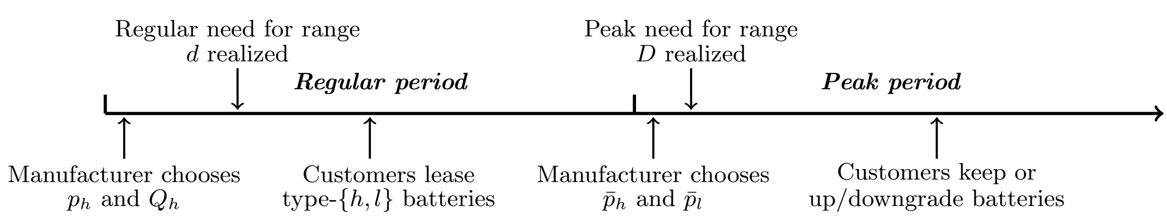



**Figure 1  Sequence of events**

## 4. Analysis with non-strategic customers

We first analyze the model assuming that, when making their battery lease decisions, customers consider the expected costs of using their leased batteries for peak usage but not the options of up/downgrading batteries. We refer to such customers as being *non-strategic*. There are two reasons why we consider non-strategic customers. First, practical customers may lack the sophistication to fully account for the up/downgrading options when making battery lease decisions. For example, based on a large-scale natural experiment, Gillingham et al. (2021) empirically find that customers largely act myopically with respect to future fuel costs in their (conventional) vehicle purchase decisions, and show their myopia to be highly robust for a wide range of valuation assumptions. In the air-travel industry, Li et al. (2014) empirically estimate that 80-95% (the interquartile range) of customers do not strategically delaying purchases of airline tickets. Furthermore, NIO's flexible battery lease program is a relatively recent experiment, and the vast majority of NIO's current BaaS customers had made their battery lease decisions before this program existed. In Section 5, we also analyze the model with strategic customers.

We analyze the model by backward induction. First, assuming the manufacturer's pricing decisions (high-capacity battery lease rate in the regular period and up/downgrade rates in the peak period), and letting $\tau$ denote the regular-period low-capacity battery lease volume, we derive customers' optimal battery up/downgrade decisions in the peak period based on their peak-period costs (see Table 1). All non-trivial proofs are relegated to the Appendix.

LEMMA 1. *Given the up/downgrade rates $\bar{p}_h$ and $\bar{p}_l$ and the regular-period low-capacity battery lease volume $\tau$, the peak-period upgrade volume is $\tau(a-\bar{p}_h)/a$ if $\bar{p}_h \le r_h$ or 0 if $\bar{p}_h > r_h$, and the downgrade volume is $(1-\tau)(p_h-\bar{p}_l)/a$ if $\bar{p}_l \in [p_h - r_h, p_h]$, or $1-\tau$ if $\bar{p}_l < p_h - r_h$, or 0 if $\bar{p}_l > p_h$. Note that $\bar{p}_h \le r_h \le a$ guarantees a non-negative upgrade volume. The non-negativity of the downgrade volume is straightforward.*

To avoid trivial cases, we focus on the cases of $\bar{p}_h \le r_h$ and $p_h - r_h \le \bar{p}_l \le p_h$ which induce interior (non-boundary) up/downgrade volumes in the subsequent consideration of the battery lease decisions. When non-strategic customers make their battery lease decisions, they are not aware of their exact peak need for range $D$. Therefore, they consider peak usage in expectation and compare the total expected cost of leasing low-capacity batteries, $\rho d + (1-\rho)\mathbb{E}[D]$, with that of leasing high-capacity batteries, $p_h + \rho(d-r_h)^+ + (1-\rho)\mathbb{E}[(D-r_h)^+]$. Lemma 2 characterizes the high- and low-capacity battery lease volumes with non-strategic customers.

Lemma 2. *Non-strategic customers with regular need for range* $d > [2ap_h - (1-\rho)r_h(2a - r_h)]/[2a\rho]$ *lease high-capacity batteries and the rest lease low-capacity batteries. The high- and low-capacity battery lease volumes are respectively* $[2a(\rho - p_h) + (1-\rho)r_h(2a - r_h)]/[2a\rho]$ *and* $[2ap_h - (1-\rho)r_h(2a - r_h)]/[2a\rho]$.

Lemma 2 shows that the regular low-capacity (high-capacity) lease volume increases (decreases) in the lease rate $p_h$. We next investigate the firm's pricing and battery acquisition decisions based on the optimal customer decisions characterized in Lemmas 1-2. We first analyze the manufacturer's optimal simple battery lease program (without peak up/downgrade options) as a benchmark, and then analyze the optimal flexible battery lease program and compare it with the former benchmark to identify the impact of the up/downgrade flexibility.

### 4.1. Benchmark: simple battery leasing

In this benchmark, the manufacturer optimizes the lease rate $p_h$ without battery up/downgrade options, and the customers use their leased batteries during the peak period. Proposition 1 presents the optimal lease rate (with superscript $b$ denoting *benchmark*) to maximize the manufacturer's profit $(1-\tau)(p_h - c_h)$ where $\tau$ is as characterized in Lemma 2.

Proposition 1. *The optimal simple battery lease program with non-strategic customers has* $p_h^b = [(1-\rho)(2ar_h - r_h^2) + 2a(c_h + \rho)]/(4a)$ *and the manufacturer's maximized profit is* $[(1-\rho)(2ar_h - r_h^2) - 2a(c_h - \rho)]^2/(16\rho a^2)$. *The low-capacity battery lease volume is* $\tau^b = [(1-\rho)r_h^2 + 2a(c_h - (1-\rho)r_h + \rho)]/(4a\rho)$ *and all customers' total cost is shown in the proof.*

Intuitively, the high-capacity battery lease rate $p_h^b$ increases in the peak need for range $a$, battery range $r_h$, and battery cost $c_h$. By contrast, as the proportion of regular usage $\rho$ increases, the lease rate $p_h^b$ for high-capacity batteries increases if they offer a range too small ($r_h \leq 1$) or too large for the need ($r_h > 1$ and $a < r_h^2/(2r_h - 2)$); otherwise, $p_h^b$ decreases in $\rho$. As a result, the low-capacity battery lease volume $\tau^b$ decreases in $a$, $r_h$, increases in $c_h$, and may both increase (if $a < r_h^2/(2r_h - 2c_h)$ ) and decrease (otherwise) in $\rho$.

### 4.2. Flexible battery leasing

Now we consider a flexible battery lease program with up/downgrade options in the peak period. The optimal peak up/downgrade volumes $\tau(a - \bar{p}_h)/a$ and $(1-\tau)(p_h - \bar{p}_l)/a$ in Lemma 1 imply an additional acquisition of high-capacity batteries $Q_h \doteq [\tau(a - \bar{p}_h)/a - (1-\tau)(p_h - \bar{p}_l)/a]^+$ to satisfy the peak-period demand. In principle, the manufacturer may also acquire additional low-capacity batteries. However, because the need for range in the peak period is statistically larger than that in the regular period, it is straightforward to verify that the manufacturer will never acquire additional low-capacity batteries at the optimal solution.

We first solve for the manufacturer's optimal peak-period up/downgrade rates $\bar{p}_h$ and $\bar{p}_l$ for given lease rate $p_h$ and additional battery acquisition quantity $Q_h$. The manufacturer's peak-period problem is to maximize its profit subject to the battery acquisition requirement:

$$\begin{aligned} \max_{\bar{p}_h,\bar{p}_l} \ & (1-\tau)p_h + (1-\tau)(\bar{p}_l - p_h)(p_h - \bar{p}_l)/a + \tau\bar{p}_h(a-\bar{p}_h)/a - c_h(1-\tau+Q_h), \\ \text{s.t.} \ & (1-\tau)(p_h - \bar{p}_l)/a + Q_h = \tau(a-\bar{p}_h)/a. \end{aligned} \tag{1}$$

The following lemma presents the manufacturer's optimal up/downgrade rates.

Lemma 3. *For given $\tau$, $p_h$ and $Q_h$, the manufacturer's optimal peak-period up/downgrade rates are respectively $\bar{p}_h^*(\tau, p_h, Q_h) = a(1+\tau-2Q_h)/2$ and $\bar{p}_l^*(\tau, p_h, Q_h) = p_h + a(2Q_h - \tau)/2$. The manufacturer's maximized peak-period profit is $[(1-\tau)p_h - c_h(1-\tau+Q_h) + a(\tau - (2Q_h-\tau)^2)/4]$.*

We then consider the manufacturer's regular-period decisions. The manufacturer chooses the lease rate $p_h$ and the high-capacity battery acquisition quantity $Q_h$ to maximize its two-period total profit:

$$\max_{p_h, Q_h} \ (1-\tau)p_h + (1-\rho)[a(\tau - (2Q_h-\tau)^2)/4] - c_h(1-\tau+Q_h). \tag{2}$$

Solving Problem (2) with $\tau$ as characterized in Lemma 2 yields the following proposition (with superscript $n$ denoting *non-strategic*).

Proposition 2. *The manufacturer's optimal decisions with non-strategic customers are:*

- *If $c_h < (1-\rho)[(1-\rho)(a^2+2r_h^2-4ar_h)+4a\rho]/[8\rho - 2a(1-\rho)]$,*

$$Q_h^n = \frac{a^2(1-\rho)^2 + 2((1-\rho)^2 r_h^2 - 4\rho c_h) + 2a(1-\rho)(c_h + 2\rho - 2(1-\rho)r_h)}{16a\rho(1-\rho)} > 0,$$

$$p_h^n = [a(1-\rho) + 2c_h - 2(1-\rho)r_h^2/a + 4(\rho + (1-\rho)r_h))]/8,$$

$$\bar{p}_h^n = (a + c_h/(1-\rho))/2, \quad \bar{p}_l^n = [a(1-\rho) - 2(1-\rho)r_h^2/a - 2c_h(1+\rho)/(1-\rho) + 4(\rho + (1-\rho)r_h)]/8.$$

- *Otherwise,*

$$Q_h^n = 0, \quad p_h^n = \frac{a^2(1-\rho)[2(1-\rho)r_h - \rho] - 2\rho(1-\rho)r_h^2 + a[4\rho(1-\rho)r_h + 4\rho(c_h+\rho) - r_h^2(1-\rho)^2]}{2a[4\rho + (1-\rho)a]},$$

$$\bar{p}_h^n = \frac{(1-\rho)(3a^2 + 2r_h^2 - 4ar_h) + 4a(c_h + 3\rho)}{16\rho + 4a(1-\rho)},$$

$$\bar{p}_l^n = \frac{(1-\rho)(a^3 - 4\rho r_h^2 + 8a\rho r_h) + 2ar_h(1-\rho)(2-\rho)(2a - r_h) - 2a^2(2c_h + \rho + \rho^2) + 8a\rho(c_h+\rho)}{4a[4\rho + (1-\rho)a]}.$$

*The threshold for $c_h$ increases in $a$ and decreases in $\rho$ and $r_h$. The manufacturer's maximum profit is included in the proof.*

Proposition 2 fully characterizes the manufacturer's optimal decisions with non-strategic customers. Overall, the manufacturer may employ two different strategies to meet the peak upgrade demand. When the battery cost is sufficiently low ($c_h < (1-\rho)[(1-\rho)(a^2+2r_h^2-4ar_h)+4a\rho)]/[8\rho-2a(1-\rho)]$), the manufacturer would acquire additional high-capacity batteries ($Q_h^n > 0$) to complement reallocating customers' high-capacity batteries. Otherwise, the manufacturer would not acquire additional high-capacity batteries and exclusively depend on reallocating customers' high-capacity batteries. The cost threshold to distinguish these two cases, $(1-\rho)[(1-\rho)(a^2+2r_h^2-4ar_h)+4a\rho)]/[8\rho-2a(1-\rho)]$, increases in $a$ and decreases in $r_h$ and $\rho$. In other words, the manufacturer is more likely to acquire additional batteries for higher peak need for range $a$, and lower battery range $r_h$ and proportion of regular usage $\rho$. Higher peak need for range, lower battery range and lower proportion of regular usage all point to customers' higher demand for high-capacity batteries, and it is intuitive that the manufacturer should acquire additional high-capacity batteries in such cases. The next corollary provides further insights into these strategies.

COROLLARY 1. *With non-strategic customers, when the manufacturer acquires additional high-capacity batteries ($Q_h^n > 0$), the peak downgrade rate is always positive ($\bar{p}_l^n > 0$). When $Q_h^n = 0$, $\bar{p}_l^n < 0$ if and only if $a > 2\rho$ and $c_h > [4\rho((1-\rho)r_h+\rho)-(1-\rho)(a^3+4\rho r_h^2)/(2a)+(2ar_h-r_h^2)(2-3\rho+\rho^2)-a\rho(1+\rho)]/[2(a-2\rho)]$.*

Recall that we assume the peak need for range to be statistically larger than the regular need for range ($a > 1$), and normalize the regular lease rate for low-capacity batteries to be zero ($p_l = 0$). Corollary 1 shows that when the manufacturer acquires additional high-capacity batteries, the peak downgrade rate for low-capacity batteries is higher than the regular lease rate for low-capacity batteries. Given that the peak need for range is statistically larger than the regular need for range, charging higher short-term rates for peak usage is reasonable. However, when the manufacturer does not acquire additional high-capacity batteries, the peak downgrade rate for low-capacity batteries may be negative, indicating a discount on the regular lease rate for low-capacity batteries despite statistically higher peak need for range. This distinction clearly shows that the manufacturer may either depend on acquiring additional high-capacity batteries to meet peak demand, in which case the up/downgrade rates are not severely distorted; or exclusively depend on reallocating customers' batteries to meet peak demand, in which case the short-term rate for low-capacity batteries (peak downgrade rate) may be heavily discounted to incentivize customers to share their unused high-capacity batteries with others in need.

We then compare parameter sensitivities of flexible battery leasing with non-strategic customers (Proposition 2) with those of simple battery leasing (Proposition 1). It is straightforward to observe that the manufacturer's sole common decision for simple and flexible battery leasing, the optimal high-capacity battery lease rate $p_h$, increases in $a$, $c_h$, and $r_h$ in both cases. However, $p_h$ increases faster in the peak need for range $a$ and slower in the battery cost $c_h$ for flexible battery leasing than for simple battery leasing; in other words, the lease rate is more sensitive to the peak need and less sensitive to the cost in the former case than the latter. This is because a customer leasing high-capacity batteries can recoup part of the cost by downgrading to a low-capacity battery in the peak period which is more likely to happen for higher peak needs. Similarly, $p_h$ may increase and decrease in the proportion of regular usage $\rho$ for both flexible and simple battery leasing, but more often decreases in $\rho$ in the former case than the latter, because with more regular usage, the manufacturer increasingly prefers to incentivize high-capacity battery leasing and reallocating these batteries to meet peak upgrade demand, than to acquire additional batteries. By contrast, the low-capacity battery lease volume $\tau$ may increase in $a$ for flexible battery leasing because the manufacturer may resort to additional high-capacity battery acquisition to meet peak upgrade demand, but always decreases in $a$ for simple battery leasing. This is particularly the case for larger peak need for range and costlier high-capacity batteries; in these cases, there is greater peak-period need for high-capacity batteries but fewer customers leasing them in the regular period, and stronger incentives are needed to reallocate limited high-capacity batteries for peak usage.

Since simple battery leasing is a special case of flexible battery leasing (with sufficiently high up/downgrade rates), it is straightforward that the latter always (weakly) improves the manufacturer's profit compared with the former. What is not straightforward is how the optimal high-capacity battery lease rate and volume compare across the two cases, and whether flexible battery leasing can reduce all customers' total cost. For all customers' total cost, we do not perform a full comparison due to the problem's complexity, but instead focus on a set of sufficient conditions where flexible battery leasing reduces all customers' total cost compared with simple battery leasing and thus yields win-win outcomes for the manufacturer and all customers.

Proposition 3. *Comparing simple and flexible battery leasing with non-strategic customers:*

- *If the manufacturer acquires additional high-capacity batteries,*
  - *(i) the high-capacity battery lease rate $p_h$ and the low-capacity battery lease volume $\tau$ are larger for flexible than simple battery leasing if and only if $a > 2c_h/(1-\rho)$;*

*(ii) all customers' total cost is lower for flexible than simple battery leasing if $r_h$ and $c_h$ are sufficiently large, $a$ is sufficiently small and $c_h$ is sufficiently large, or $\rho$ is sufficiently large.*

- *Otherwise,*

*(i) the high-capacity battery lease rate $p_h$ and the low-capacity battery lease volume $\tau$ are always smaller for flexible than simple battery leasing;*

*(ii) all customers' total cost is lower for flexible than simple battery leasing if $r_h$ is sufficiently large and $c_h$ is sufficiently small, $a$ and $c_h$ are sufficiently small, or $\rho$ is sufficiently large and $a$ is sufficiently small.*

Proposition 3 characterizes the impact of flexible battery leasing. When the manufacturer acquires additional high-capacity batteries, flexible battery leasing causes increased regular high-capacity battery lease rates which force more customers to upgrade their batteries for peak usage when the peak need for range is sufficiently large in order to improve its profitability. When the manufacturer does not acquire additional high-capacity batteries, flexible battery leasing causes reduced regular high-capacity battery lease rates which incentivize customers to lease high-capacity batteries and potentially share it with others in need during the peak period.

More crucially, Proposition 3 shows that, regardless of whether the manufacturer acquires additional batteries, flexible battery leasing can improve all customers' total cost compared with simple battery leasing and thus yield a win-win outcome considering that it always improves the manufacturer's profit. The win-win outcomes tend to occur when the proportion of regular usage time ($\rho$) is large, high-capacity batteries offer a large range ($r_h$), and the peak need for range ($a$) is small. A larger high-capacity battery range, proportion of regular usage time, and lower peak need for range all point to high-capacity batteries offering a generous range relative to customers' need. This is an encouraging observation given that EV manufacturers such as NIO are making great efforts to improve their high-end models' ranges (InsideEVs 2021) and thus are more likely to achieve win-win outcomes when adopting flexible battery leasing.

## 5. Analysis with strategic customers

So far we have analyzed the model with non-strategic customers considering both empirical evidence and the fact that flexible battery leasing is relatively new. On the other hand, once flexible battery leasing becomes prevalent and well-understood by customers, they may be better able to account for the peak up/downgrade options when making their battery lease decisions. In this section, we analyze the model with such *strategic* customers.

When strategic customers make their battery lease decisions, they anticipate their expected peak-period costs given their leased battery types and the manufacturer's peak up/downgrade rates, which are denoted by $\mathbb{E}[c_i(D)]$, $i=h,l$ and derived in the proof of Proposition 3. They compare the total expected cost of leasing low-capacity batteries batteries, $\rho d+(1-\rho)\mathbb{E}[c_l(D)]$, with that of leasing high-capacity batteries, $\rho[p_h+(d-r_h)^+]+(1-\rho)\mathbb{E}[c_h(D)]$. Lemma 4 characterizes the high- and low-capacity battery lease volumes with strategic customers.

Lemma 4. *With strategic customers, the high- and low-capacity battery lease volumes are respectively* $[2a(\rho-p_h)+(1-\rho)((p_h-\bar{p}_l)^2+2a\bar{p}_h-\bar{p}_h^2)]/[2a\rho]$ *and* $[2ap_h-(1-\rho)((p_h-\bar{p}_l)^2+2a\bar{p}_h-\bar{p}_h^2)]/[2a\rho]$.

Because simple battery leasing (no peak up/downgrade options) with strategic customers is identical to that with non-strategic customers, we can continue using the results in Proposition 1 as the benchmark to study the impact of the up/downgrade flexibility. Next we analyze flexible battery leasing with strategic customers. The manufacturer's peak-period decisions are the same as those in Lemma 3, and the manufacturer chooses the high-capacity battery lease rate $p_h$ and the acquisition quantity $Q_h$ to maximize its two-period total profit as in Problem (2). We insert the optimal peak up/downgrade rates of Lemma 3 into the low-capacity battery lease volume of Lemma 4 to obtain the equilibrium low-capacity battery lease volume $\tau=(a(1-\rho)(4Q_h-3)+8p_h)/(2a(1-\rho)+8\rho)$, with which we can finally solve Problem (2). The manufacturer's optimal decisions with strategic customers are characterized in the following proposition (with superscript $s$ denoting *strategic*).

Proposition 4. *The manufacturer's optimal decisions with strategic customers are:*

- *If* $c_h<a(1-\rho)[8\rho-5a(1-\rho)]/[8(4\rho-a(1-\rho))]$,

$$Q_h^s=\frac{8a(1-\rho)(c_h+\rho)-5a^2(1-\rho)^2-32\rho c_h}{4a(1-\rho)[16\rho-a(1-\rho)]}>0,$$

$$p_h^s=[2a(1-\rho)(10\rho-c_h)-a^2(1-\rho)^2+8\rho(3c_h+4\rho)]/[64\rho-4a(1-\rho)],$$

$$\bar{p}_h^s=[4a(1-\rho)(10\rho-c_h)-a^2(1-\rho)^2+32\rho c_h]/[4(1-\rho)(16\rho-a(1-\rho))],$$

$$\bar{p}_l^s=\frac{2a(1-\rho)[c_h+\rho(6+c_h)-10\rho^2]-a^2(2-\rho)(1-\rho)^2+8\rho[4\rho(1-\rho)-(1+3\rho)c_h]}{4(1-\rho)[16\rho-a(1-\rho)]}.$$

- *Otherwise,*

$$Q_h^s=0,\quad p_h^s=\frac{13a^2(1-\rho)^2+32\rho(c_h+\rho)+4a(1-\rho)(2c_h+9\rho)}{32a(1-\rho)+64\rho},$$

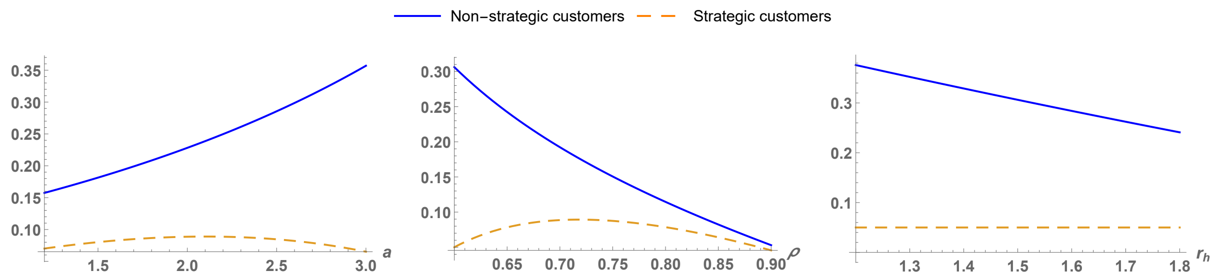
$$\bar{p}_h^s=\frac{a[9a(1-\rho)+8(c_h+3\rho)]}{16a(1-\rho)+32\rho},\quad \bar{p}_l^s=\frac{32\rho(c_h+\rho)+4a\rho(5-9\rho)-8ac_h(1+\rho)+a^2(1-\rho)(11-13\rho)}{32a(1-\rho)+64\rho}.$$

*The threshold for $c_h$ first increases then decreases in $a$ and $\rho$, and is invariant of $r_h$. The manufacturer's maximum profit is included in the proof.*

Similar to the case with non-strategic customers (Proposition 2), the manufacturer would acquire additional high-capacity batteries ($Q_h^s > 0$) if their cost is sufficiently low ($c_h < a(1-\rho)[8\rho - 5a(1-\rho)]/[8(4\rho - a(1-\rho))]$); otherwise, the manufacturer would not acquire additional high-capacity batteries and exclusively depend on reallocating customers' high-capacity batteries to meet the peak upgrade demand. Interestingly, with strategic customers, the threshold for $c_h$ beyond which the manufacturer would acquire additional high-capacity batteries behaves differently from that with non-strategic customers (see Figure 2). Specifically, Proposition 2 states that the threshold increases in $a$ and decreases in $\rho$ and $r_h$ with non-strategic customers, whereas Proposition 4 states that the threshold first increases then decreases in $a$ and $\rho$, and is invariant of $r_h$. As a result, with strategic customers, the manufacturer does not acquire additional high-capacity batteries when the peak need for range—in terms of either the range itself ($a$) or the proportion of peak usage time ($1-\rho$) is sufficiently large—which is not the case with non-strategic customers. This is because, with sufficiently large peak need for range, many strategic customers are comfortable with leasing high-capacity batteries for regular usage as they know that even if they do not need high-capacity batteries in the peak period, there will be plenty of battery upgrade demand with which they can recoup part of the cost; as a result, the manufacturer does not need to acquire additional high-capacity batteries. On the other hand, for small $a$ and large $\rho$ values, the manufacturer's battery acquisition strategies with non-strategic and strategic customers are similar because the EV usage in the peak period is insignificant. Finally, with non-strategic customers, the high-capacity battery range $r_h$ affects the manufacturer's battery acquisition strategy through the low-capacity battery lease volume $\tau$ (see Lemma 2); with strategic customers, $\tau = (a(1-\rho)(4Q_h - 3) + 8p_h)/(2a(1-\rho) + 8\rho)$ (see the proof of Proposition 4) is invariant of $r_h$ and so is the manufacturer's battery acquisition strategy. In this case, the customers' strategic consideration of peak-period up/downgrading completely drives their regular-period battery lease decisions.

The next corollary provides further insights into these strategies with strategic customers.

Corollary 2. *With strategic customers, when the manufacturer acquires additional high-capacity batteries ($Q_h^s > 0$), the peak downgrade rate is negative if and only if $a > 2\rho$ and $c_h > [12\rho a + (5\rho - 2)a^2 + 4(8 - 8a - a^2)\rho^2 + (20a + a^2 - 32)\rho^3]/[8\rho + 24\rho^2 - 2a + 2a\rho^2]$. When $Q_h^s = 0$, $\bar{p}_l^s < 0$ if and only if $a > 4\rho/(1+\rho)$ and $c_h > [32\rho^2 + 4a\rho(5 - 9\rho) + a^2(11 - 24\rho + 13\rho^2)]/[8(a - 4\rho + a\rho)]$.*




Note. The parameter values are (left) $r_h = 1.1,\ \rho = 0.7,\ a \in [1.2, 3]$;

(middle) $a = 2,\ r_h = 1.5,\ \rho \in [0.6, 0.9]$; (right) $a = 2,\ \rho = 0.6,\ r_h \in [1.2, 1.8]$.

**Figure 2 Cost threshold for additional battery acquisition for varying $a$, $\rho$ and $r_h$**

Corollary 2 with strategic customers differs from Corollary 1 with non-strategic customers in that, even when the manufacturer acquires additional high-capacity batteries, the peak downgrade rate can still be negative for large peak need for range $a$ and high-capacity battery cost $c_h$, whereas it is always positive with non-strategic customers. The negative peak downgrade rate, which incentivizes customers to share their high-capacity batteries during peak period, is driven by two factors. On the one hand, when batteries are costly, the manufacture's battery acquisition will be limited in scale. On the other hand, with sufficiently large peak need for range, many strategic customers are comfortable with leasing high-capacity batteries. The latter effect is absent with non-strategic customers, which explains why the manufacturer may acquire additional batteries and implement a negative downgrade rate at the same time with strategic customers.

We then compare parameter sensitivities of flexible battery leasing with strategic customers (Proposition 4) with those of simple battery leasing (Proposition 1), which exhibits several similarities to those with non-strategic customers (see the relevant discussion following Proposition 2). For example, with strategic customers, $p_h$ once again increases faster in the peak need for range $a$ and slower in the battery cost $c_h$ for flexible battery leasing than for simple battery leasing. By contrast, with strategic customers, the low-capacity battery lease volume $\tau$ always decreases in $a$, whereas with non-strategic customers it may increase in $a$.

The following proposition characterizes the impact of flexible battery leasing with strategic customers.

PROPOSITION 5. *Comparing simple and flexible battery leasing with strategic customers:*

- *If the manufacturer acquires additional high-capacity batteries,*
  - *(i) the high-capacity battery lease rate $p_h$ and the low-capacity battery lease volume $\tau$ are always larger for flexible than simple battery leasing;*

*(ii) all customers' total cost is higher for flexible than simple battery leasing if $r_h$ and $c_h$ are sufficiently large.*

- *Otherwise,*
  *(i) the high-capacity battery lease rate $p_h$ and the low-capacity battery lease volume $\tau$ are smaller for flexible than simple battery leasing if $r_h$ and $c_h$ are sufficiently large;*
  *(ii) all customers' total cost is lower for flexible than simple battery leasing if $r_h$ is sufficiently large, $a$ is sufficiently small, or $\rho$ is sufficiently large.*

Comparing Propositions 3 and 5, one can immediately see that the impacts of flexible battery leasing on the battery lease rate and volumes are qualitatively consistent with non-strategic and strategic customers. When not acquiring additional high-capacity batteries, flexible battery leasing with strategic customers may also reduce all customers' total cost under qualitatively similar conditions as with non-strategic customers.[4] On the other hand, when acquiring additional high-capacity batteries, we are unable to identify sufficient conditions for flexible battery leasing to reduce all customers' total cost with strategic customers as we did in Propositions 3 with non-strategic customers. Nevertheless, in our numerical studies, we find that the manufacturer rarely acquire additional high-capacity batteries with strategic customers; therefore, practically speaking, the model outcomes with strategic customers remain qualitatively similar to those with non-strategic customers. This will become evident in our numerical studies.

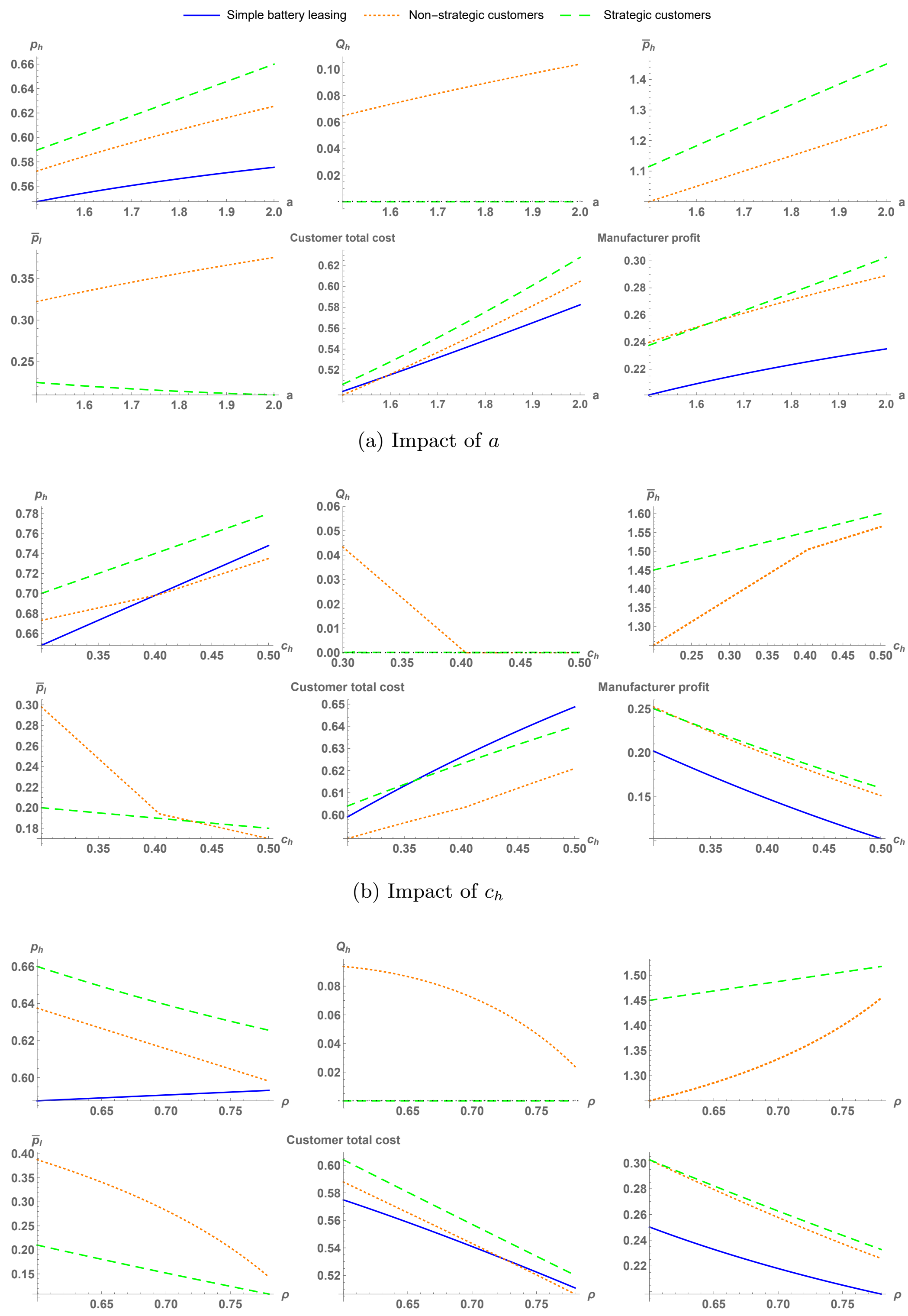
### 5.1. Numerical studies

In this section, we perform numerical studies to complement the analyses in previous sections. First, we focus on the model outcomes. Figure 3 illustrates the manufacturer's decisions, profit, and all customers' total cost for varying $a$, $c_h$ and $\rho$ for simple battery leasing[5], as well as flexible battery leasing with non-strategic and strategic customers. Note that the manufacturer's decisions $\bar{p}_h$, $\bar{p}_l$ and $Q_h$ are irrelevant for simple battery leasing and thus absent in certain plots.

One can immediately observe that the model outcomes with non-strategic and strategic customers are mostly consistent. One notable exception is that the peak downgrade rate $\bar{p}_l$ with strategic customers decreases in $a$ whereas that with non-strategic customers increases in $a$ (see Figure 3(a)). Another observation is that, with strategic customers, the manufacturer never acquires

[4] Unlike with non-strategic customers, flexible battery leasing is not in principle guaranteed to weakly increase the manufacturer's profit with strategic customers; therefore, reducing all customers' total cost does not guarantee a win-win outcome. Nevertheless, in all of our numerical experiments, we have observed flexible battery leasing with strategic customers to increase the manufacturer's profit.

[5] Recall from the discussion following Proposition 4 that the manufacturer's decisions with strategic customers do not depend on $r_h$. As such, we omit the impact of $r_h$ to save space.




Note. The parameter values are: (a) $r_h = 1.3$, $\rho = 0.6$, $c_h = 0.2$, $a \in [1.5, 2]$; (b) $a = 2$, $r_h = 1.8$, $\rho = 0.6$, $c_h \in [0.3, 0.5]$; (c) $a = 2$, $r_h = 1.5$, $c_h = 0.2$, $\rho \in [0.6, 0.78]$.

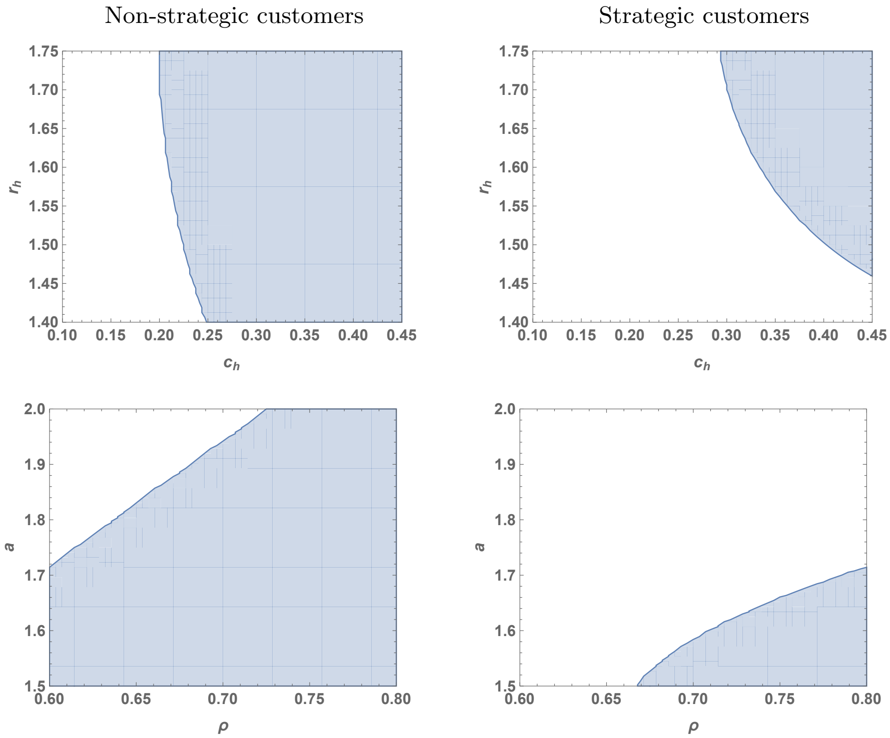
**Figure 3 Outcomes for simple and flexible battery leasing with non-strategic and strategic customers**

additional batteries ($Q_h = 0$) in our numerical experiments. In fact, these two observations are related. As discussed following Proposition 4, with sufficiently high peak need for range $a$, many strategic customers are comfortable with leasing high-capacity batteries, and the manufacturer accordingly depends more heavily on reallocating these customers' unused high-capacity batteries rather than acquiring additional batteries to meet upgrade demands. As such, the manufacturer reduces $\bar{p}_l$ to help incentivize customers with high-capacity batteries to downgrade to low-capacity batteries in the peak period and free up more high-capacity batteries for reallocation.

We can make a few more interesting observations. The high-capacity battery lease rate $p_h$ increases in the proportion of regular usage time $\rho$ for simple battery leasing but deceases in $\rho$ for flexible battery leasing with both non-strategic and strategic customers. This observation is consistent with our discussion following Proposition 2. Figure 3(b) includes a switch from acquiring additional high-capacity batteries to not acquiring them with non-strategic customers, leading to kinky price curves. The manufacturer's profit for flexible battery leasing with non-strategic and strategic customers are generally similar, although both are higher than the case of simple battery leasing. By contrast, strategic customers' total cost is generally larger than that of non-strategic customers, and either may exceed that for simple battery leasing. Therefore, the improved efficiency of flexible battery leasing primarily benefits the manufacturer, and strategic customers actually reduce flexible battery leasing's efficiency gain compared with non-strategic customers.

Next, we focus on the parameter regions where flexible battery leasing increases the manufacturer's profit and reduces all customers' total cost compared with simple battery leasing, namely the win-win regions. Because these regions exist in a four-dimensional parameter space ($r_h$, $c_h$, $a$ and $\rho$), Figure 4 presents the win-win regions with non-strategic and strategic customers in two pairs of parameters.

In Figure 4, one can clearly see that the win-win regions consistently occur for large $r_h$, $c_h$, $\rho$ and small $a$ values with both non-strategic and strategic customers. Among these parameters, the proportion of regular usage $\rho$ is largely exogenous. On the other hand, a battery's range $r_h$ and cost $c_h$ are both correlated with its capacity, and are usually compared relative to customers' peak need for range which is upper-bounded by $a$. Therefore, large $r_h$, $c_h$ and small $a$ all point to high-capacity batteries relative to the need. As we noted following Proposition 3, EV manufacturers such as NIO are making great efforts to increase their high-end models' ranges capacities, which increases the likelihood of flexible battery lease programs yielding win-win outcomes regardless of non-strategic or strategic customers. Overall, the win-win regions for strategic customers are smaller than those for non-strategic customers. As we noted following Figure 3, strategic customers




Note. The parameter values are $a = 1.8$, $\rho = 0.6$, $r_h \in [1.4, 1.75]$, $c_h \in [0.1, 0.45]$ in the top row, and $c_h = 0.2$, $r_h = 1.5$, $a \in [1.5, 2]$, $\rho \in [0.6, 0.8]$ in the bottom row.

**Figure 4 Win-win regions of flexible battery leasing**

tend to reduce flexible battery leasing's efficiency gain compared with non-strategic customers, which is not uncommon in game-theoretical models. Accordingly, the fact that real-life customers are usually not highly sophisticated decision makers lends favorably to the likelihood of flexible battery leasing yielding win-win outcomes.

# 6. Extensions

In this section, we investigate a number of model extensions to check the robustness of our base model's results and yield additional insights that may be relevant in future or alternative scenarios.

## 6.1. Noncommittal battery acquisition

In the base model, we assumed that the manufacturer can commit to the battery acquisition decision, which technically means that $Q_h$ was determined in the regular period (see Figure 1). This assumption was partly driven by the fact that, in the current EV industry, batteries are generally in short supply, and thus battery acquisition needs to be planned well ahead and is not easily adjustable. However, it is perceivable that, as the EV industry matures, batteries may become a commodity with ample supply, and an EV manufacturer may be able and willing to adapt battery acquisition to customer decisions. Therefore, in this section, we analyze an alternative model with noncommittal battery acquisition. Technically, this means that the battery acquisition decision is made during the peak period[6] (see Figure 5).

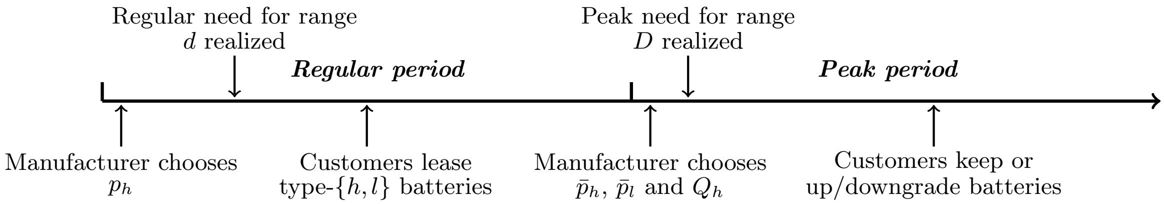



**Figure 5** **Sequence of events with noncommittal battery acquisition**

First, note that non-strategic customers do not react to the manufacturer's battery acquisition decision (which affects the peak-period up/downgrade market that non-strategic customers do not consider). Therefore, the alternative timing of the battery acquisition decision does not affect non-strategic customers, and we only need to analyze the alternative model with strategic customers. The following proposition characterizes the manufacturer's optimal decisions with strategic customers and noncommittal battery acquisition (with superscript $t$ denoting "*noncommittal*").

PROPOSITION 6. *When additional high-capacity battery quantity is chosen in the peak period, the manufacturer's optimal decisions with strategic customers, are:*

- *If* $c_h < a(1-\rho)/2$,

$$Q_h^t = [a(1-\rho)(2c_h + \rho(8+a) - a) - 16\rho c_h]/[32a\rho(1-\rho)] > 0, \quad p_h^t = [6c_h + 5a(1-\rho) + 8\rho]/16,$$

$$\bar{p}_h^t = [a + c_h/(1-\rho)]/2, \quad \bar{p}_l^t = [c_h(6 - 8/(1-\rho)) + 5a(1-\rho) + 8\rho]/16.$$

- *Otherwise,*

$$Q_h^t = 0, \quad p_h^t = \frac{13a^2(1-\rho)^2 + 32\rho(c_h+\rho) + 4a(1-\rho)(2c_h + 9\rho)}{32a(1-\rho) + 64\rho},$$

$$\bar{p}_h^t = \frac{a[9a(1-\rho) + 8(c_h + 3\rho)]}{16a(1-\rho) + 32\rho}, \quad \bar{p}_l^t = \frac{32\rho(c_h+\rho) + 4a\rho(5-9\rho) - 8ac_h(1+\rho) + a^2(1-\rho)(11-13\rho)}{32a(1-\rho) + 64\rho}.$$

*The threshold for* $c_h$ *increases in* $a$ *and decreases in* $\rho$. *The manufacturer's maximum profit is included in the proof.*

[6] Because customer decisions in the peak period are completely determined by the regular period outcome and the up/downgrade rates, it does not matter whether the manufacturer's battery acquisition decision is made before or after the customers' up/downgrade decisions; we nominally assume that the manufacturer makes all peak-period decisions at once.

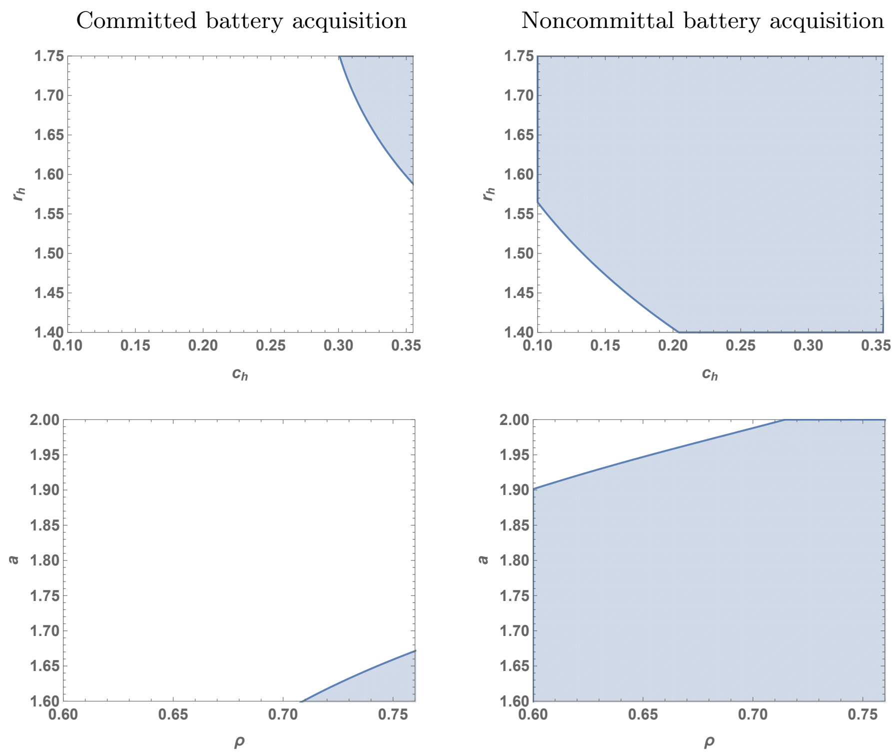
By comparing Propositions 4 and 6, one can immediately see that noncommittal battery acquisition does not qualitatively affect the model behavior. It is also intuitive that the manufacturer's optimal decisions when not acquiring additional high-capacity batteries are identical with committed and noncommittal battery acquisition. We next inspect the quantitative differences between Propositions 4 and 6.

COROLLARY 3. *With strategic customers, the battery-acquisition threshold for $c_h$ is larger with noncommittal battery acquisition than that in the base model. When acquiring additional high-capacity batteries, the lease rate $p_h$ and the peak upgrade rate $\bar{p}_h$ are smaller and the additional battery acquisition quantity $Q_h$ and the peak downgrade rate $\bar{p}_l$ are larger with noncommittal battery acquisition than those in the base model.*

Corollary 3 shows that the manufacturer generally acquires more additional high-capacity batteries (note both the increased threshold for $c_h$ and the increased $Q_h$). This finding is intuitive: in the base model, the manufacturer's commitment power regarding battery acquisition is only meaningful when committing to under-acquiring batteries, and thus the lack of such power leads to generally increased battery acquisition. Also, without such power, the manufacturer is obliged to satisfy all peak-period battery upgrade demand by acquiring costly batteries; this explains why the manufacturer is more conservative in generating peak-period battery upgrade demand with noncommittal battery acquisition, by setting lower $p_h$ to encourage long-term leasing of high-capacity batteries, and by setting lower $\bar{p}_h$ and higher $\bar{p}_l$ to limit the peak-period battery upgrade demand. In general, the manufacturer without the commitment power regarding battery acquisition is at a less advantageous position relative to its customers. One may expect that, with noncommittal battery acquisition, both the manufacturer's profit and all customers' total cost are reduced compared with the base model, which is confirmed through our numerical experiments.

When the manufacturer is worse off and the customers are better off, it is generally impossible to predict how the win-win region of flexible battery leasing will change. However, as we noted before, in all of our numerical experiments, we have observed flexible battery leasing to significantly increase the manufacturer's profit compared with simple battery leasing. Therefore, the win-win region of flexible battery leasing with noncommittal battery acquisition grows larger compared with the base model, driven by the reduced cost of all customers; see Figure 6.[7] Since noncommittal battery acquisition is more likely to occur in a mature EV industry, our finding suggests that flexible battery leasing will more likely lead to win-win outcomes compared with simple battery leasing as the industry matures, which is a promising prospect.

[7] To distinguish and compare the manufacturer's decisions with committed and noncommittal battery acquisition, Figure 6 focuses on the cases where the manufacturer acquires additional batteries in the first place.




Note. The parameter values are $a = 1.8$, $\rho = 0.6$, $r_h \in [1.4, 1.75]$, $c_h \in [0.1, 0.35]$ in the top row, and $c_h = 0.2$, $r_h = 1.5$, $a \in [1.6, 2]$, $\rho \in [0.6, 0.75]$ in the bottom row.

**Figure 6 Win-win regions of flexible battery leasing with committed and noncommittal battery acquisition**

### 6.2. Correlated regular and peak needs for range

In the base model, we assumed that customers' regular and peak needs for range are independently distributed because they represent distinct application scenarios of EVs (e.g., daily commute versus weekend road trips). However, positively and negatively correlated regular and peak needs for range are both conceivable. For example, a customer with a long daily commute may enjoy driving and thus take more weekend road trips, or s/he may be bored of driving due to the daily commute and thus take fewer weekend road trips. In this section, we investigate a model extension with correlated regular and peak needs for range.

We first generalize our demand model to allow such correlations. Specifically, we assume that, given regular need for range $d$, a customer's peak need for range $D$ is a random variable with probability density function (PDF) $[(1+\theta-2d\theta)(a-x)+(1-\theta+2d\theta)x]/a^2$ where $\theta \in [-1, 1]$ indicates the correlation (but is not the coefficient of correlation). Specifically, $\theta = 0$ reduces the PDF to $1/a$ and recovers the assumption of $D \sim U[0, a]$ independent of $d$ in the base model, and $\theta = (-)1$ indicates the most positive (negative) correlation between $D$ and $d$ in this model. For example, when $\theta = 1$, the PDF $2[(1-d)(a-x)+dx]/a^2$ with varying values of $d$ is illustrated in Figure 7; one can see that the smaller regular need for range $d$, the more likely the peak need for range $D$ takes smaller values. Technically speaking, $D$ with a larger $d$ has first-order stochastic dominance over $D$ with a smaller $d$. The model with $\theta = -1$ is the opposite, and moderate values of $\theta$ yields moderate correlations between regular and peak needs for range.

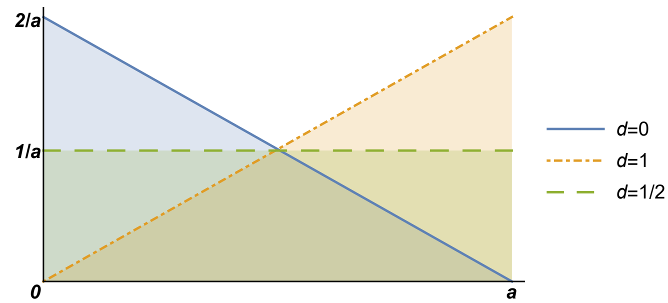
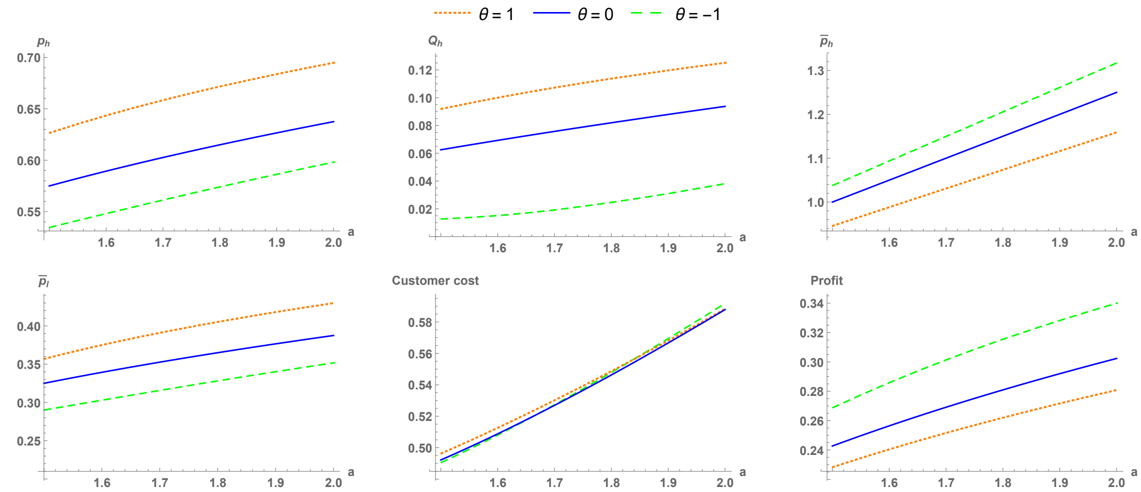



**Figure 7 Probability density function of $D$ with $\theta = 1$ for varying $d$**

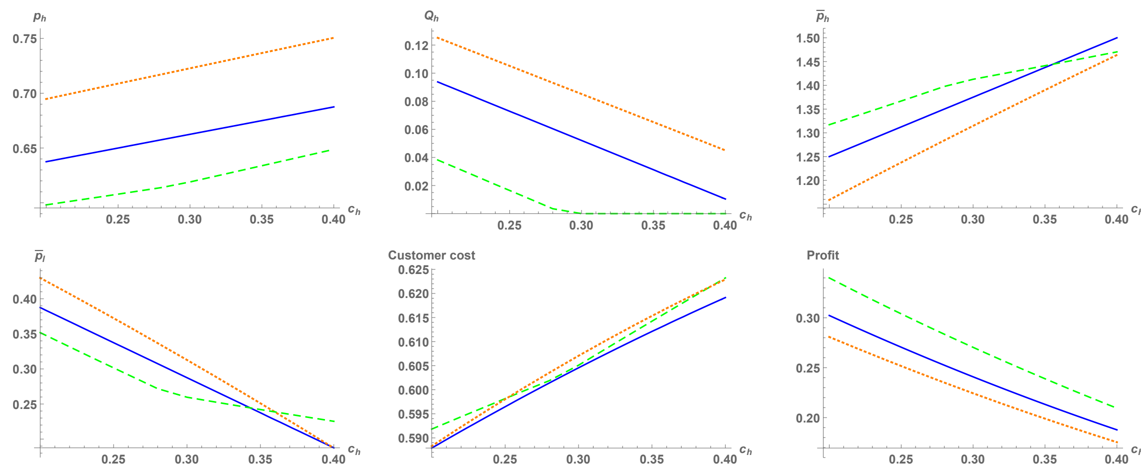
With this correlated demand model, we numerically calculate for varying correlations ($\theta = 1$, 0, -1) the model outcomes with non-strategic customers in Figure 8 (calculations with strategic customers and the correlated demand model become challenging). In most cases, correlated regular and peak needs for range do not qualitatively alter the parameter sensitivities of the outcomes with independent needs, and that positive and negative correlations cause opposite quantitative changes of the outcomes compared with independent needs. This observation shows that the results of our base model are mostly robust to correlated regular and peak needs for range.

Some notable observations can be made regarding the additional battery acquisition quantity $Q_h$ with negatively correlated regular and peak needs for range. First, in Figure 8(b), $Q_h$ reaches zero for larger $c_h$ values under a negative correlation. This is intuitive, as negatively correlated regular and peak needs for range increase the usage of both up/downgrade options in the peak period, and the manufacturer can better depend on reallocating batteries rather than acquiring additional batteries to meet the upgrade demands. The change in the manufacturer's battery acquisition strategy for larger $c_h$ values may explain the changes of the trends of $\bar{p}_l$ and $\bar{p}_h$ for larger $c_h$ in Figure 8(b). Also, Figure 8(c) shows a non-monotonic $Q_h$ in $\rho$ with negatively correlated regular and peak needs for range. Recall in the proof of Proposition 2 that $Q_h$ with non-strategic customers do not always decrease in $\rho$, and our example with a negative correlation satifies the condition for $Q_h$ increasing in $\rho$.

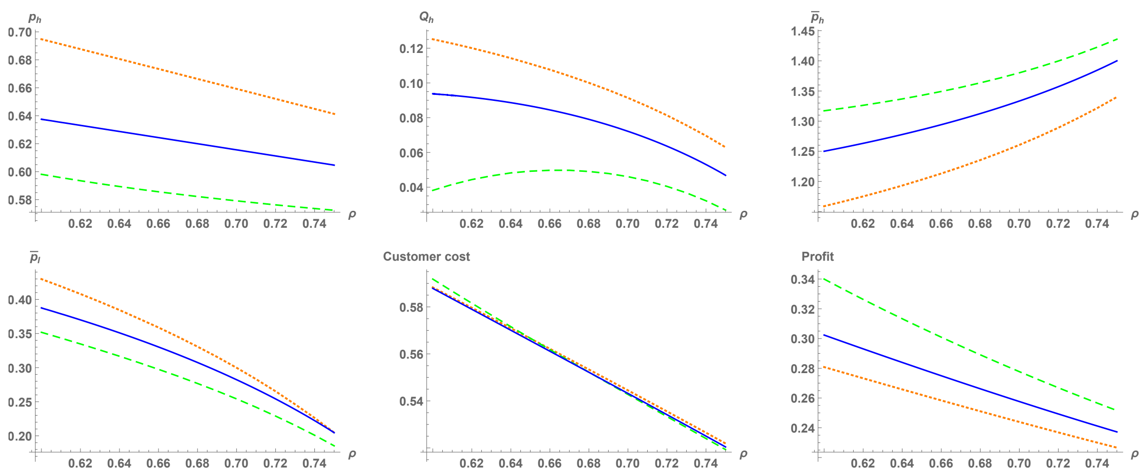
We then show the win-win regions with non-strategic customers and the correlated demand model for varying correlations ($\theta = 1,\ 0,\ -1$) in Figure 9. In this example, the win-win regions clearly shrink with a negative correlation ($\theta = -1$) compared with those with independent needs.




(a) Impact of $a$




(b) Impact of $c_h$

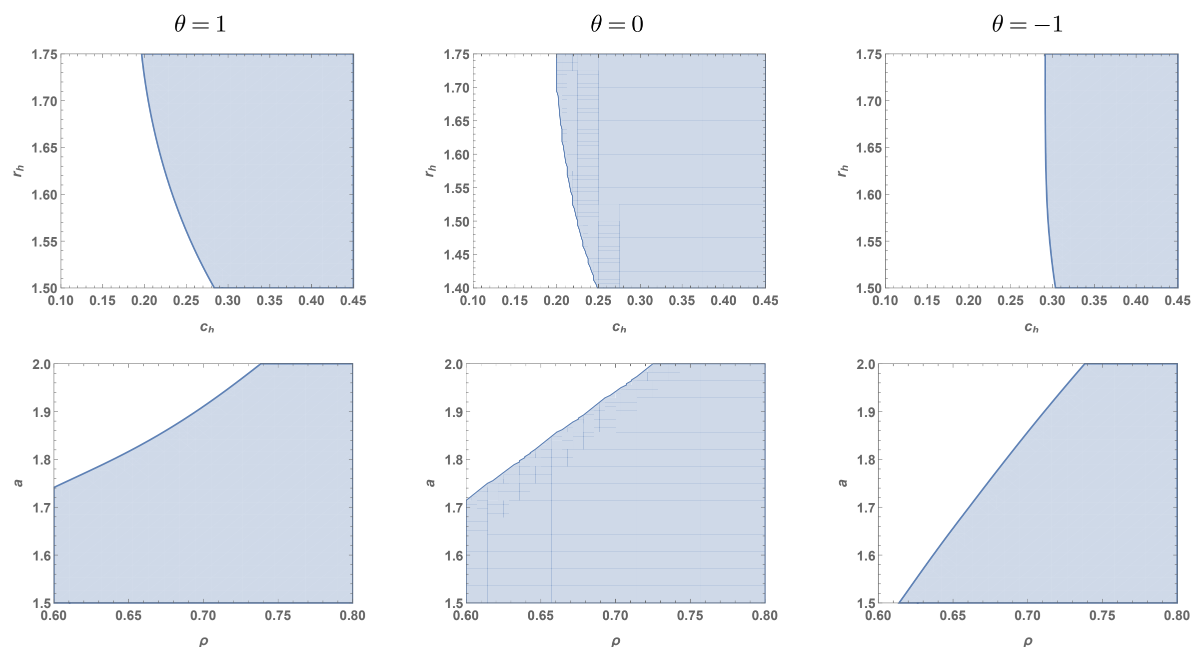



(c) Impact of $\rho$

Note. The parameter values are the same as in Figure 3.

**Figure 8 Outcomes of positively and negatively correlated needs with non-strategic customers**

The comparison with a positive correlation is however more ambiguous: although the win-win regions with a positive correlation seem smaller than those with independent needs, the former are not a subset of the latter. These observations are somewhat counterintuitive: one may expect that negative correlations significantly increase occurrences of win-win outcomes because it increases the value of flexible battery up/downgrading, whereas positive correlations significantly reduce occurrences of win-win outcomes for the opposite reason. In fact, positive correlations reduce the importance of flexible battery leasing which should have an ambiguous effect on win-win outcomes. In the extreme case of regular and peak needs being perfectly correlated, flexible battery leasing and thus win-win outcomes may become completely irrelevant. On the other hand, while negative correlations increase the value of flexible battery up/downgrading, they also make customers' up/downgrading decisions predictable. This allows the manufacturer to price the services highly effectively and extract almost the entire value of flexible battery up/downgrading. The result is that, with negatively correlated regular and peak needs, the manufacturer's profit is greatly improved whereas customers' costs may increase or decrease (see Figure 8), leading to significantly shrunken win-win regions in Figure 9.




Note. The parameter values are the same as in Figure 4.

**Figure 9 Win-win regions of positively and negatively correlated needs with non-strategic customers**

## 7. Conclusion

The electric vehicle industry is experiencing a rapid growth, and may potentially contribute to humanity's ongoing battle against climate change. EV adoptions, however, are still facing two crucial and intrinsically conflicting hurdles, namely range anxiety and purchase price. The battery swapping and leasing model is a promising solution to both issues, enabling rapid EV "refueling" and reducing the vehicle purchase price. It also provides further flexibilities and opportunities.

In this paper, inspired by the EV startup NIO which adopts the battery swapping and leasing model (referred to by the company as the Battery-as-a-Service model) and experiments with flexible battery up/downgrading intended for peak periods such as weekends and public holidays, we study a flexible EV battery lease program where customers make their long-term battery lease decisions and can temporarily up/downgrade batteries for peak usage. First assuming non-strategic customers who consider the peak usage of their leased batteries but not up/downgrading, we analyze a game-theoretical model to find that the manufacturer may depend on acquiring additional batteries or reallocating customers' batteries to satisfy the peak up/downgrade needs, and that flexible battery leasing can lead to win-win outcomes (increased manufacturer profit and reduced customer total cost) compared with simple battery leasing (without peak up/downgrade options). We then repeat the analysis for strategic customers who consider both using and up/downgrading their leased batteries during the peak period, analyze an alternative model with noncommittal battery acquisition, and numerically investigate a model extension with correlated regular and peak needs for range. Overall, we find our key results to be robust, although increasing customer sophistication and (positive and negative) correlations tend to cause the win-win regions to shrink.

While there exists a rich literature on the trend of manufacturers selling the utilities of their products as services rather than directly selling their products ("servicization") (e.g., Cohen 2012, Bustinza et al. 2015, Agrawal et al. 2022), some of which with a focus on EV battery leasing (e.g., Lim et al. 2015, Avci et al. 2015), we are the first to our best knowledge to analyze flexible battery leasing. Our results can potentially inform EV manufacturers adopting battery lease programs, especially flexible battery leasing, and highlight the value of flexible battery leasing which may improve the matching efficiency between customers and batteries and thus lead to win-win outcomes. Our finding that win-win outcomes are most likely to occur when the high-capacity batteries offer a generous range is particularly encouraging, considering the industry trend of EV manufacturers' high-end models offering increasingly impressive ranges. On a higher level, our analysis reveals intrinsic advantages and efficiencies of the battery swapping and leasing model, which may be valuable for manufacturers considering their future EV designs and business models.

In addition to flexible battery leasing analyzed in this paper, the EV battery swapping and leasing model has direct implications on other important battery lifecycle stages and events, such as production, maintenance, depreciation, repurposing (e.g., energy storage) and recycling, as well as further implications such as consumers' adverse selection and moral hazard and the manufacturer's potential battery-backed financing. Finally, swappable batteries imply the possibilities of EV manufacturers opening up their battery design to competitors or third-party battery providers (see Hu et al. 2017 for a related discussion) and/or EV manufacturers becoming battery providers to competitors (see Orsdemir et al. 2019 for a related discussion). All of these problems are potential future research directions in the exciting field of EV battery swapping and leasing model.

## References


Agrawal, Vishal V, L Beril Toktay, Şafak Yücel. 2022. Non-ownership business models for solar energy. *Manufacturing & Service Operations Management* .

Altmann, Jörn, Karyen Chu. 2001. A proposal for a flexible service plan that is attractive to users and internet service providers. *Proceedings IEEE INFOCOM 2001. Conference on Computer Communications. Twentieth Annual Joint Conference of the IEEE Computer and Communications Society (Cat. No. 01CH37213)*, vol. 2. IEEE, 953–958.

Avci, Buket, Karan Girotra, Serguei Netessine. 2015. Electric vehicles with a battery switching station: Adoption and environmental impact. *Management Science* **61**(4) 772–794.

Bove, Tristan. 2022. A top lithium expert agrees with elon musk that there's not enough of the crucial metal to meet booming demand. `https://fortune.com/2022/04/22/lithium-expert-says-supply-is-not-enough-to-keep-up-with-demand/`. Retrieved May 15, 2022.

Brandstätter, Georg, Markus Leitner, Ivana Ljubić. 2020. Location of charging stations in electric car sharing systems. *Transportation Science* **54**(5) 1408–1438.

Bustinza, Oscar F, Ali Ziaee Bigdeli, Tim Baines, Cindy Elliot. 2015. Servitization and competitive advantage: the importance of organizational structure and value chain position. *Research-Technology Management* **58**(5) 53–60.

CnEVPost. 2021. NIO allows all standard range users to temporarily upgrade their battery packs on monthly basis. `https://cnevpost.com/2021/12/05/nio-allows-all-standard-range-users-to-temporarily-upgrade-their-battery-packs-on-monthly-basis/`. Retrieved January 24, 2022.

Cohen, Maxime C, Ruben Lobel, Georgia Perakis. 2016. The impact of demand uncertainty on consumer subsidies for green technology adoption. *Management Science* **62**(5) 1235–1258.

Cohen, Maxime C, Georgia Perakis, Charles Thraves. 2015. Competition and externalities in green technology adoption. *Available at SSRN 2607688* .

Cohen, Morris A. 2012. Product performance based business models: a service based perspective. *2012 45th Hawaii International Conference on System Sciences*. IEEE, 4814–4819.

Corrêa, Henrique Luiz, Lisa M Ellram, Annibal José Scavarda, Martha C Cooper. 2007. An operations management view of the services and goods offering mix. *International Journal of Operations & Production Management* .

Eberle, Ulrich, Rittmar Von Helmolt. 2010. Sustainable transportation based on electric vehicle concepts: a brief overview. *Energy & Environmental Science* **3**(6) 689–699.

Egbue, Ona, Suzanna Long. 2012. Barriers to widespread adoption of electric vehicles: An analysis of consumer attitudes and perceptions. *Energy policy* **48** 717–729.

EIA. 2021. Energy and the environment explained: Where greenhouse gases come from. `https://www.eia.gov/energyexplained/energy-and-the-environment/where-greenhouse-gases-come-from.php`. Retrieved January 24, 2022.

EnergySage. 2021. Tesla car charging: How long does it take to charge a Tesla? `https://www.energysage.com/electric-vehicles/charging-your-ev/charging-a-tesla/`. Retrieved January 24, 2022.

Fang, Eric, Robert W Palmatier, Jan-Benedict EM Steenkamp. 2008. Effect of service transition strategies on firm value. *Journal of marketing* **72**(5) 1–14.

Garthwaite, Josie. 2021. Range anxiety: Fact or fiction? `https://www.nationalgeographic.com/culture/article/110310-electric-car-range-anxiety`. Retrieved January 24, 2022.

Gillingham, Kenneth, Sébastien Houde, Arthur Van Benthem. 2021. Consumer myopia in vehicle purchases: Evidence from a natural experiment. *American Economic Journal: Economic Policy* **13**(3) 207–238.

Girotra, K, S Netessine, P Pokala, D Gupta. 2011. Better Place: The electric vehicle renaissance. *Teaching Case, INSEAD* .

Girotra, Karan, Serguei Netessine. 2013. OM forum—business model innovation for sustainability. *Manufacturing & Service Operations Management* **15**(4) 537–544.

Gogoro. 2021. Gogoro announces 400,000 monthly battery swapping subscribers; surpasses 200 million battery swaps. https://www.gogoro.com/news/400k-gogoro-network-subscribers/. Retrieved April 24, 2022.

Guajardo, Jose A, Morris A Cohen, Sang-Hyun Kim, Serguei Netessine. 2012. Impact of performance-based contracting on product reliability: An empirical analysis. *Management Science* **58**(5) 961–979.

He, Long, Guangrui Ma, Wei Qi, Xin Wang. 2021. Charging an electric vehicle-sharing fleet. *Manufacturing & Service Operations Management* **23**(2) 471–487.

Hu, Bin, Ming Hu, Yi Yang. 2017. Open or closed? technology sharing, supplier investment, and competition. *Manufacturing & Service Operations Management* **19**(1) 132–149.

IEA. 2021. Global EV Outlook. https://www.iea.org. Retrieved January 24, 2022.

InsideEVs. 2021. NIO announces 150 kWh solid-state batteries for 2022. https://insideevs.com/news/465188/nio-150-kwh-solid-state-batteries-2022/. Retrieved February 28, 2022.

Kahlen, Micha T, Wolfgang Ketter, Jan van Dalen. 2018. Electric vehicle virtual power plant dilemma: Grid balancing versus customer mobility. *Production and Operations Management* **27**(11) 2054–2070.

Kimani, Alex. 2022. Car giants are making big bets on solid state batteries. https://oilprice.com/Energy/Energy-General/Car-Giants-Are-Making-Big-Bets-On-Solid-State-Batteries.html. Retrieved May 10, 2022.

Kök, A Gürhan, Kevin Shang, Şafak Yücel. 2020. Investments in renewable and conventional energy: The role of operational flexibility. *Manufacturing & Service Operations Management* **22**(5) 925–941.

Lacey, Gillian, Ghanim Putrus, Edward Bentley. 2017. Smart ev charging schedules: supporting the grid and protecting battery life. *IET Electrical Systems in Transportation* **7**(1) 84–91.

Li, Jun, Nelson Granados, Serguei Netessine. 2014. Are consumers strategic? structural estimation from the air-travel industry. *Management Science* **60**(9) 2114–2137.

Lim, Michael K, Ho-Yin Mak, Ying Rong. 2015. Toward mass adoption of electric vehicles: Impact of the range and resale anxieties. *Manufacturing & Service Operations Management* **17**(1) 101–119.

Mak, Ho-Yin, Ying Rong, Zuo-Jun Max Shen. 2013. Infrastructure planning for electric vehicles with battery swapping. *Management Science* **59**(7) 1557–1575.

MirHassani, SA, Roozbeh Ebrazi. 2013. A flexible reformulation of the refueling station location problem. *Transportation Science* **47**(4) 617–628.

Motavalli, Jim. 2021. There Won't Be Enough Batteries to Fulfill the Industry's EV Promises. https://www.autoweek.com/news/a37079370/ev-battery-shortage/. Retrieved May 15, 2022.

Mruzek, Martin, Igor Gajdáč, L'uboš Kučera, Dalibor Barta. 2016. Analysis of parameters influencing electric vehicle range. *Procedia Engineering* **134** 165–174.

NIO. 2020. NIO launches Battery as a Service. https://www.nio.com/news/nio-launches-battery-service. Retrieved January 24, 2022.

NIO. 2021a. NIO achieves annual target of 700 battery swap stations ahead of schedule. https://www.nio.com/news/nio-achieves-annual-target-700-battery-swap-stations-ahead-schedule. Retrieved January 24, 2022.

NIO. 2021b. NIO announces NIO Power 2025 battery swap station deployment plan. https://www.nio.com/news/nio-announces-nio-power-2025-battery-swap-station-deployment-plan. Retrieved January 24, 2022.

NIO. 2022. NIO delivers 10,489 vehicles in December and 91,429 for the full year. https://www.nio.com/news/nio-delivers-10489-vehicles-december-and-91429-full-year. Retrieved January 24, 2022.

Örsdemir, Adem, Vinayak Deshpande, Ali K Parlaktürk. 2019. Is servicization a win-win strategy? profitability and environmental implications of servicization. *Manufacturing & Service Operations Management* **21**(3) 674–691.

Orsdemir, Adem, Bin Hu, Vinayak Deshpande. 2019. Ensuring corporate social and environmental responsibility through vertical integration and horizontal sourcing. *Manufacturing & Service Operations Management* **21**(2) 417–434.

Pistoia, Gianfranco. 2010. *Electric and hybrid vehicles: Power sources, models, sustainability, infrastructure and the market*. Elsevier.

Reuters. 2022. Factbox: Swapping electric car batteries since the Gilded Age. https://www.reuters.com/business/aerospace-defense/swapping-electric-car-batteries-since-gilded-age-2022-03-24/. Retrieved April 28, 2022.

Schneider, Frank, Ulrich W Thonemann, Diego Klabjan. 2018. Optimization of battery charging and purchasing at electric vehicle battery swap stations. *Transportation Science* **52**(5) 1211–1234.

Shi, Lingling, Suresh Sethi, Metin Cakanyıldırım. 2021. Promoting electric vehicles: Reducing charging inconvenience and price via station and consumer subsidies. *forthcoming in POM* .

The White House. 2021. Fact sheet: President Biden announces steps to drive American leadership forward on clean cars and trucks. `https://www.whitehouse.gov/briefing-room/statements-releases/2021/08/05/`. Retrieved January 24, 2022.

Valogianni, Konstantina, Wolfgang Ketter, John Collins, Dmitry Zhdanov. 2020. Sustainable electric vehicle charging using adaptive pricing. *Production and Operations Management* **29**(6) 1550–1572.

Vandermerwe, Sandra, Juan Rada. 1988. Servitization of business: adding value by adding services. *European management journal* **6**(4) 314–324.

Wang, Hewu, Xiaobin Zhang, Lvwei Wu, Cong Hou, Huiming Gong, Qian Zhang, Minggao Ouyang. 2015. Beijing passenger car travel survey: implications for alternative fuel vehicle deployment. *Mitigation and Adaptation Strategies for Global Change* **20**(5) 817–835.

Widrick, Rebecca S, Sarah G Nurre, Matthew J Robbins. 2018. Optimal policies for the management of an electric vehicle battery swap station. *Transportation Science* **52**(1) 59–79.

Wise, Richard, Peter Baumgartner. 2000. Go downstream: The new profit imperative in manufacturing. *IEEE Engineering Management Review* **28**(1) 89–96.

Wu, Owen Q, Şafak Yücel, Yangfang Zhou. 2021. Smart charging of electric vehicles: An innovative business model for utility firms. *Manufacturing & Service Operations Management* .

Yu, Jiayi Joey, Christopher S Tang, Musen Kingsley Li, Zuo-Jun Max Shen. 2022. Coordinating installation of electric vehicle charging stations between governments and automakers. *Production and Operations Management* **31**(2) 681–696.

Zhang, Yiling, Mengshi Lu, Siqian Shen. 2021. On the values of vehicle-to-grid electricity selling in electric vehicle sharing. *Manufacturing & Service Operations Management* **23**(2) 488–507.

## Appendix: Proofs

*Proof of Lemma 1* We first solve for the peak-period upgrade volume. In Table 1, a low-capacity lease customer has the cost $(D - r_h)^+ + \bar{p}_h$ or $D$ if s/he uses high- or low- capacity batteries in peak period. So a low-capacity lease customer upgrades if and only if $(D - r_h)^+ + \bar{p}_h \le D$.

- $D \geq r_h$. The peak-period cost is $D - r_h + \bar{p}_h$ for high-capacity batteries, and $D$ for low-capacity batteries. A customer chooses high-capacity batteries if $D - r_h + \bar{p}_h \leq D \Longleftrightarrow \bar{p}_h \leq r_h$, and low-capacity batteries otherwise.
- $D < r_h$. The peak-period cost is $\bar{p}_h$ for high-capacity batteries, and $D$ for low-capacity batteries. A customer chooses high-capacity batteries if $\bar{p}_h \leq D$. When $\bar{p}_h > r_h$, all customers choose low-capacity batteries as $D < r_h < \bar{p}_h$. When $\bar{p}_h \leq r_h$, a customer chooses low-capacity batteries if $D < \bar{p}_h$ and high-capacity batteries if $\bar{p}_h \leq D$.

To summarize, no upgrade happens when $\bar{p}_h > r_h$. Otherwise, low-capacity lease customers upgrade if $D \geq \bar{p}_h$, i.e., $\mathbb{P}(D \geq \bar{p}_h) = (a - \bar{p}_h)/a$. Given the regular-period low-capacity battery lease volume $\tau$, the peak-period upgrade volume is $\tau(a - \bar{p}_h)/a$.

In a similar way, we can solve for the peak-period downgrade volume. From Table 1, a high-capacity lease customer downgrades if and only if $(D - r_h)^+ + p_h > D + \bar{p}_l$.

- $D \geq r_h$. A customer chooses low-capacity batteries if $D - r_h + p_h > D + \bar{p}_l \Longleftrightarrow \bar{p}_l < p_h - r_h$, and high-capacity batteries otherwise.
- $D < r_h$. A customer chooses low-capacity batteries if $p_h > D + \bar{p}_l \Longleftrightarrow D < p_h - \bar{p}_l$.

To summarize, no downgrade happens if $\bar{p}_l > p_h$. If $\bar{p}_l < p_h - r_h$, all high-capacity lease customers downgrade. If $p_h - r_h \leq \bar{p}_l \leq p_h$, the high-capacity lease customers downgrade to low-capacity batteries if $D < p_h - \bar{p}_l$, i.e., is $\mathbb{P}(D < p_h - \bar{p}_l) = (p_h - \bar{p}_l)/a$. Given the regular-period high-capacity battery lease volume $1 - \tau$, the peak-period downgrade volume is $(1 - \tau)(p_h - \bar{p}_l)/a$. $\square$

*Proof of Lemma 2* The total cost of leasing high-capacity batteries in two periods is

$$p_h + \rho(d - r_h)^+ + (1 - \rho)\mathbb{E}[(D - r_h)^+] = p_h + \rho(d - r_h)^+ + (1 - \rho)(a - r_h)^2/(2a),$$

and the total cost of leasing low-capacity batteries is $\rho d + (1 - \rho)\mathbb{E}[D] = \rho d + a(1 - \rho)/2$.

We compare the total costs of leasing high- and low-capacity batteries. It is trivial to find that all customers lease high- or low-capacity batteries when $d \geq r_h$. So we focus on $d < r_h$, where the total cost of leasing high-capacity batteries is $p_h + (1 - \rho)(a - r_h)^2/(2a)$.

$$p_h + (1 - \rho)(a - r_h)^2/(2a) > \rho d + a(1 - \rho)/2 \Longleftrightarrow d < [2ap_h - (1 - \rho)r_h(2a - r_h)]/[2a\rho].$$

So the low-capacity battery lease volume is $[2ap_h - (1 - \rho)r_h(2a - r_h)]/[2a\rho]$. We have $[(1 - \rho)r_h - (1 - \rho)r_h^2/(2a)] \leq p_h \leq [(1 - \rho)r_h - (1 - \rho)r_h^2/(2a) + \rho]$; a lower range would lead to the trivial case of all customers leasing high-capacity batteries, and a higher range would lead to the trivial case of all customers leasing low-capacity batteries. $\square$

*Proof of Lemma 3* From the constraint in the manufacturer's peak-period problem, we can write $\bar{p}_l$ in terms of $\bar{p}_h$.

$$\bar{p}_l^*(\bar{p}_h) = \frac{aQ_h + p_h - a\ \tau - \tau\ p_h + \tau\ \bar{p}_h}{1-\tau}.$$

Substituting $\bar{p}_l^*(\bar{p}_h)$ into the peak-period profit $\pi(\bar{p}_h, \bar{p}_l) = (1-\tau)p_h + (1-\tau)(\bar{p}_l - p_h)(p_h - \bar{p}_l)/a + \tau\ \bar{p}_h(a-\bar{p}_h)/a - c_h(1-\tau+Q_h)$, the second-order derivative wrt $\bar{p}_h$ is

$$\frac{\partial \pi^2(\bar{p}_h, \bar{p}_l)}{\partial \bar{p}_h^2} = -\frac{2\tau}{a(1-\tau)} < 0.$$

So the firm's profit is concave in $\bar{p}_h$, and the F.O.C yields the optimal

$$\bar{p}_h^*(\tau, p_h, Q_h) = a(1+\tau-2Q_h)/2,\ \bar{p}_l^*(\tau, p_h, Q_h) = p_h + a(2Q_h - \tau)/2,$$

and the corresponding peak-period profit in terms of $\tau$, $p_h$ and $Q_h$ is $p_h(1-\tau) - c_h(1+Q_h-\tau) + a(\tau - (2Q_h-\tau)^2)/4$. □

*Proof of Proposition 1* In the simple battery lease program with semi-strategic customers, the manufacturer's problem is

$$\max_{p_h} \quad \{(p_h - c_h)(1-\tau) : \quad \tau = [2ap_h - (1-\rho)r_h(2a-r_h)]/[2a\rho]\}.$$

which is concave in $p_h$ as the second-order derivative is negative. So the first-order condition yields the optimal price $p_h^b = [(1-\rho)(2ar_h - r_h^2) + 2a(c_h+\rho)]/(4a)$, and the maximized profit is $[(1-\rho)(2ar_h - r_h^2) - 2a(c_h-\rho)]^2/(16\rho a^2)$.

$$\partial p_h^b/\partial a = (1-\rho)r_h^2/(4a^2) > 0,\ \partial p_h^b/\partial r_h = (1-\rho)(a-r_h)/(2a) > 0,$$
$$\partial p_h^b/\partial c_h = 1/2,\ \partial p_h^b/\partial \rho = (2a - 2ar_h + r_h^2)/(4a).$$

So $p_h^b$ increases in $a$, $r_h$, $c_h$, and increases in $\rho$ if $2a - 2ar_h + r_h^2 > 0$ and decreases otherwise.

Accordingly, the low-capacity volume is $\tau^b = [2a(c_h+\rho) - (1-\rho)(2ar_h - r_h^2)]/(4a\rho)$. We have $(1-\rho)(2ar_h - r_h^2)/(2a) - \rho < c_h < (1-\rho)(2ar_h - r_h^2)/(2a) + \rho$, otherwise all customers lease low- or high-capacity batteries.

$$\partial \tau^b/\partial a = -(1-\rho)r_h^2/(4\rho a^2) < 0,\ \partial \tau^b/\partial r_h = -(1-\rho)(a-r_h)/(2a\rho) < 0,$$
$$\partial \tau^b/\partial c_h = 1/2(\rho) > 0,\ \partial \tau^b/\partial \rho = -(2ac_h - 2ar_h + r_h^2)/(4a\rho^2).$$

So $\tau^b$ decreases in $a$, $r_h$, increases in $c_h$, and increases in $\rho$ if $2ac_h - 2ar_h + r_h^2 < 0$ and decreases otherwise.

We then compute all customers' total cost. The low-capacity lease customers' total cost is

$$CT_l^b = \rho\mathbb{E}[d] + (1-\rho)\mathbb{E}[D] = \rho\tau^b/2 + a(1-\rho)/2.$$

The high-capacity lease customers' total cost is

$$\begin{aligned} CT_h^b &= \rho(\mathbb{E}[(d-r_h)^+] + p_h^b) + (1-\rho)(\mathbb{E}[(D-r_h)^+] + p_h^b) \\ &= \rho(1-r_h)^2/(2(1-\tau^b)) + (1-\rho)(a-r_h)^2/(2a) + p_h^b, \end{aligned}$$

when $r_h \le 1$, and $CT_h^b = (1-\rho)(a-r_h)^2/(2a) + p_h^b$ when $r_h > 1$.

All customers' total cost is $CT^b = \tau^b CT_l^b + (1-\tau^b)CT_h^b$, which is $[16\rho(1-\rho)a^3 - r_h^4(1-\rho)^2 + 4ar_h^2(1-\rho)(r_h - c_h + \rho(1-r_h)) + 4a^2((7-3(2-r_h)r_h)\rho^2 - (c_h-r_h)^2 + 2\rho(c_h-r_h)(1-r_h))]/(32\rho a^2)$ for $r_h \le 1$, and $[16\rho(1-\rho)a^3 - (r_h^4(1-\rho)^2 + 4a^2(c_h - r_h(1-\rho)+\rho)(r_h - c_h + \rho(3-r_h)) + 4ar_h^2(1-\rho)(r_h - c_h + (1-r_h)\rho)]/(32\rho a^2))$ for $r_h > 1$. $\square$

*Proof of Proposition 2* (i) We insert $\tau = (2ap_h - (1-\rho)r_h(2a-r_h))/(2a\rho)$ into $\Pi(p_h, Q_h)$, and then take the second-order derivative of $\Pi(p_h, Q_h)$ wrt $Q_h$,

$$\frac{\partial \Pi^2(p_h, Q_h)}{\partial Q_h^2} = -2a(1-\rho) < 0.$$

The profit is concave, so the F.O.C yields the optimal

$$Q_h^n(p_h) = \frac{2a(p_h - (1-\rho)r_h)(1-\rho) + r_h^2(1-\rho)^2 - 2\rho c_h \rho}{4a\rho(1-\rho)}.$$

Substituting $Q_h^n(p_h)$ to $\Pi(p_h, Q_h)$, we then take the second-order derivative wrt $p_h$,

$$\frac{\partial \Pi^2(p_h, Q_h^n(p_h))}{\partial p_h^2} = -2/\rho < 0.$$

The F.O.C yields the optimal $p_h^n = [a(1-\rho) + 2c_h - 2(1-\rho)r_h^2/a + 4(\rho + (1-\rho)r_h))]/8$. Substitute $p_h^n$ to up/downgrade rates and high-capacity battery acquisition quantity, we have

$$\bar{p}_h^n = (a + c_h/(1-\rho))/2,\ \bar{p}_l^n = [a(1-\rho) - 2(1-\rho)r_h^2/a - 2c_h(1+\rho)/(1-\rho) + 4(\rho + (1-\rho)r_h)]/8,$$

$$Q_h^n = \frac{a^2(1-\rho)^2 + 2((1-\rho)^2 r_h^2 - 4\rho c_h) + 2a(1-\rho)(c_h + 2\rho - 2(1-\rho)r_h)}{16a\rho(1-\rho)}.$$

The maximized profit is

$$\begin{aligned} \Pi^n = [(1-\rho)^3(a^4 + 4r_h^4) &+ 8a(c_h r_h^2(1-\rho)^2 - 2r_h^2(1-\rho)^2(\rho + (1-\rho)r_h) + 2\rho c_h^2) \\ &+ 4a^2(1-\rho)(c_h^2 - 4c_h r_h + 5r_h^2(1+\rho)^2 - 4\rho c_h(3-r_h) + 8\rho(1-\rho)r_h + 4\rho^2) \\ &+ 4a^3(1-\rho)^2(c_h + 2(\rho - (1-\rho)r_h))]/[64\rho(1-\rho)a^2]. \end{aligned}$$

We now check the interior conditions of $\bar{p}_h \le r_h$ and $p_h - r_h \le \bar{p}_l \le p_h$ at the optimal solutions. It is trivial to find that $\bar{p}_l^n \le p_h^n$.

$$\bar{p}_h^n = (a + c_h/(1-\rho))/2 \le r_h \Longleftrightarrow c_h \le (2r_h - a)(1-\rho) \text{ and } r_h \ge a/2,$$

$$\bar{p}_l^* \ge p_h^n - r_h \Longleftrightarrow c_h \le 2r_h(1-\rho).$$

As $(2r_h - a)(1-\rho) < 2r_h(1-\rho)$, the optimal solution satisfies the conditions under $r_h \ge a/2$ and $c_h \le (2r_h - a)(1-\rho)$.

By taking the first-order derivatives, we show the impact of $a,\ c_h,\ \rho$. As $a$ increases, $p_h^n,\ \bar{p}_h^n,\ \bar{p}_l^n$ and $Q_h^n$ increases. As $c_h$ increases, $p_h^n,\ \bar{p}_h^n$ increases, while $\bar{p}_l^n,\ Q_h$ decreases. As $\rho$ increase, $\bar{p}_h^n$ increases. The first-order derivatives of the other optimal decisions wrt $\rho$ are as follows.

$$\frac{\partial p_h^n}{\partial \rho} = [4 - a - 4r_h + 2r_h^2/a]/8,\ \frac{\partial \bar{p}_l^n}{\partial \rho} = [4 - a - 4r_h + 2r_h^2/a - (4c_h)/(1-\rho)^2]/8,$$
$$\frac{\partial Q_h^n}{\partial \rho} = -[a + 2c_h - 4r_h + 2(r_h^2(1-\rho)^2 + 4c_h\rho^2)/(a(1-\rho)^2)]/(16\rho^2).$$

We find that $p_h^n$ increases if $(4a - a^2 - 4ar_h + 2r_h^2)/(8a) > 0$, $\bar{p}_l^n$ increases if $c_h < (4a(1-r_h) + 2r_h^2 - a^2)(1-\rho)^2/(4a)$, and $Q_h$ increases if $c_h > (4ar_h - a^2 - 2r_h^2)(1-\rho)^2/[2a(1-\rho)^2 + 8\rho^2]$.

We then check the nonnegativity of high-capacity battery acquisition quantity.

$$Q_h^n \ge 0 \Longleftrightarrow a^2(1-\rho)^2 + 2a(1-\rho)(c_h + 2(\rho - (1-\rho)r_h)) + 2(r_h^2(1-\rho)^2 - 4\rho c_h) \ge 0$$
$$\Longleftrightarrow c_h \le (1-\rho)[(1-\rho)(a^2 + 2r_h^2 - 4ar_h) + 4a\rho]/[8\rho - 2a(1-\rho)] \doteq C^n(a, r_h, \rho).$$

Take the first-order derivatives of $C^n(a, r_h, \rho)$ wrt $a,\ r_h,\ \rho$, we find that

$$\partial C^n(a, r_h, \rho)/\partial a = \frac{(1-\rho)(2r_h^2 - a^2(1-\rho)^2 - 4\rho r_h(4 + r_h) + 8a\rho(1-\rho) + 2(8 + r_h(8 + r_h))\rho^2)}{2(a(1-\rho) - 4rho)^2},$$
$$\partial C^n(a, r_h, \rho)/\partial r_h = -[2(a - r_h)(1-\rho)^2]/[\rho(4+a) - a] < 0,$$
$$\partial C^n(a, r_h, \rho)/\partial \rho = [a^2 - 4a - 4ar_h + 2r_h^2 - 32(a - r_h)^2/(a - \rho a - 4\rho)^2]/[2(4+a)] < 0.$$

The last inequality holds because $a^2 - 4a - 4ar_h + 2r_h^2 < 0$ for $a/2 < r_h < a$. To check the sign of $\partial C^n(a, r_h, \rho)/\partial a$, we further take the second-order derivative.

$$\partial^2 C^n(a, r_h, \rho)/\partial a^2 = 2(1-\rho)^2(r_h(1-\rho) - 4\rho)^2/(\rho(a+4) - a)^3 > 0.$$

So $C^n(a, r_h, \rho)$ is convex in $a$. And we have $\partial C^n(a, r_h, \rho)/\partial a|_{a=r_h} = (1-\rho)/2 > 0$. Therefore, $C^n(a, r_h, \rho)$ increases in $a$ for $a > r_h$.

(ii) Next we optimize the manufacturer's problems in (1) and (2) with $Q_h = 0$ for $c_h \geq (1-\rho)[(1-\rho)(a^2+2r_h^2-4ar_h)+4a\rho)]/[8\rho-2a(1-\rho)]$.

From the supply and demand equation in the peak period, we have $\bar{p}_l^n(\bar{p}_h) = (p_h - a\ \tau - \tau\ p_h + \tau\ \bar{p}_h)/(1-t)$. Substituting $\bar{p}_l^n(\bar{p}_h)$ into the objective function in (1), the second-order derivative is $\partial\pi^2(\bar{p}_h, \bar{p}_l)/\partial\bar{p}_h^2 = -2\tau/(a-a\ \tau) < 0$, so the F.O.C yields the optimal $\bar{p}_h^n(p_h) = a(1+\tau)/2$, $\bar{p}_l^n(p_h) = p_h - a\tau/2$, and the corresponding profit is $\pi^n(\tau, p_h) = (1-\tau)(a\tau + 4p_h - 4c_h)/4$.

We insert $\tau = (2ap_h - (1-\rho)r_h(2a-r_h))/(2a\rho)$ into the regular period problem, and then take the second-order derivative of $\Pi(p_h)$ wrt $p_h$

$$\partial\Pi^2(p_h)/\partial p_h^2 = -[2(1-\rho)a + 8\rho]/[4\rho^2] < 0.$$

So the F.O.C yields the optimal

$$p_h^n = \frac{a^2(1-\rho)[2(1-\rho)r_h - \rho] - 2\rho(1-\rho)r_h^2 + a[4\rho(1-\rho)r_h + 4\rho(c_h+\rho) - r_h^2(1-\rho)^2]}{2a[4\rho + (1-\rho)a]}.$$

The optimal up/downgrade rates are

$$\bar{p}_h^n = \frac{(1-\rho)(3a^2+2r_h^2-4ar_h) + 4a(c_h+3\rho)}{16\rho + 4a(1-\rho)},$$

$$\bar{p}_l^n = \frac{(1-\rho)(8\rho a r_h - a^3 - 4\rho r_h^2) + 2ar_h(1-\rho)(2-\rho)(2a-r_h) - 2a^2(2c_h+\rho+\rho^2) + 8a\rho(c_h+\rho)}{4a[4\rho+(1-\rho)a]},$$

and the maximized profit is $\Pi^n = [(1-\rho)(2r_h^2 - a^2 - 4ar_h) + 4a(c_h-\rho)]^2/[16a^2(a(1-\rho)+4\rho)]$. We can similarly check the conditions for $p_h^n - r_h \leq \bar{p}_l^n \leq p_h^n$, $\bar{p}_h^n \leq r_h$ and $p_h^n \leq r_h$. □

*Proof of Corollary 1* We check the sign of $\bar{p}_l^n$ under two cases.

$c_h < (1-\rho)[(1-\rho)(a^2+2r_h^2-4ar_h)+4a\rho)]/[8\rho-2a(1-\rho)]$. We find that $\bar{p}_l^n = [a(1-\rho) - 2(1-\rho)r_h^2/a - 2c_h(1+\rho)/(1-\rho) + 4(\rho + (1-\rho)r_h)]/8 > 0$ for $r_h \leq 1$. Moreover, $\partial\bar{p}_l^n/\partial r_h = (1-\rho)(a-r_h)/(2a) > 0$ and $\bar{p}_l^n$ increases in $r_h$. Therefore, $\bar{p}_l^n > 0$ in this case.

$c_h \geq (1-\rho)[(1-\rho)(a^2+2r_h^2-4ar_h)+4a\rho)]/[8\rho-2a(1-\rho)]$. Recall that $\bar{p}_l^n = [(1-\rho)(8\rho a r_h - a^3 - 4\rho r_h^2) + 2ar_h(1-\rho)(2-\rho)(2a-r_h) - 2a^2(2c_h+\rho+\rho^2) + 8a\rho(c_h+\rho)]/[4a(4\rho+(1-\rho)a)]$. The denominator is positive, so we check the nominator. Here, $\bar{p}_l^n$ increases in $r_h$ and $\bar{p}_l^n(r_h \to 0) = -(a-2\rho)[(1-\rho)a + 4(c_h+\rho)]/[4a+4(4-a)\rho] \geq 0$ if $a \leq 2\rho$ and thus $\bar{p}_l^n > 0$. For $a > 2\rho$, we have $\partial\bar{p}_l^n/\partial c_h = -(a-2\rho)/(a(1-\rho)+4\rho) < 0$, and $\bar{p}_l^n < 0 \Longleftrightarrow c_h > [4\rho((1-\rho)r_h + \rho) - (1-\rho)(a^3 + 4\rho r_h^2)/(2a) + (2ar_h - r_h^2)(2-3\rho+\rho^2) - a\rho(1+\rho)]/[2(a-2\rho)]$. □

*Proof of Proposition 3* (i) We first compare the lease rates and low-capacity battery lease volumes under simple and flexible battery leasing, based on the results in Propositions 1 and 2.

$\underline{c_h < (1-\rho)[(1-\rho)(a^2+2r_h^2-4ar_h)+4a\rho)]/[8\rho-2a(1-\rho)]}$.

$$p_h^n > p_h^b \Longleftrightarrow 2c_h-(1-\rho)a<0,\ \tau^n>\tau^b \Longleftrightarrow \rho[2c_h-(1-\rho)a]<0.$$

It shows that $p_h^n > p_h^b$ and $\tau^n > \tau^b$ if $a > 2c_h/(1-\rho)$.

$\underline{c_h \geq (1-\rho)[(1-\rho)(a^2+2r_h^2-4ar_h)+4a\rho)]/[8\rho-2a(1-\rho)]}$.

$$p_h^n < p_h^b \Longleftrightarrow 2a((1-\rho)r_h-c_h)-(1-\rho)r_h^2<0,\ \tau^n<\tau^b \Longleftrightarrow \rho[2a((1-\rho)r_h-c_h)-(1-\rho)r_h^2]<0.$$

The inequality always holds as $a < 4\rho/(1-\rho)$ and $c_h \geq (1-\rho)[(1-\rho)(a^2+2r_h^2-4ar_h)+4a\rho)]/[8\rho-2a(1-\rho)]$, and thus $p_h^n < p_h^b$ and $\tau^n < \tau^b$.

(ii) Under flexible battery lease program, customers' regular-period cost is the same as that under simple program (except for the regular rate $p_h^n$), and thus we only solve the peak-period cost here. Note that a customer's peak-period cost is in Table 1.

A low-capacity lease customer upgrades if $D \geq \bar{p}_h$ in the peak period and keeps low-capacity batteries otherwise. So we obtain the expected peak-period cost by breaking up the integrals into two parts, which differs on using high- or low-capacity batteries in peak period.

$$\begin{aligned}\mathbb{E}[c_l(D)] &= \frac{\bar{p}_h}{a}\int_0^{\bar{p}_h} Df(D)dD + \frac{a-\bar{p}_h}{a}\int_{\bar{p}_h}^{a}((D-r_h)^+ + \bar{p}_h)f(D)dD\\ &= \frac{a^2-2ar_h+r_h^2+(2a-\bar{p}_h)\bar{p}_h}{2a}.\end{aligned}$$

The total cost of a low-capacity lease in two periods under flexible battery lease program is

$$CT_l^n = \rho\mathbb{E}[d]+(1-\rho)\mathbb{E}[c_l(D)] = \rho\tau^n/2+(1-\rho)\frac{a^2-2ar_h+r_h^2+(2a-\bar{p}_h^*)\bar{p}_h^*}{2a}.$$

Similarly, a high-capacity lease customer downgrades if $D < p_h - \bar{p}_l$ in the peak period and keeps high-capacity batteries otherwise. The expected peak-period cost of a high-capacity lease is

$$\begin{aligned}\mathbb{E}[c_h(D)] &= \frac{p_h-\bar{p}_l}{a}\int_0^{p_h-\bar{p}_l}(D+\bar{p}_l)f(D)dD + \frac{a-p_h+\bar{p}_l}{a}\int_{p_h-\bar{p}_l}^{a}((D-r_h)^+ + p_h)f(D)dD\\ &= \frac{a^2-2ar_h+r_h^2-(p_h-\bar{p}_l)^2+2ap_h}{2a}.\end{aligned}$$

The total cost of a high-capacity lease in two periods under flexible program is

$$\begin{aligned}CT_h^n &= \rho\mathbb{E}[(d-r_h)^+ + p_h^n]+(1-\rho)\mathbb{E}[c_h(D)]\\ &= \rho((1-r_h)^2/(2(1-\tau^n))+p_h^n)+(1-\rho)\frac{(a-r_h)^2+2ap_h^n-(p_h^n-\bar{p}_l^n)^2}{2a},\end{aligned}$$

when $r_h \leq 1$, and $CT_h^n = p_h^n + (1-\rho)((a-r_h)^2-(p_h^n-\bar{p}_l^n)^2)/(2a)$ when $r_h > 1$.

All customers' total cost is $CT^n = \tau^n CT_l^n + (1-\tau^n)CT_h^n$. Next we compare all customers' total cost under flexible battery leasing with that under simple battery leasing for low and high battery costs, respectively. Note that $CT^b - CT^n$ for $r_h \le 1$ and $r_h > 1$ are the same, so it is enough to write out the comparing expression for $r_h > 1$.

$c_h < (1-\rho)[(1-\rho)(a^2+2r_h^2-4ar_h)+4a\rho)]/[8\rho-2a(1-\rho)]$. All customers' total cost under flexible battery leasing for $r_h > 1$ is

$$CT^n = [(1-\rho)^3(5a^4+12r_h^4)+4a^3(1-\rho)^2(3c_h+8\rho(3+r_h)-8r_h) \\ +4(1-\rho)a^2((c_h-4r_h)^2+8\rho(c_h-(3-c_h)r_h-4r_h^2)+4(3+6r_h+4r_h^2)\rho^2) \\ +16a(r_h^2(1-\rho)^2(c_h-3(r_h(1-\rho)-\rho))-c_h^2\rho)]/[128\rho(1-\rho)a^2].$$

Now compare it with all customers' total cost under simple battery leasing.

$$CT^b > CT^n \Longleftrightarrow g_1(r_h,c_h,a,\rho) = (1+\rho)^3(5a^4+16r_h^4)+4a^3(1-\rho)^2(3c_h-8((1-\rho)r_h-\rho)) \\ -16a(\rho c_h^2+2r_h^2(1-\rho)^2(2r_h(1-\rho)-\rho-c_h))+4a^2(1-\rho)(5c_h^2+4r_h(1-\rho)(5r_h(1-\rho)-4\rho-4c_h))<0$$

When $r_h \to a$, the low battery cost condition becomes $c_h < a(1-\rho)/2$, and we have

$$g_1(r_h \to a, c_h \to a(1-\rho)/2, a, \rho) = -4\rho(1-\rho)^2a^3 < 0.$$

Because the function is continuous, $g_1(r_h,c_h,a,\rho)<0$ holds when $r_h$ and $c_h$ are sufficiently large. Note that $a$ is compared with $r_h$ and $a > r_h$, so $g_1(r_h,c_h,a,\rho)<0$ when $a$ is sufficiently low. Similarly, we show that $g_1(r_h,c_h,a,\rho)>0$ for sufficiently large $\rho$ as $g_1(r_h,c_h,a,\rho\to 1) = -16ac_h^2 < 0$.

$c_h \ge (1-\rho)[(1-\rho)(a^2+2r_h^2-4ar_h)+4a\rho)]/[8\rho-2a(1-\rho)]$. All customers' total cost under flexible battery leasing for $r_h > 1$ is

$$CT^n = [23a^5(1-\rho)^3+48\rho r_h^4(1-\rho)^2+4a^4(1-\rho)^2(8c_h-12r_h(1-\rho)+49\rho) \\ +4(1-\rho)ar_h^2(5r_h^2(1-\rho)^2-48\rho(1-\rho)r_h+16\rho(c_h+3\rho))+8(1-\rho)a^3(2c_h^2+13r_h^2(1-\rho)^2 \\ -36\rho(1-\rho)r_h+58\rho^2-4c_h(3(1-\rho)r_h-5\rho))-16a^2(5r_h^3(1-\rho)^3+4c_h^2\rho-21\rho r_h^2(1-\rho)^2 \\ +24\rho^2(1-\rho)r_h-12\rho^3-c_h(3r_h^2(1-\rho)^2-8\rho(1-\rho)r_h+8\rho^2))]/[32a^2(a(1-\rho)+4\rho)^2].$$

Now compare it with all customers' total cost under simple battery leasing.

$$CT^b > CT^n \Longleftrightarrow g_2(r_h,c_h,a,\rho) = 7\rho(1-\rho)^2a^5+64(1-\rho)\rho^2r_h^4+4a^4(1-\rho)((c_h-r_h)^2 \\ +2\rho(c_h(3+r_h)-r_h(5+r_h))+(14+r_h(10+r_h))\rho^2)+4\rho ar_h^2(7r_h^2(1-\rho)^2-64\rho(1-\rho)r_h+32\rho(c_h+\rho)) \\ +a^2r_h(r_h^3(1-\rho)^3-112\rho(1-\rho)^2r_h^2-256\rho^2(c_h+\rho)+16\rho(1-\rho)r_h(5c_h+23\rho))+4a^3(33\rho(1-\rho)^2r_h^2$$

$$+12\rho c_h^2 - r_h^3(1-\rho)^3 - 56(1-\rho)r_h\rho^2 + 28\rho^3 + c_h(r_h^2(1-\rho)^2 - 40\rho(1-\rho)r_h + 24\rho^2)) < 0$$

When $r_h \to a$ and $c_h \to a(1-\rho)/2$, we have

$$g_2(r_h \to a, c_h \to a(1-\rho)/2, a, \rho) = -\rho a^3(a + 4\rho - a\rho)^2 < 0.$$

Because the function is continuous, $g_2(r_h, c_h, a, \rho) < 0$ holds when $r_h$ is sufficiently large and $c_h$ is sufficiently low. And $g_2(r_h, c_h, a, \rho) < 0$ holds when $a$ is sufficiently low.

Similarly, we have $g_2(r_h, c_h, a \to r_h, \rho \to 1) = -16(1-c_h)(1+3c_h)r_h^3 < 0$, and thus $g_2(r_h, c_h, a, \rho) < 0$ for sufficiently low $a$ and sufficiently large $\rho$. □

*Proof of Lemma 4* From Proposition 3, the expected peak-period costs of a high- and low-capacity lease customer are

$$\mathbb{E}[c_h(D)] = \frac{a^2 - 2ar_h + r_h^2 - (p_h - \bar{p}_l)^2 + 2ap_h}{2a},\ \mathbb{E}[c_l(D)] = \frac{a^2 - 2ar_h + r_h^2 + (2a - \bar{p}_h)\bar{p}_h}{2a}.$$

If a customer leases high- or low-capacity batteries in the regular period, the total cost in two periods is $\rho[p_h + (d - r_h)^+] + (1-\rho)\mathbb{E}[c_h(D)]$ or $\rho d + (1-\rho)\mathbb{E}[c_l(D)]$. The indifferent cost must happen when $d < r_h$, otherwise all customers lease high- or low-capacity batteries. A customer leases low-capacity batteries at the beginning if $\rho d < \rho p_h + (1-\rho)(\mathbb{E}[c_h(D)] - \mathbb{E}[c_l(D)])$ and high-capacity batteries otherwise. The low-capacity battery lease volume is

$$\tau = [2ap_h - (1-\rho)((p_h - \bar{p}_l)^2 + 2a\bar{p}_h - \bar{p}_h^2)]/[2a\rho],$$

and the high-capacity volume is

$$1 - \tau = [2a(\rho - p_h) + (1-\rho)((p_h - \bar{p}_l)^2 + 2a\bar{p}_h - \bar{p}_h^2)]/[2a\rho].$$

We take the first-order derivatives of $\tau$ wrt $p_h,\ \bar{p}_h,\ \bar{p}_l$ and check the signs.

$$\frac{\partial \tau}{\partial p_h} = \frac{a - (1-\rho)(p_h - \bar{p}_l)}{a\rho} \geq 0,$$

$$\frac{\partial \tau}{\partial \bar{p}_h} = -\frac{(1-\rho)(p_h - \bar{p}_h)}{a\rho} \leq 0,\ \frac{\partial \tau}{\partial \bar{p}_l} = \frac{(1-\rho)(p_h - \bar{p}_l)}{a\rho} \geq 0.$$

So this volume with strategic customers increases in $p_h$ and $\bar{p}_l$, but decreases in $\bar{p}_h$. □

*Proof of Proposition 4* (i) We insert the peak up/downgrade rates in Lemma 3 into the low-capacity battery lease volume in Lemma 4, and obtain $\tau = (a(1-\rho)(4Q_h - 3) + 8p_h)/(2a(1-\rho) + 8\rho)$. Substituting it to $\Pi(p_h, Q_h)$, we then take the second-order derivative of $\Pi(p_h, Q_h)$ wrt $Q_h$,

$$\frac{\partial \Pi^2(p_h, Q_h)}{\partial Q_h^2} = -32a(1-\rho)\rho^2/(a(1-\rho) + 4\rho)^2 < 0.$$

The profit is concave, so the F.O.C yields the optimal

$$Q_h^s(p_h) = \frac{a^2(1-\rho)^2 + 16\rho p_h - 2a(1-\rho)(2p_h - c_h + 4\rho)}{64\rho^2} - \frac{c_h}{2a(1-\rho)}.$$

Substituting $Q_h^s(p_h)$ to $\Pi(p_h, Q_h)$, we then take the second-order derivative wrt $p_h$,

$$\frac{\partial \Pi^2(p_h, Q_h^s(p_h))}{\partial p_h^2} = (a(1-\rho) - 16\rho)/(8\rho^2).$$

As $a(1-\rho) - 4\rho \leq 0$, the profit is concave in $p_h$, and the F.O.C yields the optimal $p_h^s = [2a(1-\rho)(10\rho - c_h) + 8\rho(3c_h + 4\rho) - a^2(1-\rho)^2]/[64\rho - 4a(1-\rho)]$. Substitute $p_h^s$ to up/downgrade rates and high-capacity battery acquisition quantity, we have

$$\bar{p}_h^s = \frac{4a(1-\rho)(10\rho - c_h) - a^2(1-\rho)^2 + 32\rho c_h}{4(1-\rho)[16\rho - a(1-\rho)]},$$

$$\bar{p}_l^s = \frac{2a(1-\rho)[c_h + \rho(6 + c_h) - 10\rho^2] - a^2(2-\rho)(1-\rho)^2 + 8\rho[4\rho(1-\rho) - (1+3\rho)c_h]}{4(1-\rho)[16\rho - a(1-\rho)]},$$

$$Q_h^s = \frac{8a(1-\rho)(c_h + \rho) - 5a^2(1-\rho)^2 - 32\rho c_h}{4a(1-\rho)[16\rho - a(1-\rho)]}, \ \tau^s = \frac{2(c_h - a(1-\rho) + 4\rho)}{16\rho - a(1-\rho)}.$$

The maximized profit is

$$\Pi^s = \frac{4a^2(1-\rho)^2(c_h + 20\rho) - 3a^3(1-\rho)^3 + 64\rho c_h^2 + 32a\rho(1-\rho)(2\rho - 5c_h)}{16a(1-\rho)[16\rho - a(1-\rho)]}.$$

Now we check the interior conditions of $p_h \leq r_h$, $\bar{p}_h \leq r_h$ and $p_h - r_h \leq \bar{p}_l \leq p_h$ at the optimal solutions. It is trivial to find that $\bar{p}_l^s \leq p_h^s$.

$$p_h^s \leq r_h \Longleftrightarrow c_h \leq (a^2(1-\rho)^2 + 32\rho(2r_h - \rho) - 4a(1-\rho)(r_h + 5\rho))/[24\rho - 2a(1-\rho)],$$

$$\bar{p}_h^s \leq r_h \Longleftrightarrow c_h \leq [(1-\rho)(64\rho r_h + a(1-\rho)(a - 4r_h) - 40a\rho)]/[32\rho - 4a(1-\rho)],$$

$$\bar{p}_l^s \geq p_h^s - r_h \Longleftrightarrow c_h \leq [(1-\rho)(64\rho r_h - a(1-\rho)(a + 4r_h) - 8a\rho)]/[32\rho - 4a(1-\rho)].$$

As $a < 8\rho/(1-\rho)$, the optimal solution satisfies the conditions under $c_h \leq [(1-\rho)(64\rho r_h + a(1-\rho)(a - 4r_h) - 40a\rho)]/[32\rho - 4a(1-\rho)]$.

By taking the first-order derivatives wrt $a, \ c_h, \ \rho$, we can show that $p_h^s$ increases in $a$ and $c_h$, and may increase or decrease in $\rho$. Furthermore, $p_h^s$ increases faster in $a$, and slower in $c_h$ for flexible with strategic customers than simple battery leasing. And $p_h$ increases faster in $c_h$ for flexible with strategic customers than with non-strategic customers. We also find that $\tau^s$ decreases in $a$.

We then check the nonnegativity of high-capacity battery acquisition quantity.

$$Q_h^s \geq 0 \Longleftrightarrow 5a^2(1-\rho)^2 + 32\rho c_h - 8a(1-\rho)(c_h + \rho) \leq 0$$

$$\Longleftrightarrow c_h \le a(1-\rho)[8\rho - 5a(1-\rho)]/[8(4\rho - a(1-\rho))] \doteq C^s(a,\rho).$$

Take the second-order derivatives of $C^s(a,\rho)$ wrt $a,\ \rho$, we find that

$$\partial^2 C^s(a,\rho)/\partial a^2 = -12\rho^2(1-\rho)^2/[4\rho-(1-\rho)a]^3 < 0,$$
$$\partial^2 C^s(a,\rho)/\partial \rho^2 = -12a^2/[4\rho-(1-\rho)a]^3 < 0.$$

The threshold $C^s(a,\rho)$ is concave in $a$ and $\rho$. We can show that $\partial C^s(a,\rho)/\partial a = 0 \Longleftrightarrow a^0 = 4\rho(5-\sqrt{15})/[5(1-\rho)]$ and $\partial C^s(a,\rho)/\partial \rho = 0 \Longleftrightarrow \rho^0 = [a+4\sqrt{3}\sqrt{a(8+5a)}/(8+5a)]/(a+4)$. So $C^s(a,\rho)$ increases in $a$ ($\rho$) if $a < a^0$ ($\rho < \rho^0$) and decreases otherwise.

(ii) Next we optimize the manufacturer's problems in (1) and (2) with $Q_h = 0$ for $c_h \ge a(1-\rho)[8\rho - 5a(1-\rho)]/[8(4\rho - a(1-\rho))]$.

The problem in the peak period is the same as that in the proof of Proposition 2, and the optimal peak decisions in terms of $p_h$ are $\bar{p}_h^s(p_h) = a(1+\tau)/2,\ \bar{p}_l^s(p_h) = p_h - a\ \tau/2,\ \pi^s(\tau, p_h) = (1-\tau)(a\ \tau + 4p_h - 4c_h)/4$. We insert the peak rates into the low-capacity battery lease volume in Lemma 4 and obtain $\tau = [8p_h - 3a(1-\rho)]/[2a(1-\rho)+8\rho]$. Then we substitute $\tau$ in the regular-period problem, and take the second-order derivative of $\Pi(p_h)$ wrt $p_h$

$$\partial\Pi^2(p_h)/\partial p_h^2 = -[16a(1-\rho)+32\rho]/[a(1-\rho)+4\rho]^2 < 0.$$

So the F.O.C yields the optimal

$$p_h^s = \frac{13a^2(1-\rho)^2 + 32\rho(c_h+\rho) + 4a(1-\rho)(2c_h+9\rho)}{32a(1-\rho)+64\rho}.$$

The optimal up/downgrade rates are

$$\bar{p}_h^s = \frac{a[9a(1-\rho)+8(c_h+3\rho)]}{16a(1-\rho)+32\rho},\ \bar{p}_l^s = \frac{32\rho(c_h+\rho)+4a\rho(5-9\rho)-8ac_h(1+\rho)+a^2(1-\rho)(11-13\rho)}{32a(1-\rho)+64\rho},$$

the low-capacity battery lease volume is $\tau^s = [a - a\rho + 8(c_h+\rho)]/[8(a+2\rho-a\rho)]$, and the maximized profit is $\Pi^s = [8(c_h-\rho)+7a(1-\rho)]^2/[128(a(1-\rho)+2\rho)]$.

We can similarly check the conditions for $p_h^s - r_h \le \bar{p}_l^s \le p_h^s$, $\bar{p}_h^s \le r_h$ and $p_h^s \le r_h$. $\square$

*Proof of Corollary 2* We check the sign of $\bar{p}_l^s$ under two cases.

$\underline{c_h < a(1-\rho)[8\rho-5a(1-\rho)]/[8(4\rho-a(1-\rho))]}$. We find that $\bar{p}_l^s < 0$ for $a \le 2\rho$. When $a > 2\rho$, $\bar{p}_l^s < 0 \Longleftrightarrow c_h > [12\rho a + (5\rho-2)a^2 + 4(8-8a-a^2)\rho^2 + (20a+a^2-32)\rho^3]/[8\rho+24\rho^2-2a+2a\rho^2]$.

$\underline{c_h \ge a(1-\rho)[8\rho-5a(1-\rho)]/[8(4\rho-a(1-\rho))]}$. We find that $\bar{p}_l^s < 0 \Longleftrightarrow a > 4\rho/(1+\rho)$ and $c_h > [32\rho^2 + 4a\rho(5-9\rho) + a^2(11-24\rho+13\rho^2)]/[8(a-4\rho+a\rho)]$. $\square$

*Proof of Proposition 5* (i) We first compare the lease rates and low-capacity battery lease volumes under simple and flexible battery leasing, based on the results in Propositions 1 and 4.

$\underline{c_h < a(1-\rho)[8\rho - 5a(1-\rho)]/[8(4\rho - a(1-\rho))}$. We find that $p_h^s > p_h^b$ and $\tau^s > \tau^b$ always hold.

$\underline{c_h \geq a(1-\rho)[8\rho - 5a(1-\rho)]/[8(4\rho - a(1-\rho))}$. We first compare the lease rates $p_h$.

$$p_h^s < p_h^b \Longleftrightarrow a[8r_h(4\rho - (1-\rho)r_h) - 13a^2(1-\rho) + 4a(2c_h + 4r_h - 5\rho - 4\rho r_h)] - 16\rho r_h^2 > 0.$$

The left-hand side of the last inequality increases in $r_h$. We can further show that this inequality holds if $c_h > (4\rho + 5(1-\rho)a)/8$ and $r_h \to a$. So $p_h^s > p_h^b$ if $c_h < (4\rho + 5(1-\rho)a)/8$.

Similarly, we compare the low-capacity battery lease volume $\tau$.

$$\tau^s < \tau^b \Longleftrightarrow 4\rho r_h^2 + a^2(4c_h - 4r_h(1-\rho) + 3\rho) - 2ar_h(4\rho - (1-\rho)r_h) > 0.$$

The left-hand side of the last inequality decreases in $r_h$. So $\tau^s > \tau^b$ if $r_h$ is sufficiently large. We can further show that this inequality holds if $c_h > (4\rho + 5(1-\rho)a)/8$ and $r_h \to a$. So $\tau^s < \tau^b$ if $c_h > (4\rho + 5(1-\rho)a)/8$.

(ii) We first compute all customers' total cost under flexible battery leasing with strategic customers, and then compare it with that under simple battery leasing. Similarly as in the proof of Proposition 3, the total cost of a low-capacity lease under flexible battery leasing is

$$CT_l^s = \rho\mathbb{E}[d] + (1-\rho)\mathbb{E}[c_l(D)] = \rho\tau^s/2 + (1-\rho)\frac{a^2 - 2ar_h + r_h^2 + (2a - \bar{p}_h^s)\bar{p}_h^s}{2a},$$

and the total cost of a high-capacity lease in two periods under flexible battery leasing is

$$\begin{aligned} CT_h^s &= \rho\mathbb{E}[(d - r_h)^+ + p_h^s] + (1-\rho)\mathbb{E}[c_h(D)] \\ &= \rho((1-r_h)^2/(2(1-\tau^s)) + p_h^n) + (1-\rho)\frac{(a-r_h)^2 + 2ap_h^s - (p_h^s - \bar{p}_l^s)^2}{2a}, \end{aligned}$$

when $r_h \leq 1$, and $CT_h^s = p_h^s + (1-\rho)((a-r_h)^2 - (p_h^s - \bar{p}_l^s)^2)/(2a)$ when $r_h > 1$.

All customers' total cost is $CT^s = \tau^s CT_l^s + (1-\tau^s)CT_h^s$. Note that $CT^b - CT^n$ for $r_h \leq 1$ and $r_h > 1$ are the same, so it is enough to write out the comparing expression of all customers' total cost under flexible and simple battery leasing for $r_h > 1$.

$\underline{c_h < a(1-\rho)[8\rho - 5a(1-\rho)]/[8(4\rho - a(1-\rho))}$. All customers' total cost under flexible battery leasing for $r_h > 1$ is

$$\begin{aligned} CT^s = [&8a^3(3c_h - 4r_h(1+\rho) - 110\rho)(1-\rho)^3 + 23a^4(1-\rho)^4 - 1024(c_h^2 - 4\rho^2 r_h^2(1-\rho)^2) \\ &+ 64\rho a(1-\rho)(3c_h^2 - 8r_h^2(1-\rho)^2 + 32\rho c_h + 128\rho r_h(1-\rho) + 48\rho^2) + 16a^2(1-\rho)^2(r_h^2(1-\rho)^2 - c_h^2 \\ &- 20\rho c_h + 64\rho r_h(1-\rho) + 428\rho^2)]/[32a(1-\rho)(a(1-\rho) - 16\rho)^2]. \end{aligned}$$

Now compare it with all customers' total cost under simple battery leasing.

$$CT^b > CT^s \iff h_1(r_h, c_h, a, \rho) = (1-\rho)(a(1-\rho)-16\rho)^2[-r_h^4(1-\rho)^2 + 16\rho a^3(1-\rho) + 4a^2(c_h - r_h(1+\rho)+\rho)(r_h - c_h + (3-r_h)\rho) + 4ar_h^2(1-\rho)(r_h - c_h + (1-r_h)\rho)] + a\rho[1024\rho^2(c_h^2 - 4r_h^2(1-\rho)^2) - 8a^3(3c_h - 4r_h(1-\rho) - 110\rho)(1-\rho)^3 - 23a^4(1-\rho)^4 - 64\rho a(1-\rho)(3c_h^2 - 8r_h^2(1-\rho)^2 + 32\rho c_h - 128\rho r_h(1-\rho) + 48\rho^2) - 16a^2(1-\rho)^2(r_h^2(1-\rho)^2 - c_h^2 - 20\rho c_h + 64\rho r_h(1-\rho) + 428\rho^2)] > 0.$$

When $r_h \to a$ and $c_h \to a(1-\rho)[8\rho - 5a(1-\rho)]/[8(4\rho - a(1-\rho))$, we have $h_2(r_h \to a, c_h \to a(1-\rho)[8\rho - 5a(1-\rho)]/[8(4\rho - a(1-\rho)), a, \rho) < 0$. So $CT^b < CT^s$ when $r_h$ and $c_h$ is sufficiently large.

$c_h \geq a(1-\rho)[8\rho - 5a(1-\rho)]/[8(4\rho - a(1-\rho))$. All customers' total cost under flexible battery leasing for $r_h > 1$ is

$$CT^s = [463(1-\rho)^3a^4 + 1024(1-\rho)\rho^2 r_h^2 + 4a^3(1-\rho)^2(28c_h - 128r_h(1-\rho) + 499\rho) - 256a\rho(c_h - 2r_h(1-\rho)+\rho)(c_h + 2r_h - 3\rho - 2\rho r_h) - 64(1-\rho)a^2(c_h^2 - 4r_h^2 - 9\rho c_h + 8\rho r_h(4+r_h) - 4(10 + r_h(8+r_h))\rho^2)]/[512a(a(1-\rho)+2\rho)^2].$$

Now compare it with all customers' total cost under simple battery leasing.

$$CT^b > CT^s \iff h_2(r_h, c_h, a, \rho) = 16(a(1-\rho)+2\rho)^2[(1-\rho)^2 r_h^4 - 16\rho(1-\rho)a^3 + 4a^2(c_h - r_h(1-\rho)+\rho)(c_h - r_h - (3-r_h)\rho) + 4(1-\rho)ar_h^2(c_h - r_h - (1-r_h)\rho)] + a\rho[463a^4(1-\rho)^3 + 1024r_h^2(1-\rho)\rho^2 + 4a^3(1-\rho)^2(28c_h - 128r_h(1-\rho) + 499\rho) - 256a\rho(c_h - 2r_h(1-\rho)+\rho)(c_h + 2r_h - 3\rho - 2r_h\rho) - 64a^2(1-\rho)(c_h^2 - 4r_h^2 - 9c_h\rho + 8r_h(4+r_h)\rho - 4(10 + r_h(8+r_h))\rho^2)] < 0$$

When $r_h \to a$, we have $h_2(r_h \to a, c_h, a, \rho) < 0$. Because the function is continuous, $h_2(r_h, c_h, a, \rho) < 0$ holds when $r_h$ is sufficiently large. Note that $a$ is compared with $r_h$ and $a > r_h$, so $h_2(r_h, c_h, a, \rho) < 0$ when $a$ is sufficiently low.

Similarly, when $\rho \to 1$, we have

$$h_2(r_h, c_h, a, \rho \to 1) = 64a^2(3-c_h)(1+c_h)[4\rho - (2\rho + (1-\rho)a)^2] < 0.$$

So we have $h_2(r_h, c_h, a, \rho) < 0$ when $\rho$ is sufficiently large. □

*Proof of Proposition 6* (i) In the peak period, the customers make their up/downgrade decisions as in Lemma 1. The peak up/downgrade volumes imply an additional acquisition of high-capacity batteries $Q_h = \tau(a - \bar{p}_h)/a - (1-\tau)(p_h - \bar{p}_l)/a$ to satisfy the peak demand. We insert this equality to the manufacturer's peak-period problem

$$\max_{\bar{p}_h, \bar{p}_l} \; (1-\tau)p_h + (1-\tau)(\bar{p}_l - p_h)(p_h - \bar{p}_l)/a + \tau\bar{p}_h(a - \bar{p}_h)/a - c_h[1 - \tau + Q_h/(1-\rho)],$$

and obtain $\bar{p}_h^t(p_h) = [a + c_h/(1-\rho)]/2$, $\bar{p}_l^t(p_h) = p_h - c_h/(2(1-\rho))$. Accordingly, $Q_h^t(p_h) = [\tau - c_h/(a(1-\rho)]/2$ and the peak-period profit is $[c_h^2/(a(1-\rho)^2) + a\tau - 2\tau c_h/(1-\rho) + 4(p_h - c_h)(1-\tau)]/4$.

Inserting $\bar{p}_h^t(p_h)$, $\bar{p}_l^t(p_h)$ into Lemma 4, the low-capacity battery lease volume becomes $\tau^t(p_h) = [8p_h - 2c_h - 3a(1-\rho)]/(8\rho)$. Then we solve the manufacturer's regular-period problem

$$\max_{p_h} \rho(p_h - c_h)(1 - \tau^t(p_h)) + (1-\rho)[c_h^2/(a(1-\rho)^2) + a\tau - 2\tau c_h/(1-\rho) + 4(p_h - c_h)(1-\tau)]/4.$$

The second-order derivative of the regular-period problem wrt $p_h$ is $-2/\rho$, so the F.O.C yields the optimal $p_h^t = [6c_h + 5a(1-\rho) + 8\rho]/16$. The optimal up/downgrade rates and high-capacity battery acquisition quantity are

$$\bar{p}_h^t = [a + c_h/(1-\rho)]/2,\ \bar{p}_l^t = [c_h(6 - 8/(1-\rho)) + 5a(1-\rho) + 8\rho]/16,$$
$$Q_h^t = [2a(1-\rho)(2c_h + \rho(8+a) - a) - 32\rho c_h]/[64a\rho(1-\rho)],$$

the low-capacity lease volume is $\tau^t = (2c_h + \rho(8+a) - a)/(16\rho)$, and the maximized profit is

$$\Pi^t = [-5a^3(1-\rho)^3 + 4a^2(1-\rho)^2(c_h + 4r_h + 8\rho - 4\rho r_h) + 16(c_h r_h^2(1-\rho)^2 + 4\rho c_h^2 - 4\rho r_h^2(1-\rho)^2)$$
$$+ 4a(1-\rho)(3c_h^2 - 8c_h(r_h + 6\rho - \rho r_h) + 2(2\rho r_h(8+r_h) + (8 - r_h(16+r_h))\rho^2 - r_h^2)]/[256a\rho(1-\rho)].$$

Similarly, we can check the conditions for $p_h^t - r_h \le \bar{p}_l^t \le p_h^t$, $\bar{p}_h^t \le r_h$ and $p_h^t \le r_h$. We can also show that $\bar{p}_l^t$ is negative if and only if $a > 2\rho$ and $c_h > [4\rho(1-\rho) + 5a(1-\rho)^2]/[1+3\rho]$. We then check the nonnegativity of high-capacity battery acquisition quantity.

$$Q_h^t > 0 \Longleftrightarrow c_h < a(1-\rho)/2.$$

The cost threshold increases in $a$ and decreases in $\rho$. We can further show that the cost threshold for $c_h$ $a(1-\rho)/2$ is more than that in Proposition 4 ($a(1-\rho)[8\rho - 5a(1-\rho)]/[8(4\rho - a(1-\rho))]$) but less than that in Proposition 2 ($(1-\rho)[(1-\rho)(a^2 + 2r_h^2 - 4ar_h) + 4a\rho]/[8\rho - 2a(1-\rho)]$).

(ii) Next we optimize the manufacturer's problems with $Q_h = 0$ for $c_h \ge a(1-\rho)/2$.
From the supply and demand equation in the peak period, we have $\bar{p}_h^t(\bar{p}_l) = a - (1-\tau)(p_h - \bar{p}_l)/\tau$. Substituting $\bar{p}_h^t(\bar{p}_l)$ into the peak-period problem, the second-order derivative is negative, so the F.O.C yields the optimal $\bar{p}_l^t(p_h) = p_h - a\tau/2$, $\bar{p}_h^t(p_h) = a(1+\tau)/2$, and the corresponding profit is $(1-\tau)(a\tau + 4p_h - 4c_h)/4$.

Inserting $\bar{p}_h^t(p_h)$, $\bar{p}_l^t(p_h)$ into Lemma 4, the low-capacity battery lease volume becomes $\tau^t(p_h) = [8p_h - 3a(1-\rho)]/[2a(1-\rho) + 8\rho]$. Then we solve the regular-period problem and obtain

$$p_h^t = \frac{13a^2(1-\rho)^2 + 32\rho(c_h + \rho) + 4a(1-\rho)(2c_h + 9\rho)}{32a(1-\rho) + 64\rho}.$$

The optimal up/downgrade rates are

$$\bar{p}_h^t = \frac{a[9a(1-\rho)+8(c_h+3\rho)]}{16a(1-\rho)+32\rho}, \ \bar{p}_l^t = \frac{32\rho(c_h+\rho)+4a\rho(5-9\rho)-8ac_h(1+\rho)+a^2(1-\rho)(11-13\rho)}{32a(1-\rho)+64\rho},$$

the low-capacity battery lease volume is $\tau^t = [a-a\rho+8(c_h+\rho)]/[8(a+2\rho-a\rho)]$, and the maximized profit is $\Pi^t = [8(c_h-\rho)+7a(1-\rho)]^2/[128(a(1-\rho)+2\rho)]$.

We can similarly check the conditions for $p_h^s - r_h \le \bar{p}_l^s \le p_h^s$, $\bar{p}_h^s \le r_h$ and $p_h^s \le r_h$. $\square$

*Proof of Corollary 3* We compare the thresholds for $c_h$ and the manufacturer's optimal decisions when acquiring additional batteries in noncommittal battery acquisition and the base model.

$$a(1-\rho)/2 > a(1-\rho)[8\rho-5a(1-\rho)]/[8(4\rho-a(1-\rho)) \Longleftrightarrow \rho > a/(4+a),$$

$$p_h^t = [6c_h+5a(1-\rho)+8\rho]/16 < p_h^s[2a(1-\rho)(10\rho-c_h) + 8\rho(3c_h+4\rho)-a^2(1-\rho)^2]/[64\rho-4a(1-\rho)] \Longleftrightarrow \rho > a/(4+a),$$

$$Q_h^t = [2a(1-\rho)(2c_h+\rho(8+a)-a)-32\rho c_h]/[64a\rho(1-\rho)] > Q_h^s = [8a(1-\rho)(c_h+\rho) - 5a^2(1-\rho)^2-32\rho c_h]/[4a(1-\rho)[16\rho-a(1-\rho)]] \Longleftrightarrow \rho > a/(4+a),$$

$$\bar{p}_h^t = [a+c_h/(1-\rho)]/2 < \bar{p}_h^s = \frac{4a(1-\rho)(10\rho-c_h)-a^2(1-\rho)^2+32\rho c_h}{4(1-\rho)[16\rho-a(1-\rho)]} \Longleftrightarrow \rho > a/(4+a),$$

$$\bar{p}_l^t = [c_h(6-8/(1-\rho))+5a(1-\rho)+8\rho]/16 > \bar{p}_l^s = [2a(1-\rho)(c_h+\rho(6+c_h)-10\rho^2)-a^2(2-\rho)(1-\rho)^2 + 8\rho(4\rho(1-\rho)-(1+3\rho)c_h)]/[4(1-\rho)(16\rho-a(1-\rho))] \Longleftrightarrow \rho > a/(4+a).$$

As $\rho > a/(4+a)$, the threshold for $c_h$ is larger with noncommittal battery acquisition than that in the base model, and we have $p_h^t < p_h^s$, $Q_h^t > Q_h^s$, $\bar{p}_h^t < \bar{p}_h^s$ and $\bar{p}_l^t > \bar{p}_l^s$. $\square$