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Innovative Applications of O.R.

Electric vehicle battery capacity allocation and recycling with downstream competition

Mengping Zhu^a, Zhixue Liu^a, Jianbin Li^{a,*}, Stuart X. Zhu^b^a School of Management, Huazhong University of Science and Technology, Wuhan 430074, China^b Department of Operations, University of Groningen, P.O. Box 800, AV Groningen 9700, The Netherlands

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ABSTRACT

We study the optimal channel choice and battery capacity allocation strategies of an electric vehicle (EV) manufacturer in the presence of battery recycling. The EV manufacturer also produces EV batteries. As an upstream manufacturer, this firm has the option to supply batteries to its competitor, a downstream EV manufacturer which is unable to produce batteries. We characterise the equilibrium decisions of the two EV manufacturers under different channel structures. One finding is that the optimal channel choice of each EV manufacturer depends on the procurement cost from an external battery supplier. *If the procurement cost is moderate*, the downstream manufacturer prefers to order from the upstream manufacturer and the upstream manufacturer will supply batteries to satisfy the order. In addition, we investigate the effects of key parameters on the equilibrium capacity allocation decisions and manufacturers' profits using numerical experiments. We also show that to maximise social welfare, the upstream EV manufacturer should not supply batteries to its competitor if the procurement cost from the external supplier is low, which is contrary to the case of profit maximisation.

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1. Introduction

Nowadays, sustainable development has attracted increasing attention due to the rising threat of climate change. Among the factors that cause environmental pollution, petroleum fuel consumption is recognised to be a critical one. Electric vehicles (EVs), which are powered by batteries and consume less petroleum fuel, are a promising contributor to environmental protection (Kieckhäfer, Volling, & Spengler, 2014). Owing to their benefits, governments in many countries are providing strong support to encourage the development of EVs. For example, in Germany, consumers who purchase EVs can obtain subsidies from both the government and EV manufacturers. The French government has constructed more public charging facilities for EVs. Similar preferential policies have been adopted in other developed countries, including the United States and Japan. As the largest developing country, China has also devoted itself to creating the largest EV market in the world by providing considerable economic subsidies and support policies. In 2018, the total sales volume of EVs in China reached 1.256 million, including 1.053 million passenger cars. Furthermore, in the 13th Five-Year Plan, the Chinese government aims to sell five million

EVs by 2020. With the support of governments, the EV market is undergoing explosive development all around the world.

As the core component of an EV, the EV battery accounts for about 40% of the total production cost. Therefore, the issue of battery procurement is an important challenge for an EV manufacturer. In practice, some EV manufacturers obtain batteries from external specialised suppliers such as Contemporary Amperex Technology Co., Limited (CATL), which is the largest EV battery manufacturer in the world. In contrast, other EV manufacturers obtain batteries from internal suppliers. Build Your Dreams (BYD) is an example; as the leader of the EV industry in China, BYD used to produce EV batteries only for its own use. Now, BYD is planning to change its battery supply strategy and provide batteries for other competing EV manufacturers such as Dongfeng Motor Corporation, which is one of the four largest automobile groups in China. In such a situation, the relationship between BYD and Dongfeng becomes complicated. On one hand, they are competitors in the consumer market; on the other hand, they are partners in the supply chain for batteries. Although similar situations can be found in other industry sectors—for example, the telecommunications (Weisman & Kang, 2001) and mobile phone (Qing, Deng, & Wang, 2017) industries—it remains uncertain whether this strategy is appropriate for BYD in the EV industry.

Moreover, battery recycling is another important issue faced by EV manufacturers. According to statistics, the output value of

* Corresponding author.

E-mail addresses: mpzhu@hust.edu.cn (M. Zhu), lsy868@hust.edu.cn (Z. Liu), jbli@hust.edu.cn (J. Li), x.zhu@rug.nl (S.X. Zhu).

EV batteries in China was about \$9.7 billion in 2016. However, a well-known fact is that EV batteries may cause potential harm to the environment and threaten human health when they retire from EVs and are not properly disposed of. As predicted by the China Automotive Technology and Research Center, the volume of scrapped EV batteries in China will reach 120–170 thousand tons by the year 2020. In practice, many EV manufacturers are legally responsible for recycling used batteries. For example, BYD is required by the Chinese government to do so (Gu, Liu, & Qing, 2017). In addition to legislative pressure, the scrapped EV batteries can also be recycled for economic benefits. Specifically, when an EV battery's capacity decays to around 80% of its original level, it no longer meets the power requirement of the EV and has to be replaced (Gu, Ieromonachou, & Zhou, 2018). After a series of performance testing and reprocessing, the retired batteries can be reused for other purposes which have lower battery performance requirements such as energy storage systems (Tong, Same, & Kootstra, 2013). The existing literature on battery recycling generally focuses on technical processes (Ku, Jung, & Jo, 2016; Li, Liu, & Han, 2016; Swain, 2017; Zou, Gratz, & Apelian, 2013) or the economic/environmental impacts of battery reuse (Hao, Qiao, & Liu, 2017; Heymans, Walker, & Young, 2014). However, few studies investigate the EV manufacturer's battery capacity allocation decision in the context of battery recycling.

To understand why BYD changes its battery supply strategy in the presence of battery recycling, we consider two cases: non-cooperation and cooperation. In the non-cooperative case, BYD (the upstream EV manufacturer) does not provide batteries to its competitor (the downstream EV manufacturer) and the latter has to procure batteries from an external battery supplier. In the cooperative case, BYD decides to share its battery capacity with its competitor. In addition, the two EV manufacturers recycle retired batteries for echelon use. Echelon use means economically utilising the residual value of used EV batteries (Wang & Wu, 2017). In this context, we investigate the equilibrium decisions of firms. Specifically, we seek to answer the following questions. Given an outside option, should the downstream manufacturer procure batteries from the upstream manufacturer? Should the upstream manufacturer supply batteries? If so, under what conditions and how much capacity should be allocated? What are the effects of key factors (e.g. the battery's price and the value of echelon use) on the optimal capacity allocation decisions and manufacturers' profits?

To address these questions, we construct two stylised models in which the upstream manufacturer (e.g. BYD) allocates no or partial capacity to its competitor (e.g. Dongfeng Motor Corporation). By adopting the game-theoretic method, we characterise the equilibrium decisions under two different models/channel structures. We further derive the conditions under which the downstream manufacturer should procure batteries from the upstream manufacturer and the upstream manufacturer should supply batteries. Our work shows that if the procurement cost is within a certain range, the downstream manufacturer prefers to order from the upstream manufacturer and the upstream manufacturer will supply batteries to satisfy the order. In addition, we investigate the effects of key parameters on the equilibrium capacity allocation decisions and manufacturers' profits using numerical experiments. We also show that the optimal channel choice changes when maximising social welfare.

The remainder of this paper is organised as follows. Section 2 reviews the relevant literature and clarifies the innovativeness of our research. Section 3 describes our model. Section 4 characterises the equilibrium channel choice and capacity allocation decisions. Section 5 investigates the effects of key factors using numerical experiments. Section 6 presents the extension of dual-channel procurement and endogenous battery

price. Section 7 summarises the main findings and points out the managerial implications as well as future research direction. All proofs are in the appendix.

2. Literature review

This paper is mainly related to the studies on capacity allocation. A lot of the existing supply chain literature considers a supply chain structure consisting of one upstream manufacturer and several downstream retailers. Cachon and Lariviere (1999a) analyse equilibrium ordering decisions, supplier's capacity choice, and supply chain performance under various allocation mechanisms, including proportional allocation and lexicographic allocation. Cachon and Lariviere (1999b) compare the performance of three allocation mechanisms: linear, proportional, and uniform. Liu (2012) studies the capacity allocation problem under a structure comprising a supplier and two competing retailers. Chen, Li, and Zhang (2013) extend the framework to multiple retailers. Cho and Tang (2014) propose a new allocation mechanism to solve the problem of retailers' order inflation. They discover that competitive allocation can reduce the supplier's profit but generate higher average profits for the retailers and the supply chain. In summary, the aforementioned studies only consider horizontal competition among retailers. An alternative structure comprising co-opetitive firms is now attracting the attention of a few scholars (Niu, Wang, & Guo, 2015; Wang, Niu, & Guo, 2013). As the name suggests, several firms not only compete but also cooperate with each other. Our research is most closely related to Qing et al. (2017), who study a supplier's capacity allocation problem under bargaining when the supplier competes with the manufacturer in a downstream market. However, they only consider the forward channel. We differ from these works by combining the reverse and forward channels. In other words, we incorporate the issues of capacity building and allocation (in the forward channel) together with battery recycling and echelon use (in the reverse channel) in the specific models.

Our research is also closely related to the literature on EV battery recycling. As far as we know, the majority of the existing literature focuses on two research topics: technical issues during the process of battery recycling (Diekmann, Hanisch, and Froböse, 2017; Ku et al., 2016, e.g.) and the economic/environmental impacts of battery recycling and reuse (Hao et al., 2017; Heymans et al., 2014, e.g.). To the best of our knowledge, the literature hardly pays attention to firms' decision-making problems regarding EV battery recycling (Gu et al., 2017; Tang, Zhang, & Li, 2018). In particular, some important issues, including building the optimal production capacity, pricing competing products, and recycling the optimal quantity of retired batteries are rarely studied. However, it is very important to investigate the dynamics of firms' decision-making processes, especially the interaction between several firms in the supply chain. Thus, to some extent, our work can fill the research gap on EV battery recycling and provide important managerial insights for firms and policymakers in this industry.

In summary, in contrast to the existing research on capacity allocation, we explicitly consider two novel issues. One is the channel structure of cooperation and competition between two manufacturers; the other is battery recycling and reuse, which is an important characteristic of the EV industry. We also extend the current research on EV battery recycling by modelling the dynamic decision process. On one hand, our research provides relevant contributions for researchers. We construct two models where two manufacturers cooperate or not. We obtain the optimal order strategy of the downstream manufacturer and the optimal capacity allocation strategy of the upstream manufacturer. By adopting the game-theoretic method, we derive two EV manufacturers' equilibrium strategies and examine the effects of key

Fig. 1. Channel structures for two EV manufacturers with battery recycling.

parameters on them. By comparing two models, we find the conditions under which two manufacturers perform cooperation. We also find that the channel choice based on profit may be different from that based on social welfare. On the other hand, our research provides relevant contributions for practitioners. The findings of our study offer a useful guideline to EV manufacturers when selecting procurement and capacity allocation strategies in a competitive environment.

3. Model description and notations

We consider a duopolistic market wherein two EV manufacturers produce differentiated EVs. In the forward channel, one upstream manufacturer (e.g. BYD) is able to produce batteries and assemble EVs. The other downstream manufacturer (e.g. Dongfeng Motor Corporation) can only assemble EVs and does not have the ability to produce batteries. They compete with each other for consumers who may potentially purchase either brand. The downstream manufacturer can obtain EV batteries from the upstream manufacturer or an external battery supplier. In the reverse channel, when the batteries are retired from EVs, they are recycled by the two EV manufacturers for echelon use to gain economic benefits. For ease of exposition, the upstream manufacturer is named manufacturer 1 (hereafter, 'he') and the downstream manufacturer is named manufacturer 2 (hereafter, 'she').

The channel structures are illustrated in Fig. 1 (see the notations in Table 1 in which all the variables and parameters are one-dimensional). Depending on whether manufacturer 1 supplies batteries to manufacturer 2, two different channel structures are considered. Model NC in Fig. 1(a) represents the channel structure where manufacturer 1 produces batteries only to satisfy his own demand and manufacturer 2 has to purchase batteries from another battery supplier. In this case, no cooperation exists between these two manufacturers. Model C in Fig. 1(b) represents the channel structure where manufacturer 1 partially allocates his battery capacity to manufacturer 2. In this case, both cooperation and competition exist between these two manufacturers.

The steps relating to battery capacity decisions are as follows. In Model NC, manufacturer 1 builds battery capacity only for his own EV production. Meanwhile, manufacturer 2 determines her EV production quantity. In Model C, manufacturer 2 first decides to order batteries from manufacturer 1, after which manufacturer 1 decides to build his total battery capacity, part of which is allocated to manufacturer 2. The surplus batteries are for his own use.

In the reverse channel, batteries are recycled by the two manufacturers for echelon use when they are retired from EVs. The

recycling rates of manufacturer 1 and manufacturer 2 are denoted by τ_1 and τ_2 , respectively. Accordingly, the quantities of returned batteries are $\tau_1 q_1$ and $\tau_2 q_2$, respectively.

On the demand side, market demand is deterministic and dependent on prices. Using the notations in Table 1, the inverse demand functions can be written as $p_1 = \alpha - q_1 - \beta q_2$ and $p_2 = \alpha - q_2 - \beta q_1$, where $\alpha > 0$ and $\beta \in (0, 1)$. Parameter β represents the degree of substitution between the EVs produced by the two manufacturers. The inverse demand functions are widely adopted in much of the literature to model the competition between/among alternative products (Arya, Mittendorf, & Sappington, 2007; Chen et al., 2013; Cho & Tang, 2014; Liu, 2012).

4. Equilibrium analysis

In this section, we characterise the equilibrium decisions of the two manufacturers under two different channel structures. We first study Model NC as the benchmark case, before analysing Model C. By comparing the two models, we can determine the optimal channel choice of each manufacturer.

4.1. Analysis of model NC

In this model, manufacturer 1 does not supply batteries to manufacturer 2; manufacturer 2 thus purchases batteries from another battery supplier. There are two decision stages. In stage 1, manufacturer 1 builds his battery capacity K , which is also his production quantity of EVs. That is, $q_1 = K$. Manufacturer 2 orders from an external supplier with excess capacity. Obviously, the supplier is self-interested and willing to satisfy manufacturer 2's entire order, which is also equal to her production quantity of EVs. We denote the production quantity of EVs using q_2 (see Table 1). The retail prices of the two brands of EVs are $p_1 = \alpha - K - \beta q_2$ and $p_2 = \alpha - q_2 - \beta K$, respectively. In stage 2, the batteries are retired from the EVs and the two manufacturers make decisions on recycling rates, that is, τ_1 and τ_2 , respectively.

The profit of manufacturer 1 is from both the forward and reverse channels, given as follows:

$$\Pi_1 = \max_{K, \tau_1} \{ (\alpha - K - \beta q_2 - c_1)K - (F + cK) - \gamma \tau_1^2 + \nu \tau_1 K \}. \quad (1)$$

In Eq. (1), the first term represents the profit from selling EVs. The total capacity setup cost for producing batteries is $F + cK$, including the fixed and variable capacity setup cost. The cost of recycling used EV batteries from consumers is $\gamma \tau_1^2$, which is

Table 1
Notations.

Decision variables	
q_2^0	Manufacturer 2's order quantity (Model C)
q_2	The EV production quantity of manufacturer 2
K	The total battery capacity of manufacturer 1
τ_1	Manufacturer 1's recycling rate
τ_2	Manufacturer 2's recycling rate
Model parameters	
α	Market potential
β	Degree of substitution between EVs produced by the two manufacturers
F	Fixed cost of building capacity
c	Variable cost of building capacity
c_1	Manufacturer 1's cost of producing an EV excluding battery cost
c_2	Manufacturer 2's cost of producing an EV excluding battery cost
c_0	Manufacturer 2's cost of purchasing a battery unit from an external supplier (Model NC)
w	Price of a battery unit charged by manufacturer 1 (Model C)
γ	Scaling parameter of recycling investment
b	The buy-back payment to manufacturer 2 for a used EV battery unit
v	Value of retired EV battery unit via echelon use
e	Environmental benefit of unit recycled EV battery
Other notations	
q_1	Manufacturer 1's EV production quantity
p_1	Retail price of manufacturer 1's EV
p_2	Retail price of manufacturer 2's EV
Π_1	Manufacturer 1's profit
Π_2	Manufacturer 2's profit
CS	Consumer surplus
E	Environmental benefit

widely used in the literature on post-consumer product collection (Chuang, Wang, & Zhao, 2014; Panda & Modak, 2017; Savaskan, Bhattacharya, & Van Wassenhove, 2004; Savaskan & Van Wassenhove, 2006). On average, we assume that manufacturer 1 receives value v from each retired battery unit for echelon use. Given the returned quantity $\tau_1 K$, the last term represents the total value of recycled EV batteries.

The profit function of manufacturer 2 is given by

$$\Pi_2 = \max_{q_2, \tau_2} \{(\alpha - q_2 - \beta K - c_0 - c_2)q_2 - \gamma \tau_2^2 + b \tau_2 q_2\}. \quad (2)$$

In Eq. (2), the first term is manufacturer 2's profit from selling EVs. The second term represents the cost of recycling used EV batteries from consumers. Note that in practice, the echelon use of EV batteries can be only implemented by the battery manufacturer due to the technical processes involved. Due to her lack of technical expertise, manufacturer 2 has no access to echelon use and has to transfer recycled batteries to the external battery supplier. On average, manufacturer 2 gets a fixed buy-back payment b from the supplier for each recycled battery unit. In Eq. (2), the last term represents the total buy-back payment that manufacturer 2 can obtain.

Similar to Savaskan et al. (2004), we assume that parameter γ defined in the recycling cost function is sufficiently large to guarantee $\tau_1 < 1$ and $\tau_2 < 1$. This assumption indicates that recycling is sufficiently costly such that it is not economically viable to recycle all used EV batteries.

By solving the maximisation problems in Eqs. (1) and (2), we can obtain the optimal recycling rates τ_1^* and τ_2^* given by the following lemma.

Lemma 1. For any given K , manufacturer 1's optimal recycling rate $\tau_1^* = \frac{vK}{2\gamma}$. For any given q_2 , manufacturer 2's optimal recycling rate $\tau_2^* = \frac{bq_2}{2\gamma}$.

Lemma 1 shows that for each manufacturer, the optimal recycling rate increases with his or her own EV production quantity. In addition, the recycling rate increases with the buy-back payment (b) or the value of a battery retired to echelon use (v).

In stage 1, the two manufacturers determine the optimal EV production quantities. The result is shown in the following lemma.

Lemma 2. In Model NC, the optimal EV production quantity of manufacturer 2 is

$$q_2^* = \frac{2\gamma[(4\gamma - v^2)(\alpha - c_0 - c_2) - 2\beta\gamma(\alpha - c - c_1)]}{(4\gamma - v^2)(4\gamma - b^2) - 4\beta^2\gamma^2}$$

The optimal capacity and EV production quantity of manufacturer 1 is

$$K^* = q_1^* = \frac{2\gamma[(4\gamma - b^2)(\alpha - c - c_1) - 2\beta\gamma(\alpha - c_0 - c_2)]}{(4\gamma - v^2)(4\gamma - b^2) - 4\beta^2\gamma^2}$$

By Lemma 2, we find that the production quantity of each manufacturer decreases with his or her own production cost, but increases with the competitor's production cost. Denote $\bar{c}_0 = \alpha - c_2 - \frac{2\beta\gamma(\alpha - c - c_1)}{4\gamma - v^2}$. To ensure the non-negative production quantity, we can obtain that $c_0 \leq \bar{c}_0$.

4.2. Analysis of Model C

In this model, manufacturer 2 orders batteries from manufacturer 1. We model the interaction between the two manufacturers as a three-stage Stackelberg game. In stage 1, manufacturer 2 makes the ordering decision q_2^0 . In stage 2, manufacturer 1 builds his battery capacity K and then decides on the capacity to be allocated to manufacturer 2, denoted by q_2 . $q_2 \leq q_2^0$ holds because manufacturer 1 cannot allocate a capacity that exceeds manufacturer 2's order. Consequently, the quantity of batteries that manufacturer 2 obtains is also q_2 , and the quantity of batteries remaining for manufacturer 1 is $q_1 = K - q_2$. In stage 3, the batteries are retired from EVs and the two manufacturers decide their respective recycling rates.

Manufacturer 1's profit is from the forward channel by selling batteries and EVs plus the reverse channel by recycling batteries. The retail price of his EV is $p_1 = \alpha - (K - q_2) - \beta q_2$. Taking into account his specific constraints, we can write manufacturer 1's

profit function as follows:

$$\Pi_1 = \max_{K, q_2, \tau_1} \left\{ [\alpha - (K - q_2) - \beta q_2 - c_1](K - q_2) + wq_2 - (F + cK) - \gamma\tau_1^2 - b\tau_2 q_2 + v[\tau_1(K - q_2) + \tau_2 q_2] \right\} \quad (3)$$

$$\text{s.t. } 0 \leq q_2 \leq q_2^0. \quad (4)$$

Similar to Model NC, in Eq. (3), the first term represents the profit from selling EVs. The second term represents the revenue from selling batteries. The total cost of producing batteries is $F + cK$. The cost of recycling used EV batteries from consumers is $\gamma\tau_1^2$. The total buy-back payment to manufacturer 2 is $b\tau_2 q_2$. The last term represents the total value of all EV batteries recycled into echelon use. Constraint (4) states that manufacturer 1 can partially fulfil the order but cannot allocate more than what manufacturer 2 orders.

Manufacturer 2's objective is to maximise her profit by determining an ordering quantity and recycling rate taking into account manufacturer 1's allocation strategy. Her profit function is given as follows:

$$\Pi_2 = \max_{q_2^0, \tau_2} \left\{ (\alpha - q_2 - \beta(K - q_2) - w - c_2)q_2 - \gamma\tau_2^2 + b\tau_2 q_2 \right\} \quad (5)$$

In Eq. (5), the first term is manufacturer 2's profit from selling EVs. The second term represents the cost of recycling used EV batteries from consumers. The last term is the buy-back payment from manufacturer 1 for transferring used batteries.

We solve the two manufacturers' problems using the backward induction method (Geng & Mallik, 2007). That is, we first solve the problem in stage 3. Given q_2^0 , K , and q_2 , these two manufacturers decide their recycling rates τ_1 and τ_2 , respectively. By solving the maximisation problems in Eqs. (3)–(5), we can obtain the optimal recycling rates τ_1^* and τ_2^* . The following lemma summarises the optimal decisions.

Lemma 3. In stage 3, let τ_1^* and τ_2^* be the optimal recycling rates of manufacturer 1 and manufacturer 2, respectively. For a given q_2^0 , q_2 , and K , we have $\tau_1^* = \frac{v(K - q_2)}{2\gamma}$ and $\tau_2^* = \frac{bq_2}{2\gamma}$.

Lemma 3 indicates that for these two manufacturers, the optimal recycling rates increase with their allocated capacity. Therefore, manufacturer 1 can induce manufacturer 2 to recycle by allocating more battery capacity to her.

In stage 2, given q_2^0 , manufacturer 1 decides his optimal capacity K^* and allocated capacity q_1^* and q_2^* . For ease of exposition, we denote $A_1 = \frac{-2\gamma(4\gamma - v^2)}{(4\gamma - v^2)b(v - b) + 2\beta^2\gamma^2}$ and $A_2 = \frac{2\gamma[(4\gamma - v^2)c + 2\beta\gamma(\alpha - c - c_1)]}{(4\gamma - v^2)b(v - b) + 2\beta^2\gamma^2}$. The results are shown in Lemma 4.

Lemma 4. In stage 2, given that manufacturer 2 orders q_2^0 , manufacturer 1's best response decisions are given by the following:

- (1) If $q_2^0 < A_1 w + A_2$, then $K^* = \frac{2\gamma(\alpha - c - c_1)}{4\gamma - v^2}$, $q_2^* = 0$, and thereby $q_1^* = \frac{2\gamma(\alpha - c - c_1)}{4\gamma - v^2}$.
- (2) If $q_2^0 \geq A_1 w + A_2$, then $K^* = \frac{2\gamma(\alpha - c - c_1) + (4\gamma - v^2 - 2\beta\gamma)q_2^0}{4\gamma - v^2}$, $q_2^* = q_2^0$, and thereby $q_1^* = \frac{2\gamma(\alpha - c - c_1 - \beta q_2^0)}{4\gamma - v^2}$.

Lemma 4 shows the effect of manufacturer 2's ordering decisions on manufacturer 1's capacity decisions. To achieve a better understanding of the two cases in Lemma 4, we describe manufacturer 1's optimal strategy in different regions in terms of w and q_2^0 in Fig. 2.

Fig. 2 indicates that manufacturer 1 allocates either no capacity or the desired quantity to manufacturer 2. In Region I, where manufacturer 2's order quantity is relatively small ($q_2^0 < A_1 w + A_2$),

Fig. 2. The regions of manufacturer 1's optimal capacity allocation strategy.

manufacturer 1 allocates no capacity to manufacturer 2. In Region II, where manufacturer 2's order quantity is relatively large ($q_2^0 \geq A_1 w + A_2$), manufacturer 1 satisfies the entire order of manufacturer 2 (i.e. $q_2^* = q_2^0$). The reason for the above is as follows. In the first case, the profit from selling batteries to the competitor cannot offset the loss in the consumer market due to downstream competition. In contrast, in the second case, the profit from selling batteries is higher than that loss.

Another finding is about the effect of the intensity of competition on the capacity allocation strategy. When manufacturer 1 allocates battery capacity to manufacturer 2, his own quantity decreases with β . The explanation is as follows: as competition becomes fiercer, the marginal profit of manufacturer 1 in the consumer market decreases, indicating that this market is less attractive to him. Consequently, he conserves less capacity and allocates more capacity to manufacturer 2 so that he can gain more profit from selling batteries.

In stage 1, manufacturer 2 decides the optimal order quantity q_2^{0*} . Although q_2^0 is not explicit in the objective function of manufacturer 2 in Eq. (5), manufacturer 2 can maximise her profit by choosing a value of q_2^0 that determines q_2 , as Lemma 4 shows.

For ease of exposition, we denote $A_3 = (4\gamma - v^2)c + 2\beta\gamma(\alpha - c - c_1)$, $A_4 = (4\gamma - v^2)(4\gamma - b^2) - 8\beta^2\gamma^2$, $A_5 = (4\gamma - v^2)b(v - b) + 2\beta^2\gamma^2$, and $A_6 = (4\gamma - v^2)(\alpha - c_2) - 2\beta\gamma(\alpha - c - c_1)$. Lemma 5 shows manufacturer 2's optimal order decisions.

Lemma 5. In stage 1, we denote $\tilde{w} = \min\{\frac{A_3}{4\gamma - v^2}, \frac{A_3 A_4 - A_5 A_6}{(4\gamma - v^2)(A_4 - A_5)}\}$. Manufacturer 2's optimal ordering strategy is then given by the following:

- (1) If $w \leq \tilde{w}$, then $q_2^{0*} = \frac{2\gamma[A_3 - (4\gamma - v^2)w]}{A_5}$. Thus, $K^* = \frac{2\gamma(\alpha - c - c_1)A_5 + 2\gamma[A_3 - (4\gamma - v^2)w](4\gamma - v^2 - 2\beta\gamma)}{(4\gamma - v^2)A_5}$, $q_2^* = \frac{2\gamma[A_3 - (4\gamma - v^2)w]}{A_5}$, and thereby $q_1^* = \frac{2\gamma\{(\alpha - c - c_1)A_5 - 2\beta\gamma[A_3 - (4\gamma - v^2)w]\}}{(4\gamma - v^2)A_5}$.
- (2) If $w > \tilde{w}$, then $q_2^{0*} = \frac{2\gamma[A_6 - (4\gamma - v^2)w]}{A_4}$. Thus, $K^* = \frac{2\gamma(\alpha - c - c_1)A_4 + 2\gamma[A_6 - (4\gamma - v^2)w](4\gamma - v^2 - 2\beta\gamma)}{(4\gamma - v^2)A_4}$, $q_2^* = \frac{2\gamma[A_6 - (4\gamma - v^2)w]}{A_4}$, and thereby $q_1^* = \frac{2\gamma\{(\alpha - c - c_1)A_4 - 2\beta\gamma[A_6 - (4\gamma - v^2)w]\}}{(4\gamma - v^2)A_4}$.

By Lemma 5, we find that manufacturer 2's optimal order strategy mainly depends on the battery's price (w). Interestingly, for manufacturer 2, the order quantity is independent on her EV production cost when the battery's price is lower than a certain threshold. Lemma 5 also reveals that in equilibrium, manufacturer 1 always supplies batteries to manufacturer 2, regardless of the battery's price. This fact results from the first-mover advantage.

As the leader of the Stackelberg game, manufacturer 2 moves first to make her order decision in stage 1. To avoid the disadvantageous case in which she receives no batteries even if she orders, she adjusts her order quantity above a certain threshold so that manufacturer 1 can also benefit from allocating partial capacity to her, which is a win-win situation.

4.3. Optimal channel choice

In Model NC, manufacturer 1 produces batteries only for his own use, while in Model C, he sets up a new channel to sell batteries to his competitor. It is still unclear whether setting up a new channel yields more profit. To address this issue, we study manufacturer 1's optimal channel choice in this subsection. Specifically, we are interested in the conditions under which manufacturer 1 should supply batteries to manufacturer 2. For ease of exposition, we denote

$$\hat{c}_0 = \alpha - c_2 - \frac{(4\gamma - b^2)(\alpha - c - c_1)}{2\beta\gamma} + \frac{[(4\gamma - v^2)(4\gamma - b^2) - 4\beta^2\gamma^2] \sqrt{\frac{b(v-b)B_1^2 + 2\gamma(w-c)B_1}{2\gamma^2} (4\gamma - v^2) + (\alpha - c - c_1 - \beta B_1)^2}}{2\beta\gamma(4\gamma - v^2)},$$

where $B_1 = \frac{2\gamma[A_6 - (4\gamma - v^2)w]}{A_4}$. Proposition 1 summarises the results of channel choice.

Proposition 1.

- (1) If $w > \tilde{w}$ and $c_0 \leq \hat{c}_0$ or $w \leq \tilde{w}$, then manufacturer 1 chooses to supply batteries to manufacturer 2.
- (2) If $w > \tilde{w}$ and $c_0 > \hat{c}_0$, then manufacturer 1 chooses not to supply batteries to manufacturer 2.

Proposition 1 suggests that whether manufacturer 1 should supply batteries to the competitor depends on his battery price and manufacturer 2's procurement cost from an external battery supplier. Specifically, as Lemma 4 shows, if manufacturer 1's battery price is low ($w \leq \tilde{w}$), manufacturer 2 has to order a large enough quantity, which brings considerable revenue to manufacturer 1 and therefore he would like to supply batteries. Otherwise, manufacturer 1 decides to supply or not by strategically considering manufacturer 2's procurement cost from the external supplier. When the procurement cost is high, manufacturer 2 has to purchase from this expensive channel and her EV quantity is small, which creates a beneficial consumer market for manufacturer 1. In this case, manufacturer 1 decides not to supply. In contrast, when the procurement cost is low, manufacturer 1 maximises his profit by motivating manufacturer 2 to purchase batteries from him instead of from the external supplier.

Proposition 1 provides some clues as to why BYD began to supply batteries to its competing EV manufacturers. In the EV industry, with the entrance of CATL into the EV battery market, EV manufacturers can purchase batteries at lower prices. Specifically, statistical data from CATL shows that battery prices were about \$0.32, \$0.29, and \$0.20 per Wh in 2015, 2016, and 2017, respectively. Faced with the continuous decline in the price of batteries from external suppliers, it is optimal for BYD to supply batteries to other competing EV manufacturers, as Proposition 1 shows.

We proceed to analyse manufacturer 2's channel choice. Manufacturer 2 would like to cooperate with manufacturer 1 only if her profit is higher in Model C than that in Model NC. For ease of exposition, we denote $B_2 = w(v^2 - 4\gamma) + A_3$. Additionally, we denote two thresholds that determine the optimal procurement strategy of manufacturer 2 in different regions of w , i.e., $\tilde{c}_0 = \alpha - c_2 - \frac{2\beta\gamma(\alpha - c - c_1)}{4\gamma - v^2} -$

$$\frac{(A_4 + 4\beta^2\gamma^2) \sqrt{B_2 \{ [2A_5(\alpha - c_2 - w) - (4\gamma - b^2)B_2] (4\gamma - v^2) + 8\beta^2\gamma^2 B_2 - 4\beta\gamma A_5(\alpha - c - c_1) \}}}{A_5(4\gamma - v^2) \sqrt{(4\gamma - b^2)(4\gamma - v^2)}} \\ \text{and } \tilde{c}_0 = \alpha - c_2 - \frac{(A_4 + 4\beta^2\gamma^2)[A_6 - w(4\gamma - v^2)]}{(4\gamma - v^2) \sqrt{A_4(4\gamma - b^2)(4\gamma - v^2)}} - \frac{2\beta\gamma(\alpha - c - c_1)}{4\gamma - v^2}.$$

The following proposition summarizes the channel choice of manufacturer 2.

Proposition 2.

- (1) If $w \leq \tilde{w}$ and $c_0 \geq \tilde{c}_0$ or $w > \tilde{w}$ and $c_0 \geq \tilde{c}_0$, then manufacturer 2 chooses to procure batteries from manufacturer 1.
- (2) If $w \leq \tilde{w}$ and $c_0 < \tilde{c}_0$ or $w > \tilde{w}$ and $c_0 < \tilde{c}_0$, then manufacturer 2 chooses not to procure batteries from manufacturer 1.

Proposition 2 shows that manufacturer 2's channel choice is also determined by w that influences her profit in Model C and c_0 that influences her profit in Model NC. Given w , there exists a threshold about c_0 above which manufacturer 2 procures batteries from manufacturer 1 instead of the external supplier.

An important question arises under what conditions both manufacturers benefit from cooperation, in other words, both of them can gain more profit in Model C than Model NC. Based on Propositions 1 and 2, we have the following theorem:

Theorem 1. Both Manufacturer 1 and Manufacturer 2 choose cooperation under the following conditions: (1) $w \leq \tilde{w}$ and $c_0 \in [\tilde{c}_0, \hat{c}_0]$ or (2) $w > \tilde{w}$ and $c_0 \in [\tilde{c}_0, \hat{c}_0]$.

Theorem 1 indicates that there exists an interval about c_0 where both manufacturers are willing to cooperate. In other words, if c_0 is on the interval $[\tilde{c}_0, \hat{c}_0]$ or $[\tilde{c}_0, \hat{c}_0]$, then manufacturer 1 will supply batteries to manufacturer 2, and manufacturer 2 will buy the batteries from him.

5. Numerical study

In this section, we investigate three main issues: (1) the effects of key parameters on allocated capacity and profits in Model C; (2) the channel choice of each manufacturer under different business environments; (3) comparing social welfare between the two models. Following the aforementioned assumptions and taking into account actual costs, we set the following basic parameters: $\alpha = 10$, $F = 2.0$, $c = 2.0$, $c_1 = 4.0$, $c_2 = 4.0$, $\beta = 0.5$, $\gamma = 10$, $b = 1.0$, and $v = 1.5$. Unless otherwise specified, the parameters in the numerical experiments follow these basic settings. If necessary, we change one or several parameters and make a clear statement in corresponding parts.

5.1. The effects of key parameters on system performance

In the above analytic sections, some prices such as w and b are assumed to be exogenous parameters so that we can focus on the capacity allocation decision. To further investigate the effects of these key parameters on equilibrium decisions and manufacturers' profits, we conduct the following extensive numerical experiments.

5.1.1. The effect of the battery price

This subsection investigates the effect of battery price on the equilibrium capacity allocation decision and manufacturers' profits. In these numerical experiments, w is limited to a certain range to guarantee positive profits for the two manufacturers. Fig. 3 shows the numerical results. Manufacturer 2's order quantity and EV production quantity decrease with the price of batteries. Consequently, manufacturer 1 produces and sells more EVs as w increases. As for profits, manufacturer 2's profit decreases with w while manufacturer 1's profit is concave in w . The concavity is reasonable because a higher w increases the profit margin and decreases the order quantity at the same time.

Fig. 3. The effect of the battery price on allocated capacity and profits.

Fig. 4. The effect of the buy-back payment on recycling rates and profits.

5.1.2. The effect of the buy-back payment

In this subsection, we investigate the effect of the buy-back payment b on manufacturers' recycling rates and profits. The results are shown in Fig. 4. In the left panel, manufacturer 2's recycling rate increases with b , as Lemma 3 shows. Manufacturer 1's recycling rate remains almost unchanged as b varies. Consequently, manufacturer 2's profit increases slowly while manufacturer 1's profit remains unchanged as b increases. The robustness of b , to some extent, rationalises why we set b as an exogenous parameter rather than a decision variable.

5.2. Optimal channel choice

In this subsection, we examine the effects of the external procurement cost c_0 and the value of echelon use ν on the optimal channel choice.

5.2.1. The effect of external procurement cost

In the numerical experiment, we vary c_0 to investigate its effect on channel choices. As Propositions 1 and 2 show, w plays an important role in determining the channel choice of two manufacturers. Therefore, we choose two values of w to represent the cases of $w \leq \tilde{w}$ and $w > \tilde{w}$, respectively. The results of the numerical experiments are shown in Fig. 5. For each manufacturer, the profit gap between Models C and NC determines which model brings more profit. Specifically, positive profit gap implies that Model C is more profitable than Model C and negative profit gap implies that Model NC is more profitable.

The left panel shows the case of $w \leq \tilde{w}$. In Model NC, manufacturer 2's profit decreases with c_0 while manufacturer 1's profit increases with c_0 . This interesting result lies in the following reasons. Manufacturer 2's procurement cost from the external supplier actually influences her EV production cost and determines the

Fig. 5. The channel choices of two manufacturers as c_0 varies.

market competitiveness. If manufacturer 2 purchases batteries at a high cost, she has to set a high retail price and loses consumers in the market. Consequently, manufacturer 1 can attract more consumers and gain higher profits. On the other hand, the profits of two manufacturers in Model C are constant as c_0 varies. As a result, the profit gap of manufacturer 1 (manufacturer 2) between Models C and NC decreases (increases) with c_0 . We can conclude that Model C is more profitable for manufacturer 1 if c_0 is below a certain threshold, denoted by $\bar{c}_0$. Meanwhile, Model C is more profitable for manufacturer 2 if c_0 is above a certain threshold, denoted by $\bar{c}_0$. In other words, Model C is more profitable for both manufacturers if $c_0 \in [\bar{c}_0, \bar{c}_0]$. The analysis of the right panel is similar and we omit the detail. In summary, the numerical results in Fig. 5 validate Theorem 1.

5.2.2. The effect of echelon use

We investigate the effect of ν on the optimal channel choices. In this numerical experiment, we vary ν and compare the profits between two models. Corresponding to the two cases in Theorem 1, we set two values of w , represented by the left and right panels in Fig. 6. They show that: (1) The profit gap between Models C and NC is always positive. However, it decreases as ν increases, which holds for both manufacturers. In other words, the increase of ν lowers their willingness to cooperate. (2) In the left panel, as ν increases, the profit gap of manufacturer 2 decreases more dramatically than that of manufacturer 1, which implies ν shows more significant impact on manufacturer 2. The result in the right panel is opposite, which implies ν shows more significant impact on manufacturer 1.

5.3. Comparing social welfare between the two models

In the above sections, we investigate manufacturer 1's optimal channel choice from the perspective of profit maximisation. In this section, we compare the two channels from the perspective of social welfare maximisation. Consistent with Atasu, Van Wassenhove, and Sarvary (2009), Atasu, Özdemir, and Van Wassenhove (2013), Jacobs and Subramanian (2012), and Esenduran, Kemahlioglu-Ziya, and Swaminathan (2017), the total social welfare is defined as the sum of firms' profits, consumer surplus, and environmental benefit.

We specify consumer surplus and environmental benefit as follows. Similar to Yu, Tang, and Shen (2018), the consumer surplus with differentiated products is $CS = \alpha q_1 - \frac{q_1^2}{2} - \beta q_1 q_2 + \alpha q_2 - \frac{q_2^2}{2} - (p_1 q_1 + p_2 q_2)$. Consistent with Esenduran et al. (2017), we define the environmental benefit as a function of total recycling quantity. Without loss of generality, we denote the economic measure of environmental benefit for each recycled battery unit with e . Therefore, the total environmental benefit can be written as $E = e(\tau_1 q_1 + \tau_2 q_2)$.

With the above definitions, we can express the social welfare of both Models NC and C, that is, SW^{NC} and SW^C , as follows. We have $SW^{NC} = \Pi_1^{NC} + \Pi_2^{NC} + \Pi_s + CS^{NC} + E^{NC}$ and $SW^C = \Pi_1^C + \Pi_2^C + CS^C + E^C$. Note that the superscripts NC and C are used to differentiate these two models. Π_s is the profit of the external battery supplier and it is only involved in Model NC.

First, we examine the social welfare as c_0 varies. We set two different values of e to represent low and high environmental benefits, respectively. The results are shown in Fig. 7. In Model NC, the social welfare decreases with c_0 . The reason is that manufacturer 2's order quantity, the recycling quantity, and therefore environmental benefit, decrease as c_0 increases. Another important finding is that the social welfare in Model NC is larger than that in Model C when c_0 is below a certain threshold. Interestingly, the channel choice may be different if the objective is to maximise social welfare instead of individual profit. For example, when $c_0 = 3.5$ and $e = 0.1$, Model C maximises manufacturer 1's profit while Model NC maximises social welfare.

Second, we examine social welfare as e varies. The range of e is consistent with Esenduran et al. (2017). To enhance robustness, we repeat the numerical experiments with $c_0 = 3.5$ and $c_0 = 4.5$. The numerical results are shown in Fig. 8. The most important finding is that in the two models, social welfare increases linearly with e .

6. Extension

6.1. Dual-channel procurement

In this case, manufacturer 2 purchases batteries from both manufacturer 1 and the external supplier, as is shown in Fig. 9. We model the interaction as a three-stage Stackelberg game. In

Fig. 6. The channel choices of two manufacturers as ν varies.

Fig. 7. A comparison of social welfare in both models as c_0 varies.

stage 1, manufacturer 2 makes the ordering decision. Her order quantity from manufacturer 1 is q_{2m} and the quantity from the supplier is q_{2s} . In stage 2, manufacturer 1 builds his battery capacity K and then decides on the capacity to be allocated to manufacturer 2, denoted by q_2 . $q_2 \leq q_{2m}$ holds because manufacturer 1 cannot allocate a capacity that exceeds manufacturer 2's order. Consequently, the quantity of batteries that manufacturer 2 obtains from manufacturer 1 is also q_2 , and the quantity of batteries remaining for manufacturer 1 is $q_1 = K - q_2$. The quantity of batteries that manufacturer 2 obtains from the supplier is equal to her order quantity q_{2s} . Therefore, the total EV production quantity of manufacturer 2 is $q_2 + q_{2s}$. In stage 3, the batteries are retired from EVs and the two manufacturers decide their recycling rates.

Manufacturer 1's profit is from the forward channel by selling batteries and EVs plus the reverse channel by recycling batteries.

The retail price of his EV is $p_1 = \alpha - (K - q_2) - (q_2 + q_{2s})$. Taking into account his specific constraints, we can write manufacturer 1's profit function as follows:

$$\Pi_1 = \max_{K, q_2, \tau_1} \left\{ [\alpha - (K - q_2) - \beta(q_2 + q_{2s}) - c_1](K - q_2) + wq_2 - (F + cK) - \gamma\tau_1^2 - b\tau_2q_2 + \nu[\tau_1(K - q_2) + \tau_2q_2] \right\} \quad (6)$$

$$s.t. \quad 0 \leq q_2 \leq q_{2m}. \quad (7)$$

Manufacturer 2's objective is to maximize her profit by determining the ordering quantity and recycling rate taking into account manufacturer 1's allocation strategy. Her profit function is given as follows:

$$\Pi_2 = \max_{q_{2m}, q_{2s}, \tau_2} \{ [\alpha - (q_2 + q_{2s}) - \beta(K - q_2) - c_2](q_2 + q_{2s})$$

Fig. 8. A comparison of social welfare in both models as e varies.

Fig. 9. The dual-channel structure for two EV manufacturers with battery recycling.

$$-wq_2 - c_o q_{2s} - \gamma \tau_2^2 + b\tau_2(q_2 + q_{2s}) \quad (8)$$

We solve the two manufacturers' problems using the backward induction method. That is, we first solve the problem in stage 3. Given q_{2m} , q_{2s} , K and q_2 , these two manufacturers decide their recycling rates τ_1 and τ_2 , respectively. By solving the maximization problems, we can obtain the optimal recycling rates τ_1^* and τ_2^* .

Lemma 6. In stage 3, let τ_1^* and τ_2^* be the optimal recycling rates of manufacturer 1 and manufacturer 2, respectively. For given q_{2m} , q_{2s} , K and q_2 , we have $\tau_1^* = \frac{v(K-q_2)}{2\gamma}$ and $\tau_2^* = \frac{b(q_2+q_{2s})}{2\gamma}$.

Lemma 6 indicates that for these two manufacturers, the optimal recycling rates increase with their allocated capacity. This result is consistent with **Lemma 3** in our paper.

In stage 2, given q_{2m} and q_{2s} , manufacturer 1 decides his optimal capacity K^* and allocated capacity q_2^* . For ease of exposition, we denote $H_1 = \frac{(4\gamma-v^2)b(v-b)+4\beta^2\gamma^2}{(4\gamma-v^2)b(v-b)+2\beta^2\gamma^2}$ and $H_2 = \frac{2\gamma[2\beta\gamma(\alpha-c-c_1)-(4\gamma-v^2)(w-c)]}{(4\gamma-v^2)b(v-b)+2\beta^2\gamma^2}$. The results are shown in **Lemma 7**.

Lemma 7. In stage 2, given that manufacturer 2 orders q_{2m} from manufacturer 1 and q_{2s} from the supplier, manufacturer 1's best response decisions are given by the following:

$$(1) \text{ If } q_{2m} + H_1 q_{2s} \leq H_2, \text{ then } K^* = \frac{2\gamma(\alpha-c-c_1-\beta q_{2s})}{4\gamma-v^2} \text{ and } q_2^* = 0.$$

$$(2) \text{ If } q_{2m} + H_1 q_{2s} > H_2, \text{ then } K^* = \frac{[2(2-\beta)\gamma-v^2]q_{2m}+2\gamma(\alpha-c-c_1-\beta q_{2s})}{4\gamma-v^2} \text{ and } q_2^* = q_{2m}.$$

Lemma 7 shows the effect of manufacturer 2's ordering decisions on manufacturer 1's capacity allocation decisions. It indicates that manufacturer 1 allocates no capacity if manufacturer 2's order quantity is relatively small ($q_{2m} + H_1 q_{2s} \leq H_2$). Otherwise, manufacturer 1 satisfies her entire order ($q_2^* = q_{2m}$). The results are also consistent with **Lemma 4**.

In stage 1, manufacturer 2 decides the optimal order quantities q_{2m} and q_{2s} . Based on **Lemmas 6–7**, we have

$$(a) \quad \Pi_2^1 = \max_{q_{2m}, q_{2s}} \left\{ \left[\alpha - q_{2s} - \frac{2\beta\gamma(\alpha-c-c_1-\beta q_{2s})}{4\gamma-v^2} - c_2 \right] q_{2s} - c_o q_{2s} + \frac{b^2(q_{2s})^2}{4\gamma} \right\} \quad (9)$$

$$\text{s.t. } q_{2m} + H_1 q_{2s} \leq H_2 \quad (10)$$

$$(b) \quad \Pi_2^2 = \max_{q_{2m}, q_{2s}} \left\{ \left[\alpha - (q_{2m} + q_{2s}) - \frac{2\beta\gamma(\alpha-c-c_1-\beta q_{2m}-\beta q_{2s})}{4\gamma-v^2} - c_2 \right] (q_{2m} + q_{2s}) - wq_{2m} - c_o q_{2s} + \frac{b^2(q_{2m} + q_{2s})^2}{4\gamma} \right\} \quad (11)$$

$$\text{s.t. } q_{2m} + H_1 q_{2s} > H_2 \quad (12)$$

Because the expressions of Π_2^{1*} and Π_2^{2*} are too complicated, we cannot obtain the closed-form solutions of q_{2m}^* and q_{2s}^* . Thus, by numerical experiments, we vary c_o and w to examine the conditions under which manufacturer 2 procures batteries from single supplier or two suppliers, respectively. The results are shown in **Fig. 10**.

From **Fig. 10**, we find that manufacturer 2 only procures batteries from manufacturer 1 in Region II. In Region III, manufacturer 2 only procures from the external supplier. In Region I, she will procure from both manufacturer 1 and the external supplier.

Fig. 10. The procurement strategy of manufacturer 2. Note. In Region I, $q_{2m} > 0$, $q_{2s} > 0$ where we set $\beta = 0.7$ to make this region remarkable.

We can find that in Region I, manufacturer 2 still procures from the external supplier even if $c_o > w$. The reason is as follows. If manufacturer 2 procures batteries only from manufacturer 1, her EV production quantity is constrained by manufacturer 1's capacity allocation strategy. As Lemma 4 shows, she is forced to order a quantity above a certain threshold. Instead, if she procures batteries from the external supplier, her EV production quantity is determined by herself. Therefore, manufacturer 2 can benefit from more freedom to make an ordering decision. From the perspective of manufacturer 2, when making decisions on battery procurement channel, she should make the trade-off between a lower procurement cost and more freedom of decision making. In other words, due to the competition relationship between two manufacturers, manufacturer 2 becomes more conservative to choose manufacturer 1 as the supplier. For the upper-left corner of Region III, even if c_o is much larger than w , manufacturer 2 only procures from the external supplier instead of manufacturer 1. The reason is as follows. When w is low, manufacturer 2 has to procure from manufacturer 1 with the quantity that is above a certain threshold (see Lemmas 4 and 5), which may be not profitable compared with procuring from the external supplier.

6.2. Endogenous battery price

In the previous section, we bypassed the pricing decisions to focus on the interplay between two manufacturers regarding quantities decisions. Therefore, we assume the battery price is given. In this extension, we relax the assumption and study the case of endogenous battery price. That is, manufacturer 1 decides the battery price in the initial stage. Afterwards, two manufacturers make decisions on production and recycling, which has been discussed in detail in Section 4.2.

Substituting the optimal solutions given by Lemma 5 into the profit function of manufacturer 1 in Eq. (3), we can obtain the optimal battery price w^* . For ease of exposition, we denote $A_7 = (4\gamma - v^2)b^2(\alpha - c)[4(1 - \beta)\gamma - v^2]$, $A_8 = v^2[(8\gamma - v^2)(\alpha + c) - \beta^2\gamma(3\alpha + 2c)] + 2\gamma^2[c(4\beta^2 + \beta^3 - 8) - \alpha(8 - 6\beta^2 + \beta^3)]$, $A_9 = (4\gamma - v^2)b(2v - b) - 4\gamma[(4 - 3\beta^2)\gamma - v^2]$ and $A_{10} = 2\beta\gamma(\alpha - c) - (4\gamma - v^2)\alpha$. Then, we have the following results.

Corollary 1. Let $\tilde{\beta} = \frac{(4\gamma - v^2)(\alpha - c - c_2)}{4\gamma(\alpha - c - c_1)}$, (1) if $\beta < \tilde{\beta}$, then $w^* = \frac{A_7 + 2bv(4\gamma - v^2)A_{10} - 4\gamma A_8 - 4\beta\gamma c_1 A_5 + (4\gamma - v^2)c_2 A_9}{2(4\gamma - v^2)(A_4 - A_5)}$; (2) if $\beta \geq \tilde{\beta}$, $w^* = \frac{A_3}{4\gamma - v^2}$.

Corollary 1 shows that the optimal battery price of manufacturer 1 is determined by the substitution degree β . To further examine the effect, we vary β to observe the change of the optimal battery price and corresponding EV production quantities of two manufacturers, which are shown in Fig. 11. We find that when β is smaller than a certain threshold ($\beta < \tilde{\beta}$), the battery price changes rather mildly as β increases. However, as β begins to exceed the threshold, the optimal battery price increases dramatically. By Lemma 5, we find that manufacturer 2 decides to order nothing under such a battery price. In other words, manufacturer 1 actually decides not to supply batteries to manufacturer 2 by adjusting the battery price. This result coincides with intuition that a firm would not cooperate with a highly threatening competitor.

7. Conclusions

7.1. Main findings

In this research, we study an upstream EV manufacturer's optimal strategies of capacity allocation and battery recycling with his competitor, a downstream EV manufacturer. As a supplier, the upstream EV manufacturer can supply batteries to his competitor. In such a situation, the relationship between the two EV manufacturers is complicated. They are partners and competitors at the same time. We consider two cases where the upstream EV manufacturer cooperates with his competitor or not and obtain some important findings as follows.

First, we find the optimal strategies of two manufacturers. In the cooperation model, the upstream manufacturer would like to satisfy the competitor's entire order if the order quantity is higher than a certain threshold; otherwise, he does not supply batteries. Knowing the upstream EV manufacturer's capacity allocation strategy, the downstream manufacturer orders above the threshold.

Second, we find the channel choices of two manufacturers. By comparing the cooperation model with the non-cooperation model, we find that the channel choice is determined by the battery prices of the upstream EV manufacturer and the external supplier. Both manufacturers can gain more profit through

Fig. 11. The optimal battery price and EV production quantities as β varies.

cooperation if the procurement cost from the external supplier is within a certain range given the upstream manufacturer's battery price.

Third, we find that the channel choices are different with different objectives, including maximising profit and social welfare. To maximise social welfare, the upstream EV manufacturer should not supply batteries to its competitor if the procurement cost from the external supplier is low, which is contrary to the case of profit maximisation.

Finally, we investigate the case of endogenous battery price. Based on Stackelberg game model where the upstream EV manufacturer is the leader and determines the battery price to the downstream manufacturer, we find the optimal pricing strategy is determined by the substitution degree and relevant costs. If the substitution degree is below a certain threshold, the upstream EV manufacturer sets a battery price so that the competitor orders from him.

7.2. Managerial implications

This research also provides meaningful managerial insights to EV manufacturers. First, for the EV manufacturer that has the ability to produce batteries (e.g., BYD), with the rapid technology improvement and decline of battery price in the EV industry, it is actually optimal to supplies batteries to other EV manufacturers and satisfy their entire orders. In addition, if he can unilaterally determine the battery price sold to other manufacturers, he should supply batteries to his competitor when the substitution degree is low.

For the EV manufacturer that is not able to produce batteries (e.g., Dongfeng Motor Corporation), if she decides to procure batteries from her competitor (e.g., BYD), she should order above a threshold to guarantee that BYD has the incentive to supply, considering their competition relationship in the EV market. Because a lower battery price increases the threshold quantity and may potentially harm her profit, she should avoid a low battery price set by BYD, which may be counter-intuitive. In addition, with the option of an external battery supplier (e.g., CATL), she should alternatively procure from it instead of BYD if the procurement cost is below a certain threshold.

Further, in the automotive industry, the shifting relationship between suppliers and manufacturers can also be widely observed

beyond electrification. For example, some car manufacturers and ICT companies aim at designing smartphone-based valued-added applications for users on wheels (Campolo, Iera, & Molinaro, 2012). Ford has showed the beta version of the MyFord Mobile app, allowing users to monitor charging status of their electric vehicles, receive alerts, find recharging stations, etc (<http://social.ford.com/our-articles/cuvs/c-max/how-a-smartphone-appcan-maximize-your-electric-vehicle-driving-experience/>). Moreover, the growth of mobility-as-a-service schemes put carmakers into service providers. For example, Daimler acquired both a car sharing service (Car2Go) as well as a trip planning smartphone app (RideScout) (<https://venturebeat.com/2014/12/13/mobility-as-a-service-turning-transportation-into-a-software-industry/>).

Some questions remain for future research. For example, when studying the procurement process between the two manufacturers, we may further investigate other contract types and consider pricing issues. Another direction is to consider differences in battery quality between the upstream EV manufacturer and the external battery supplier. We may also consider the recycling cost function that captures the interdependence between the scaling parameter and the total battery capacity.

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Appendix

Proof of Lemma 1. In stage 2, manufacturer 1 decides τ_1 to optimise his profit function in Eq. (1). Since the profit function is concave in τ_1 , we can obtain $\tau_1^* = \frac{vK}{2\gamma}$ by the first-order condition. Similarly, manufacturer 2 decides τ_2 to optimise her profit function in Eq. (2). Since the profit function is concave in τ_2 , we can obtain $\tau_2^* = \frac{bq_2}{2\gamma}$ by the first-order condition.

Proof of Lemma 2. Substituting $\tau_1^* = \frac{vK}{2\gamma}$ into Eq. (1), we can obtain the transformed profit function:

$$\Pi_1 = \max_K \left\{ (\alpha - K - \beta q_2 - c_1 - c)K - F + \frac{v^2 K^2}{4\gamma} \right\}. \quad (\text{A.1})$$

Since manufacturer 1's profit function in Eq. (A.1) is concave in K , we can obtain $K = \frac{2\gamma(\alpha - c - c_1 - \beta q_2)}{4\gamma - v^2}$ by the first-order condition.

Similarly, in stage 1, manufacturer 2 decides q_2 to optimise her profit function in Eq. (2). Substituting τ_2^* into Eq. (2), we can obtain the transformed equation:

$$\Pi_2 = \max_{q_2} \left\{ (\alpha - q_2 - \beta K - c_2 - c_0)q_2 + \frac{b^2 q_2^2}{4\gamma} \right\}. \quad (\text{A.2})$$

Since manufacturer 2's profit function in Eq. (A.2) is concave in q_2 , we can obtain $q_2 = \frac{2\gamma(\alpha - c_0 - c_2 - \beta K)}{4\gamma - b^2}$ by the first-order condition.

By simultaneously solving the two equations $K = \frac{2\gamma(\alpha - c - c_1 - \beta q_2)}{4\gamma - v^2}$ and $q_2 = \frac{2\gamma(\alpha - c_0 - c_2 - \beta K)}{4\gamma - b^2}$, we can obtain $K^* = q_1^* = \frac{2\gamma[(4\gamma - b^2)(\alpha - c - c_1) - 2\beta\gamma(\alpha - c_0 - c_2)]}{(4\gamma - v^2)(4\gamma - b^2) - 4\beta^2\gamma^2}$ and $q_2^* = \frac{2\gamma[(4\gamma - v^2)(\alpha - c_0 - c_2) - 2\beta\gamma(\alpha - c - c_1)]}{(4\gamma - v^2)(4\gamma - b^2) - 4\beta^2\gamma^2}$.

Proof of Lemma 3. In stage 3, manufacturer 1 decides τ_1 to maximise his profit in Eq. (3). Since the profit function is concave in τ_1 , we can obtain $\tau_1^* = \frac{v(K - q_2)}{2\gamma}$ by the first-order condition.

Similarly, in stage 3, manufacturer 2 decides τ_2 to maximise her profit in Eq. (5). Since the profit function is concave in τ_2 , we can obtain $\tau_2^* = \frac{bq_2}{2\gamma}$ by the first-order condition.

Proof of Lemma 4. In stage 2, manufacturer 1 decides K and q_2 to optimise his profit function in Eq. (3). It is clear that $q_2 \leq q_2^0$, which indicates that the capacity allocated to manufacturer 2 will not exceed her order quantity. Substituting τ_1^* and τ_2^* into Eq. (3), we can obtain the transformed equation:

$$\Pi_1 = \max_{K, q_2} \left\{ (\alpha - (K - q_2) - \beta q_2 - c_1)(K - q_2) + wq_2 - (F + cK) + \frac{v^2(K - q_2)^2}{4\gamma} + \frac{bq_2^2(v - b)}{2\gamma} \right\}. \quad (\text{A.3})$$

$$\text{s.t. } 0 \leq q_2 \leq q_2^0 \quad (\text{A.4})$$

Since manufacturer 1's profit function in Eq. (A.3) is concave in K , we can obtain $K^* = \frac{2\gamma(\alpha - c - c_1) + (4\gamma - v^2 - 2\beta\gamma)q_2}{4\gamma - v^2}$ by the first-order condition. Substituting this equation into Eq. (A.3), we obtain

$$\begin{aligned} \Pi_1 = \max_{q_2} \left\{ \left[\alpha - \frac{2\gamma(\alpha - c - c_1 - \beta q_2)}{4\gamma - v^2} - \beta q_2 - c_1 \right] \right. \\ \times \frac{2\gamma(\alpha - c - c_1 - \beta q_2)}{4\gamma - v^2} + wq_2 - F \\ \left. - c \left[\frac{2\gamma(\alpha - c - c_1 - \beta q_2)}{4\gamma - v^2} + q_2 \right] \right. \\ \left. + \frac{\gamma v^2(\alpha - c - c_1 - \beta q_2)^2}{(4\gamma - v^2)^2} + \frac{bq_2^2(v - b)}{2\gamma} \right\}. \quad (\text{A.5}) \end{aligned}$$

Further, we find that manufacturer 1's profit function in Eq. (A.5) is convex in q_2 . Taking into account the constraint $0 \leq q_2 \leq q_2^0$, we can conclude that the optimal decision, q_2^* , is either 0 or q_2^0 . Specifically, when $q_2 = 0$, $\Pi_1(0) = \frac{Fv^2 + \gamma[(\alpha - c)^2 + c_1(2c - 2\alpha + c_1) - 4F]}{4\gamma - v^2}$; and when $q_2 = q_2^0$, $\Pi_1(q_2^0) = \{b(v - b)(4\gamma - v^2)(q_2^0)^2 + 2\gamma\{v^2[F + (c - w)q_2^0] + [(c - \alpha)^2 - 4F + c_1^2 + 2c_1(c - \alpha + \beta q_2^0) + q_2^0(4w + 2c(\beta - 2) - 2\alpha\beta +$

$\beta^2 q_2^0]\gamma\}\}/[2\gamma(4\gamma - v^2)]$. We then have $\Pi_1(q_2^0) - \Pi_1(0) = \frac{\{b(v - b)(4\gamma - v^2) + 2\beta^2\gamma^2\}q_2^0 + 2\gamma[(4\gamma - v^2)(w - c) + 2\beta\gamma(c - \alpha + c_1)]q_2^0}{2\gamma(4\gamma - v^2)}$, which is denoted by $f(q_2^0)$ for ease of exposition.

We then compare $\Pi_1(q_2^0)$ and $\Pi_1(0)$. Firstly, we let the two roots of the equation $f(q_2^0) = 0$ be $r_1 = 0$ and $r_2 = \frac{-2\gamma[(4\gamma - v^2)(w - c) + 2\beta\gamma(c - \alpha + c_1)]}{b(v - b)(4\gamma - v^2) + 2\beta^2\gamma^2}$, respectively. There are two subcases to analyse as follows:

- (1) When $(4\gamma - v^2)(w - c) + 2\beta\gamma(c - \alpha + c_1) \leq 0$, we have $r_1 = 0$ and $r_2 \geq 0$. It is obvious that if $0 \leq q_2^0 < r_2$, then $f(q_2^0) = \Pi_1(q_2^0) - \Pi_1(0) \leq 0$ and, therefore, $q_2^* = 0$. Otherwise, $\Pi_1(q_2^0) - \Pi_1(0) > 0$ and therefore $q_2^* = q_2^0$.
- (2) When $(4\gamma - v^2)(w - c) + 2\beta\gamma(c - \alpha + c_1) > 0$, we have $r_1 = 0$ and $r_2 < 0$. Evidently, $f(q_2^0) = \Pi_1(q_2^0) - \Pi_1(0) \geq 0$ always holds, and, therefore, $q_2^* = q_2^0$.

Note that $(4\gamma - v^2)(w - c) + 2\beta\gamma(c - \alpha + c_1) \leq 0$ is equivalent to $w \leq \frac{(4\gamma - v^2 - 2\beta\gamma)c + 2\beta\gamma(\alpha - c_1)}{4\gamma - v^2}$. Therefore, we can obtain manufacturer 1's optimal strategies as follows:

Case 1: If $w \leq \frac{(4\gamma - v^2)c + 2\beta\gamma(\alpha - c_1)}{4\gamma - v^2}$ and $0 \leq q_2^0 < r_2$, then $q_1^* = \frac{2\gamma(\alpha - c - c_1)}{4\gamma - v^2}$, $q_2^* = 0$, and $K^* = \frac{2\gamma(\alpha - c - c_1)}{4\gamma - v^2}$.

Case 2: If $w \leq \frac{(4\gamma - v^2)c + 2\beta\gamma(\alpha - c_1)}{4\gamma - v^2}$ and $q_2^0 \geq r_2$, or $w > \frac{(4\gamma - v^2)c + 2\beta\gamma(\alpha - c_1)}{4\gamma - v^2}$, then $q_1^* = \frac{2\gamma(\alpha - c - c_1 - \beta q_2^0)}{4\gamma - v^2}$, $q_2^* = q_2^0$, and $K^* = \frac{2\gamma(\alpha - c - c_1) + (4\gamma - v^2 - 2\beta\gamma)q_2^0}{4\gamma - v^2}$.

Denoting $A_1 = \frac{-2\gamma(4\gamma - v^2)}{(4\gamma - v^2)b(v - b) + 2\beta^2\gamma^2}$ and $A_2 = \frac{2\gamma[(4\gamma - v^2)c + 2\beta\gamma(\alpha - c_1)]}{(4\gamma - v^2)b(v - b) + 2\beta^2\gamma^2}$, we then obtain Lemma 4.

Proof of Lemma 5. In stage 1, manufacturer 2 decides q_2^0 to maximise her profit in Eq. (5). If manufacturer 2 chooses the strategy in case 1 of Lemma 4, then manufacturer 1 allocates no capacity to her and she gains no profit. For a self-interested and profit-maximised firm, manufacturer 2 will not choose this strategy. In other words, case 1 brings no profit and is suboptimal to manufacturer 2. Therefore, we only consider case 2 which is the optimal strategy. By Lemmas 3 and 4, we obtain $K^* = \frac{2\gamma(\alpha - c - c_1) + (4\gamma - v^2 - 2\beta\gamma)q_2^0}{4\gamma - v^2}$, $q_2^* = q_2^0$, and $\tau_2^* = \frac{bq_2^0}{2\gamma}$. Taking into account the constraints on w in case 2 of Lemma 4, the profit function in Eq. (5) can be rewritten as follows:

- (1) If $w \leq \frac{(4\gamma - v^2)c + 2\beta\gamma(\alpha - c_1)}{4\gamma - v^2}$, then

$$\Pi_2 = \max_{q_2^0} \left\{ \left[\alpha - w - c_2 - \frac{2\beta\gamma(\alpha - c - c_1) + (4\gamma - v^2 - 2\beta^2\gamma)q_2^0}{4\gamma - v^2} \right] q_2^0 + \frac{b^2(q_2^0)^2}{4\gamma} \right\}, \quad (\text{A.6})$$

$$\text{s.t. } q_2^0 \geq \frac{-2\gamma[(4\gamma - v^2)w - (4\gamma - v^2 - 2\beta\gamma)c - 2\beta\gamma(\alpha - c_1)]}{b(v - b)(4\gamma - v^2) + 2\beta^2\gamma^2}. \quad (\text{A.7})$$

- (2) If $w > \frac{(4\gamma - v^2)c + 2\beta\gamma(\alpha - c_1)}{4\gamma - v^2}$, then

$$\Pi_2 = \max_{q_2^0} \left\{ \left[\alpha - w - c_2 - \frac{2\beta\gamma(\alpha - c - c_1) + (4\gamma - v^2 - 2\beta^2\gamma)q_2^0}{4\gamma - v^2} \right] q_2^0 + \frac{b^2(q_2^0)^2}{4\gamma} \right\}. \quad (\text{A.8})$$

We now analyse the above two cases in turn. For $w \leq \frac{(4\gamma - v^2)c + 2\beta\gamma(\alpha - c_1)}{4\gamma - v^2}$, since the profit function in Eq. (A.6) is concave in q_2^0 , we can obtain the first-order solution to Eq. (A.6), $q_2^0 = \frac{2\gamma[(4\gamma - v^2)(\alpha - c_2 - w) - 2\beta\gamma(\alpha - c - c_1)]}{(4\gamma - b^2)(4\gamma - v^2) - 8\beta^2\gamma^2}$.

Considering the constraint in Eq. (A.7), it is obvious that when $\frac{2\gamma[(4\gamma-v^2)(\alpha-c_2-w)-2\beta\gamma(\alpha-c-c_1)]}{(4\gamma-b^2)(4\gamma-v^2)-8\beta^2\gamma^2} \leq \frac{-2\gamma[(4\gamma-v^2)w-(4\gamma-v^2-2\beta\gamma)c-2\beta\gamma(\alpha-c_1)]}{b(v-b)(4\gamma-v^2)+2\beta^2\gamma^2}$, which is equivalent to $w \leq \frac{[(4\gamma-b^2)(4\gamma-v^2)-8\beta^2\gamma^2][2\beta\gamma(\alpha-c-c_1)+(4\gamma-v^2)c]-[b(v-b)(4\gamma-v^2)+2\beta^2\gamma^2][(4\gamma-v^2)(\alpha-c_2)-2\beta\gamma(\alpha-c-c_1)]}{(4\gamma-v^2)[(4\gamma-bv)(4\gamma-v^2)-10\beta^2\gamma^2]}$, we have $q_2^{0*} = \frac{-2\gamma[(4\gamma-v^2)w-(4\gamma-v^2-2\beta\gamma)c-2\beta\gamma(\alpha-c_1)]}{b(v-b)(4\gamma-v^2)+2\beta^2\gamma^2}$. Otherwise, $q_2^{0*} = \frac{2\gamma[(4\gamma-v^2)(\alpha-c_2-w)-2\beta\gamma(\alpha-c-c_1)]}{(4\gamma-b^2)(4\gamma-v^2)-8\beta^2\gamma^2}$.

For $w > \frac{(4\gamma-v^2)c+2\beta\gamma(\alpha-c-c_1)}{4\gamma-v^2}$, since the profit function in Eq. (A.8) is concave in q_2^0 , we can obtain $(q_2^0)^* = \frac{2\gamma[(4\gamma-v^2)(\alpha-c_2-w)-2\beta\gamma(\alpha-c-c_1)]}{(4\gamma-b^2)(4\gamma-v^2)-8\beta^2\gamma^2}$.

For ease of exposition, we denote $A_3 = (4\gamma-v^2)c + 2\beta\gamma(\alpha-c-c_1)$, $A_4 = (4\gamma-v^2)(4\gamma-b^2) - 8\beta^2\gamma^2$, $A_5 = (4\gamma-v^2)b(v-b) + 2\beta^2\gamma^2$, and $A_6 = (4\gamma-v^2)(\alpha-c_2) - 2\beta\gamma(\alpha-c-c_1)$.

In conclusion, the two manufacturers' optimal strategies are given by:

- (1) $w \leq \min\{\frac{A_3}{4\gamma-v^2}, \frac{A_3A_4-A_5A_6}{(4\gamma-v^2)(A_4-A_5)}\}$, then $q_2^{0*} = \frac{2\gamma[A_3-(4\gamma-v^2)w]}{A_5}$, $q_1^* = \frac{2\gamma[(\alpha-c-c_1)A_5-2\beta\gamma[A_3-(4\gamma-v^2)w]]}{(4\gamma-v^2)A_5}$, $q_2^* = \frac{2\gamma[A_3-(4\gamma-v^2)w]}{A_5}$, and $K^* = \frac{2\gamma(\alpha-c-c_1)A_5+2\gamma[A_3-(4\gamma-v^2)w](4\gamma-v^2-2\beta\gamma)}{(4\gamma-v^2)A_5}$.
- (2) $w > \min\{\frac{A_3}{4\gamma-v^2}, \frac{A_3A_4-A_5A_6}{(4\gamma-v^2)(A_4-A_5)}\}$, then $q_2^{0*} = \frac{2\gamma[A_6-(4\gamma-v^2)w]}{A_4}$, $q_1^* = \frac{2\gamma[(\alpha-c-c_1)A_4-2\beta\gamma[A_6-(4\gamma-v^2)w]]}{(4\gamma-v^2)A_4}$, $q_2^* = \frac{2\gamma[A_6-(4\gamma-v^2)w]}{A_4}$, and $K^* = \frac{2\gamma(\alpha-c-c_1)A_4+2\gamma[A_6-(4\gamma-v^2)w](4\gamma-v^2-2\beta\gamma)}{(4\gamma-v^2)A_4}$.

The above results are presented in Lemma 5, denoting $\tilde{w} = \min\{\frac{A_3}{4\gamma-v^2}, \frac{A_3A_4-A_5A_6}{(4\gamma-v^2)(A_4-A_5)}\}$.

Proof of Proposition 1. According to Lemma 2, substituting K^* and q_2^* into Eq. (A.1) we can obtain manufacturer 1's profit in Model NC

$$\Pi_1^{NC*} = \frac{\gamma(4\gamma-v^2)[(4\gamma-b^2)(\alpha-c-c_1)-2\beta\gamma(\alpha-c_0-c_2)]^2}{[(4\gamma-v^2)(4\gamma-b^2)-4\beta^2\gamma^2]^2} - F.$$

According to Lemma 5, substituting q_2^* into Eq. (A.5), we can obtain manufacturer 1's profit when he supplies batteries to manufacturer

2. If $w \leq \tilde{w}$, then $\Pi_1^{C*} = \frac{\gamma(\alpha-c-c_1)^2}{4\gamma-v^2} - F$. Otherwise, $\Pi_1^{C*} = (w-c)q_2^* + \frac{b(v-b)(q_2^*)^2}{2\gamma} + \frac{\gamma(\alpha-c-c_1-\beta q_2^*)^2}{4\gamma-v^2} - F$ ($q_2^* = \frac{2\gamma[A_6-(4\gamma-v^2)w]}{A_4}$).

We then compare Π_1^{NC*} and Π_1^{C*} . Depending on the range of w , there are two cases to analyse as follows.

For $w \leq \tilde{w}$, we have $\Pi_1^{C*} - \Pi_1^{NC*} = \frac{\gamma(\alpha-c-c_1)^2}{4\gamma-v^2} - F - \left\{ \frac{\gamma(4\gamma-v^2)[(4\gamma-b^2)(\alpha-c-c_1)-2\beta\gamma(\alpha-c_0-c_2)]^2}{[(4\gamma-v^2)(4\gamma-b^2)-4\beta^2\gamma^2]^2} - F \right\} \geq 0 \Leftrightarrow \alpha - c - c_1 - \frac{(4\gamma-v^2)[(4\gamma-b^2)(\alpha-c-c_1)-2\beta\gamma(\alpha-c_0-c_2)]}{(4\gamma-v^2)(4\gamma-b^2)-4\beta^2\gamma^2} \geq 0 \Leftrightarrow c_0 \leq \alpha - c_2 - \frac{2\beta\gamma(\alpha-c-c_1)}{4\gamma-v^2}$. This inequation always holds. Therefore, we have $\Pi_1^{C*} - \Pi_1^{NC*} \geq 0$. In this case, manufacturer 1 should supply batteries to manufacturer 2.

For $w > \tilde{w}$, we have

$$\begin{aligned} \Pi_1^{C*} - \Pi_1^{NC*} &= (w-c)q_2^* + \frac{b(v-b)(q_2^*)^2}{2\gamma} + \frac{\gamma(\alpha-c-c_1-\beta q_2^*)^2}{4\gamma-v^2} - F - \left\{ \frac{\gamma(4\gamma-v^2)[(4\gamma-b^2)(\alpha-c-c_1)-2\beta\gamma(\alpha-c_0-c_2)]^2}{[(4\gamma-v^2)(4\gamma-b^2)-4\beta^2\gamma^2]^2} - F \right\} \geq 0 \Leftrightarrow \\ &\sqrt{\frac{b(v-b)(q_2^*)^2+2\gamma(w-c)q_2^*}{2\gamma^2}(4\gamma-v^2) + (\alpha-c-c_1-\beta q_2^*)^2 - \frac{(4\gamma-v^2)[(4\gamma-b^2)(\alpha-c-c_1)-2\beta\gamma(\alpha-c_0-c_2)]}{(4\gamma-v^2)(4\gamma-b^2)-4\beta^2\gamma^2}} \geq 0 \Leftrightarrow c_0 \leq \alpha - c_2 - \\ &\frac{(4\gamma-v^2)(4\gamma-b^2)(\alpha-c-c_1)-[(4\gamma-v^2)(4\gamma-b^2)-4\beta^2\gamma^2]\sqrt{\frac{b(v-b)(q_2^*)^2+2\gamma(w-c)q_2^*}{2\gamma^2}(4\gamma-v^2) + (\alpha-c-c_1-\beta q_2^*)^2}}{2\beta\gamma(4\gamma-v^2)}. \end{aligned}$$

Therefore, if $c_0 \leq \alpha - c_2 - \frac{(4\gamma-v^2)(4\gamma-b^2)(\alpha-c-c_1)-[(4\gamma-v^2)(4\gamma-b^2)-4\beta^2\gamma^2]\sqrt{\frac{b(v-b)(q_2^*)^2+2\gamma(w-c)q_2^*}{2\gamma^2}(4\gamma-v^2) + (\alpha-c-c_1-\beta q_2^*)^2}}{2\beta\gamma(4\gamma-v^2)}$, then $\Pi_1^{C*} - \Pi_1^{NC*} \geq 0$. In this case, manufacturer 1 should supply batteries to manufacturer 2. Otherwise, he should not supply batteries to manufacturer 2.

For ease of exposition, we denote $\hat{c}_0 = \alpha - c_2 - \frac{(4\gamma-v^2)(4\gamma-b^2)(\alpha-c-c_1)-[(4\gamma-v^2)(4\gamma-b^2)-4\beta^2\gamma^2]\sqrt{\frac{b(v-b)(q_2^*)^2+2\gamma(w-c)q_2^*}{2\gamma^2}(4\gamma-v^2) + (\alpha-c-c_1-\beta q_2^*)^2}}{2\beta\gamma(4\gamma-v^2)}$ where $B_1 = \frac{2\gamma[A_6-(4\gamma-v^2)w]}{A_4}$. We then conclude manufacturer 1's channel choice decision as follows:

- (1) If $w > \tilde{w}$ and $c_0 \leq \hat{c}_0$ or $w \leq \tilde{w}$, then manufacturer 1 chooses to supply batteries to manufacturer 2.
- (2) If $w > \tilde{w}$ and $c_0 > \hat{c}_0$, then manufacturer 1 chooses not to supply batteries to manufacturer 2.

Proof of Proposition 2. We prove Proposition 2 by comparing manufacturer 2's profits between Model NC and Model C. First, substituting the equilibrium decision variables in Lemma 2 into manufacturer 2's profit function in Eq. (2), we can obtain

$$\Pi_2^{NC*} = \frac{(4\gamma-b^2)\gamma[(4\gamma-v^2)(\alpha-c_2-c_0)-2\beta\gamma(\alpha-c-c_1)]^2}{[(4\gamma-b^2)(4\gamma-v^2)-4\beta^2\gamma^2]^2}.$$

Analogously, substituting the equilibrium decision variables in Lemma 5 into manufacturer 2's profit function in Eq. (5), we can obtain

$$\Pi_2^{C*} = \begin{cases} \frac{\gamma B_2 \{ b^2 B_2 (4\gamma-v^2) + 2[(4\gamma-v^2)(\alpha-c_2-w)A_5 + 2\gamma(B_2(v^2-2(2-\beta^2)\gamma)-\beta A_5(\alpha-c-c_1))] \}}{(A_5)^2(4\gamma-v^2)}, & \text{if } w \leq \tilde{w}; \\ \frac{\gamma[(4\gamma-v^2)(\alpha-c_2-w)-2\beta\gamma(\alpha-c-c_1)]^2}{(4\gamma-v^2)\{4\gamma[2(2-\beta^2)\gamma-v^2]-(4\gamma-v^2)b^2\}}, & \text{if } w > \tilde{w}, \end{cases}$$

where $B_2 = w(v^2-4\gamma) + A_3$. We can compare the above profit expressions of Π_2^{NC*} and Π_2^{C*} and obtain the threshold functions in Proposition 2 by some simple algebra.

Proof of Corollary 1. Based on Lemma 5, substituting K^* and q_2^* into Eq. (A.3), we can obtain manufacturer 1's profit function in Model C:

(1) If $w \leq \tilde{w}$, then

$$\Pi_1^1 = \max_w \left\{ \frac{\gamma(\alpha - c - c_1)^2}{4\gamma - v^2} - F \right\} \quad (\text{A.9})$$

(2) If $w > \tilde{w}$, then

$$\Pi_1^2 = \max_w \left\{ (w - c)B_3 + \frac{b(v - b)(B_3)^2}{2\gamma} + \frac{\gamma(\alpha - c - c_1 - \beta B_3)^2}{4\gamma - v^2} - F \right\} \quad (\text{A.10})$$

$$\text{where } B_3 = \frac{2\gamma[A_6 - (4\gamma - v^2)w]}{A_4}.$$

In case (1), we find that the profit function in Eq. (A.9) is independent of w . Therefore, $\Pi_1^{1*} = \frac{\gamma(\alpha - c - c_1)^2}{4\gamma - v^2} - F$.

In case (2), since the profit function in Eq. (A.10) is concave in w , we can obtain the first-order solution. For ease of exposition, we denote $A_7 = (4\gamma - v^2)b^2(\alpha - c)[4(1 - \beta)\gamma - v^2]$, $A_9 = (4\gamma - v^2)b(2v - b) - 4\gamma[(4 - 3\beta^2)\gamma - v^2]$, $A_8 = v^2[(8\gamma - v^2)(\alpha + c) - \beta^2\gamma(3\alpha + 2c)] + 2\gamma^2[c(4\beta^2 + \beta^3 - 8) - \alpha(8 - 6\beta^2 + \beta^3)]$ and $A_{10} = 2\beta\gamma(\alpha - c) - (4\gamma - v^2)\alpha$. We can obtain $w^* = \frac{A_7 + 2bv(4\gamma - v^2)A_{10} - 4\gamma A_8 - 4\beta\gamma c_1 A_5 + (4\gamma - v^2)c_2 A_9}{2(4\gamma - v^2)(A_4 - A_5)}$ by the first-order condition.

Considering the constraint $w > \tilde{w}$, we have

(a) If $\beta \geq \frac{(4\gamma - v^2)(\alpha - c - c_2)}{4\gamma(\alpha - c - c_1)}$, then $\tilde{w} = \frac{A_3}{4\gamma - v^2}$ and $\frac{A_7 + 2bv(4\gamma - v^2)A_{10} - 4\gamma A_8 - 4\beta\gamma c_1 A_5 + (4\gamma - v^2)c_2 A_9}{2(4\gamma - v^2)(A_4 - A_5)} \leq \tilde{w}$. Therefore,

we can obtain $w^* = \frac{A_3}{4\gamma - v^2}$. Substituting w^* into Eq. (A.10), we have $\Pi_1^{2*} - \Pi_1^{1*} = \frac{2\gamma A_5 (A_6 - A_3)^2}{(4\gamma - v^2)(A_4)^2} \geq 0$.

(b) If $\beta < \frac{(4\gamma - v^2)(\alpha - c - c_2)}{4\gamma(\alpha - c - c_1)}$, then $\tilde{w} = \frac{A_3 A_4 - A_5 A_6}{(4\gamma - v^2)(A_4 - A_5)}$ and $\frac{A_7 + 2bv(4\gamma - v^2)A_{10} - 4\gamma A_8 - 4\beta\gamma c_1 A_5 + (4\gamma - v^2)c_2 A_9}{2(4\gamma - v^2)(A_4 - A_5)} > \tilde{w}$. Therefore, we

can obtain $w^* = \frac{A_7 + 2bv(4\gamma - v^2)A_{10} - 4\gamma A_8 - 4\beta\gamma c_1 A_5 + (4\gamma - v^2)c_2 A_9}{2(4\gamma - v^2)(A_4 - A_5)}$. Substituting w^* into Eq. (A.10), we have $\Pi_1^{2*} - \Pi_1^{1*} = \frac{\gamma(A_6 - A_3)^2}{2(4\gamma - v^2)(A_4 - A_5)} > 0$.

In summary, we can obtain manufacturer 1's optimal battery price as follows:

(1) If $\beta \geq \frac{(4\gamma - v^2)(\alpha - c - c_2)}{4\gamma(\alpha - c - c_1)}$, then $w^* = \frac{A_3}{4\gamma - v^2}$.

(2) If $\beta < \frac{(4\gamma - v^2)(\alpha - c - c_2)}{4\gamma(\alpha - c - c_1)}$, then $w^* = \frac{A_7 + 2bv(4\gamma - v^2)A_{10} - 4\gamma A_8 - 4\beta\gamma c_1 A_5 + (4\gamma - v^2)c_2 A_9}{2(4\gamma - v^2)(A_4 - A_5)}$.

Supplementary material

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.ejor.2019.10.040.

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