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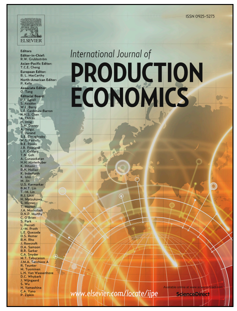

Electric Vehicle Battery Secondary Use Under Government Subsidy: a Closed-loop Supply Chain Perspective

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PII: S0925-5273(21)00011-6

DOI: https://doi.org/10.1016/j.ijpe.2021.108035

Reference: PROECO 108035

To appear in: *International Journal of Production Economics*

Received Date: 13 June 2020

Revised Date: 17 November 2020

Accepted Date: 5 January 2021

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Abstract

Electric vehicle batteries should normally be removed from electric vehicles when their power capacity fall to 70% ∼ 80% of new batteries. However, removed batteries can still be secondary used for other purposes, such as energy storage, before remanufacturing. To promote electric vehicle battery secondary use, this research studies a two-period battery secondary use closed-loop supply chain model consisting of a battery (re)manufacturer, a secondary user and a government. The government may provide subsidies for the secondary users to incentivize electric vehicle battery secondary use. It is found that, only when the recycled batteries' remaining power capacity is relatively high or their remanufacturing rate is relatively low, the government will consider a subsidy. In addition, under government's subsidy regulation, secondary battery users need to determine the quantities of batteries with relatively high power capacity for secondary use. Theoretically, this study enriches the research field of sustainable development of electric vehicle battery industry. Practically, this study also helps practitioners to better manage closed-loop supply chains with battery secondary use, and to enhance supply chain efficiency. Also, this study contributes to governments' regulatory decisions toward electric vehicle industries to balance economy and sustainability in society.

Keywords: Battery secondary use, Recycle and remanufacturing, Incentive policy design

1. Introduction

Currently, electric vehicles (EVs) are considered one of the future development directions for the automotive industry. According to International Energy Agency (2016), from 2005 to 2010, the number of EV sales worldwide, including both battery EVs and plug-in hybrid EVs (PHEVs), increased from 1,670 to 12,480. By 2015, the number of EV sales reached 1,256,900, which is almost 752 times that 10 years ago. Moreover, for the full year 2019, the numbers of EV sales were approximately 3,300,000 in China, 1,800,000 in Europe, and 1,400,000 in the United States (International Energy Agency, 2019, 2020).

The biggest difference between EVs and gasoline vehicles (GVs) is that EVs are powered by batteries rather than fossil fuels. One of the most important parts of EVs is the battery. First, approximately 30∼40% of the cost of an EV is attributed to the battery (Lih et al., 2012). Second, compared to GVs, which just have a short refuelling time (5 minutes) for a 300 km driving range, the EV charging time is long. A typical EV model (Nissan LEAF 40 kWh) takes 8 hours to charge from empty with a 6 kW home charging point or 30 minutes to super charge from empty to 80% of electricity capacity (Nissan, 2018). With the development of electricity techniques, Tesla can achieve the effect of a five-minute charge to achieve Tesla's 120 km range (Tesla, 2020). However, frequent super-fast charging can cause significant wear and tear on a battery, reducing its lifespan. According to Ober (2020), the industry super-fast charging technique causes capacity to fade much faster— after 40 charging cycles the batteries kept only 60% of their storage capacity. Batteries charged using the general method retained more than 80% capacity after the 40th cycle. Normally, due to performance and safety concerns, an EV battery (EVB) has to be removed when its capacity falls to a percentage (McIntire-Strasburg, 2015; Saxena et al., 2015), which also means that an EV cannot use its original battery until the end of its life. Based on the global EV sales data described earlier, by 2025, approximately 525,000 EV batteries (EVBs) will reach the end of their life running on the EV, and over 1 million EVBs will reach the end of their life by 2030 (Kelleher Environmental, 2019). Discarding these used batteries may constitute bad environmental practice. Therefore, there retired batteries is being considered for recycling or secondary use rather than being directly discarded (Yu et al., 2013).

According to Newbauer and Pesaran (2010), retired EVBs can be reused in the following ways: (a) grid-based stationary use, such as energy time shifting and renewable capacity firming; (b) off-grid stationary use, for instance, as backup power and remote installations (see also Heymans et al. (2014)); and (c) mobile use, for example, as commercial idle management or public transportation. These applications for the secondary use of EVBs would significantly increase the total lifetime value of batteries, both economically and environmentally. Currently, an increasing number of EV manufacturers are considering the secondary use of EVBs. BMW and Nissan are expected to secondary use returned batteries as home energy storage (Ayre, 2016; Dalton, 2016). Chevrolet has set up an energy storage station using old EVBs at the General Motors facility in Michigan (Voelcker, 2016). While the collection and secondary use of used batteries represent a tremendous business opportunity, it is also accompanied by various technical and economic challenges. In the absence of an efficient battery collection network, sorting, secondary use, dismantling and recycling of batteries can be expensive and time-consuming (Holland and Jiao, 2020). At the same time, the economics of recycling may be compromised by low quality or high costs of recovered batteries, which leads to that the incentives for secondary use of retired EVBs have yet to be strengthened (Casals et al., 2017; Ahmadi et al., 2017) and makes the profit model for the battery secondary use industry uncertain. In addition, improving the secondary use efficiency of returned batteries by secondary utilizers in the closed-loop supply chain (CLSC) is becoming a challenge as well.

Accordingly, this research article will develop an EVB secondary use CLSC model that investigates secondary use and subsidy policy to optimize the total profits of the supply chain. In detail, this research attempts to answer the following research questions: (1) How will EVB secondary use affect the relationships between entities in the CLSC? (2) How will government subsidy policies affect supply chain members' corresponding decisions and economical benefits? (3) For the government, how to design a proper subsidy regulation to promote EVB secondary use and maximize the supply chain welfare?

The rest of this research article is organized as follows. The next section, Section 2, reviews relevant studiess. Section 3 describes the model and derives the optimal subsidy and relevant optimal parameters. Section 4 conducts a numerical experiment and analyses and discusses the model. Section 5 concludes and discusses the limitations of the research. Appendix A and Appendix B list expressions and proofs that are needed but may be too trivial for the model within the limited length.

2. Literature Review

This section will review some relevant articles in CLSC, EV and EVB secondary use, government incentive policy design, etc. And then try to define current research gap.

The CLSC is a well-studied yet challenging area, particularly when it expands to a multi-period model. A number of papers have studied a two-period model (Atasu et al., 2008; Ferguson and Toktay, 2006; Mitra and Webster, 2008; Webster and Mitra, 2007; Majumder and Groenevelt, 2001), most of which focus on the relationship and decision making between manufacturer and remanufacturer. Specifically, both Atasu et al. (2008) and Ferguson and Toktay (2006) designed a two-period competition model. In the first period, only the new product exists on the market, and in the second period the remanufactured product competes with the new product. Majumder and Groenevelt (2001) studied a two-period competition model involving an original equipment manufacturer (OEM) and a local remanufacturer in which the total cost for dealing with the returned items was fixed. In the first period as he defined, only the OEM manufacturers sells new products. In the second period, a fraction of these items are returned for remanufacturing. The model developed by Webster and Mitra (2007) details the impact of take-back laws in remanufacturing competitive strategy in two periods. The first period is the life of using the product. At the end of the first period, some or all of the usable returns may be purchased by the remanufacturer, and the manufacturer and remanufacturer will compete for sales in the second period. Next, the authors developed another model to analyse the regulation of remanufacturing activities in two periods. In the first period, a manufacturer introduces a new generation of a product. The length of this period corresponds to the useful life of the product. After that, some of the products are returned, and a remanufacturer enters the market in the second period (Mitra and Webster, 2008). Ferrer and Swaminathan (2010) analyse the (re)manufacturer monopoly environment from a two-period to a multi-period planning horizon and develop a strategy for optimizing the price for the firm in the model. These CLSC studies did not take into consideration the process of secondary product use.

In terms of EVBs, current research mainly studied the secondary use of EVBs from technology aspect, such as Patten et al. (2011); Lacey et al. (2013); Tong et al. (2017); Abdel-Monem et al. (2017). For example, in terms of energy storage, Patten et al. (2011) suggested a wind energy storage system to increase the energy capacity factor, improve utilization, and make more efficient use of EVBs prior to recycling. Tong et al. (2017) proposed a solar energy time-shifting and demand-side management system for secondary use of EVBs with the objectives to maximize economic benefits, minimize grid energy consumption, or balance the two. Meanwhile, there are several studies examining how to promote EVs and expand the market for EVs, such as Gu et al. (2019); Sheldon and Dua (2020); Kong et al. (2020). There are also a few studies examining how both secondary used batteries and recycled EVBs jointly affect the operational performance and profit of a CLSC. In other words, from an EV's first use to its secondary use for other purposes and then its entry to the recycling or remanufacturing process, the EVB CLSC is able to be considered as a multi-period CLSC. This is also supported by Yu et al.

(2013).

In terms of research on government subsidies, as a common means of regulating the economy, they have a relatively important significance in promoting industrial development. The choice of government subsidies has always been a research hotspot, and in the face of different industries and different market structures, the optimal way of government subsidies also differs. Toshimitsu (2010) constructs the Cournot duopoly model of product differentiation and investigates the optimal government subsidy policy when considering the environmental and welfare effects. Guo et al. (2016) examine the impact of two government subsidy policies on social welfare and the profits of supply chain members, using a supply chain system consisting of three members: supplier, manufacturer, and government. Hattori (2017) constructed a model of upstream monopolistic innovators developing cleaner production technologies and licensing them to downstream polluting firms and discussed the optimal environmental policies of the government in R&D subsidies, adoption subsidies, and emission taxes. Chen et al. (2019) studied the impact on the level of innovation and the distribution of innovation costs in a supply chain consisting of a single manufacturer and a single retailer when the government uses R&D and product subsidies, respectively.

However, there is not much literature relating to EVB secondary use and secondary use incentive designs from an economic perspective. Earlier relevant research was performed by Neubauer et al. (2012); Neubauer and Pesaran (2011). In detail, Neubauer et al. (2012) found that used batteries have sufficient performance for other energy storage applications. The secondary use of batteries will increase the total life of the batteries. This will reduce the cost of using EVs and the total cost of energy storage for secondary users, such as grid companies. Neubauer and Pesaran (2011) estimated the impact of EVB secondary use on the initial cost of PHEV/EV batteries for automotive consumers and explored the potential applications for grid-based energy storage. Although the secondary use of batteries is not expected to significantly affect today's PHEV/EV prices, it has the potential to become a common component in future EVB life cycles and to transform markets in need of cost-effective energy storage. Richa et al. (2014) forecast the value and quantity of EVB waste and then suggested that, to increase economic efficiency, an EV end-of-life battery management system must include an increase in secondary use avenues before recycling or disposal. Lih et al. (2012) discussed the technology challenges, cost issues and business model for EVB secondary use applications. The results showed that secondary use of EVB is a perfect win-win deal that will probably create long-term and stable profits. The research also estimated that, the profit rate could reach approximately 35% in the 15 service years of a 10 kWh Li-ion battery pack. Jiao and Evans (2016) presented business models of different EV stakeholders that facilitate battery secondary use. Based on interviews, industry reports and academic literature, they analysed the deciding factors for battery "post-vehicle" applications and their potential impacts on EV business models. The findings emphasized the importance of inter-industry partnerships and related policies, and authors believed that government support constitutes the most important factor for battery secondary use.

The above review suggests that there is little research studying EVBs combined with recycling and secondary use processes and there are even fewer studies discussing how government subsidize the EVB secondary use. Meanwhile, existing CLSC models are not able to reflect the practices of used EVB secondary use and incentive policies and characteristics of the CLSC. Unlike other goods, EVBs cannot be reused for their original purpose when their capacity decreases to two thirds of their full capacity, which significantly complicates CLSC operations. Moreover, most studies and their results in the relevant literature appear to be too complicated for general practitioners to understand, e.g., Cai et al. (2014) and Bulmus et al. (2014), which significantly limits the application and implication of their research outcomes.

Hence, this study aims to fill the research gap in EVB CLSC and government incentive policy design aspects and to help managers/governments better understand this CLSC. The objective of this research article is to design a model to describe a two-period EVB CLSC, then explores the relationship between EVB manufacturers and remanufacturers and discusses how to promote returned EVBs' secondary use through the government subsidy.

3. Model Description

The structure of the model is described in Fig. 1. And all notations (include input parameters, intermediate parameters, decision variables and objective variables) used in this model are listed in Table 1 below.

Table 1: Notations

Input parameters	
θ	Battery return yield

α	Quality (also refers to remaining power capacity) demarcation between low-quality and high-quality returned batteries
α_L, α_H	Minimum/Maximum quality of returned batteries
λ	Remanufacturing rate
δ_m	A ratio between EV price and EVB price
c_{envir}	Cost for environmental pollution improvement
c_{manu}	Cost in producing the EVB
c_{remanu}	Cost in remanufacturing the used EVB
c_{ntr}	Battery material cost
Q_{PG}	Equivalent quantity of new batteries required by the power grid company
M_{EV}	EV market size
R_{engy}	Revenue per battery in operating by PGC
C_n	Utility of using the EV
S_L	Ceiling on subsidy percentage by the government
N_d	Parameter about the residual value for the batteries after secondary use ($N_d > 1$)
ρ	Quality demarcation of secondary usable batteries
Intermediate parameters	
Q_{tyu}	Quality of secondary usable batteries
s_{su2}	Subsidy of using each used batteries
β	High-quality battery sorting rate
Decision variables	
η	Subsidy ratio
γ	Secondary usable batteries sorting rate
$p_{EVi}; i \in \{1,2\}$	EV price in period i
$p_i; i \in \{1,2\}$	Battery price in period i
p_{su2}	Price of used batteries bought by secondary user in period 2
p_{dsc2}	Price of selling discarded batteries to the EBR
$q_i; i \in \{1,2\}$	Quantity of EVBs in period i
$q_{ni}; i \in \{1,2\}$	Battery quantity made from raw material in period i

$q_{EVi}; i \in \{1,2\}$	EV quantity in period i
q_{h2}	Quantity of batteries remanufactured from high-quality returns in period 2
q_{l2}	Quantity of batteries remanufactured from low-quality returns in period 2
q_{old2}	Batteries made by used batteries in period 2
q_{su2}	Purchasing quantity about used batteries by secondary user in period 2
$q_{PGi}; i \in \{1,2\}$	Demand quantity for new batteries needed by the PGC in period i
$q_{oldorl2}$	Original returned used batteries in period 2
π_{ebr2}	Profit for the secondary user (power grid company) in period 2
$\pi_{oemi}; i \in \{1,2\}$	Profit for the battery OEM in period i
π_{pgc2}	Profit for the remanufacturer in period 2
Objective variables	
π_{gvnmt}	Profit for the government (as well as the social welfare)

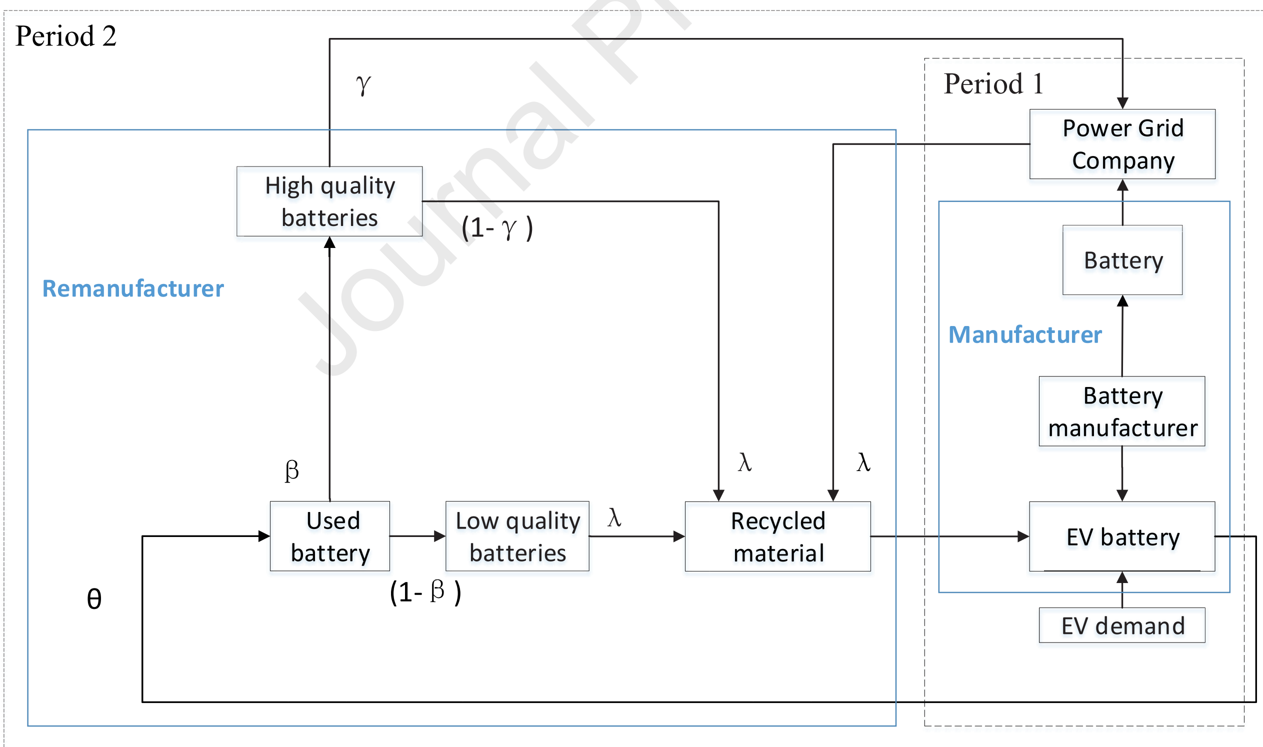


Fig. 1: A two-period model in manufacturing/remanufacturing system

We consider a two-period CLSC model. In period 1, all batteries are made from raw natural materials by the battery manufacturer (OEM). Some of these batteries will be used for EVs, and others will be used by the power grid company (abbreviated as PGC) to satisfy the PGC's power demand Q_{PG}.

Then, in period 2, θ of EVBs reach their end of life on the EV and will be collected as used batteries. With quality and security inspection by the remanufacturer, β of them are sorted as high-quality batteries and the others are sorted as low-quality batteries (Gu et al., 2018). Low-quality batteries, which have less use value, will be remanufactured to materials directly. Afterwards, based on the quality, those high-quality batteries will be considered by the PGC and EVB remanufacturer (EBR) for secondary use (Lih et al., 2012; Nassar et al., 2019). The PGC will purchase γ of them as reusable batteries for secondary use, while the others will be remanufactured to materials, which is similar to those low-quality batteries. Those batteries used by the PGC in period 1 will be remanufactured to materials directly as well. The average remanufacturing rate of all returned batteries is set to λ $(0 < \lambda < 1)$. Furthermore, as secondary usable batteries and recycled materials are not able to satisfy the whole demand for both EVs and PGC in period 2, batteries made by raw natural materials and batteries made from recycled materials will jointly meet the demand of EVs and PGC (Brent, 2020; Garthwaite, 2013). In addition, we suppose that electricity demand of PGC in period 1 and period 2 is equivalent to the power provided by Q_{PG} new batteries. In order to maximize the joint profit, PGC and EBR will decide the optimal γ together. We have $0 \leq \gamma \leq 1$ and there are three possible values of γ: (1) $\gamma = 0$: PGC does not use any high-quality batteries for secondary use and all of these batteries will be remanufactured directly by the EBR; (2) $\gamma = 1$: PGC purchases all high-quality batteries for secondary use; (3) $0 < \gamma < 1$: PGC uses a part of high-quality batteries for secondary use and the rest will be remanufactured by the EBR. Then, the OEM will decide the number of new batteries (q_{n2}) made by raw natural materials. Government, as a policymaker, will decide the optimal subsidy by considering maximizing the social welfare (π_{gvnmt}) in a comprehensive manner. Due to the limit of government's budget, we denote that the subsidy that government pays to CLSC is $s_{su2} = \eta p_{su2}$, where η is the subsidy ratio with a cap S_L (that is $0 \leq \eta \leq S_L$), and p_{su2} is the price of used batteries paid by the PGC in period 2.

We also have some assumptions about this research which are summarized below:

(1) The quality of the returned batteries obeys a uniform distribution. Actually, uniform distribution is a relatively simple distribution. As an approximation, it provides a direct reflection of the average quality characteristics of returned batteries. Similar assumption is used by Gu et al. (2018).

(2) The price of a battery is linear positively correlated to its quality. It is common sense that

quality and price have a positive proportional relationship. For computational convenience, we assume that they are linear positive. This is a quite common assumption, e.g., Neubauer et al. (2012), Tong et al. (2017), Gu et al. (2018), etc.

(3) In both periods, the PGC's demand for electricity is fixed to the power provided by Q_{PG} new batteries. Here, we have the demand for electricity by citizens is constant over a period, and therefore the capacity of the PGC to supply electricity is also constant.

3.1. Period 1

Period 1 could be considered the early development stage for the EV and EVB. In this period, as described before, all batteries used on EV and used by the PGC are made from raw natural materials. By adopting a utility-based approach similar to that of Bulmus et al. (2014) and Gu et al. (2018), customer's utility of using an EV is $(C_n - p_{EV1})$. And consumers will only choose to buy car if utility is positive $(C_n - p_{EV1} > 0)$. Therefore, the probability that a consumer is willing to buy a car is $(1 - p_{EV1}/C_n)$. The EVB price accounts for the EV price times a ratio (i.e., $p_1 = \delta_m p_{EV1}; 0 < \delta_m < 1$). The quantity of EVs sold in this period becomes

$$q_{EV1} = M_{EV}(1 - p_{EV1}/C_n) = M_{EV}(1 - \frac{p_1}{C_n\delta_m}) \tag{1}$$

The demand for new batteries is derived from the demand of the EVs and from the PGC's electricity demand, that is $q_1 = q_{n1} = q_{EV1} + q_{PG1}$. In this period, all of the PGC's power demand will be provided by batteries made from the raw natural materials $(q_{PG1} = Q_{PG})$, as will all EVBs. By substituting q_1 and p_1 into Eq. 1, the total battery needed in period 1 is

$$q_1 = M_{EV}(1 - \frac{p_1}{C_n\delta_m}) + Q_{PG} \tag{2}$$

Through formula transformation, the battery price can be

$$p_1 = C_n\delta_m\left(1 - \frac{q_{n1} - Q_{PG}}{M_{EV}}\right) \tag{3}$$

There are two parties in period 1: the OEM and the PGC. We assume that EVBs are no different from batteries used by the PGC. The profit for the PGC is $\pi_{pgc1} = Q_{PG}(R_{engy} - p_1)$ and the OEM's profit is the sale price minus the new EVB cost (including both raw material cost and manufacturing cost) multiplied by the quantity sold, which is $\pi_{oem1} = q_{n1}(p_1 - c_{ntr} - c_{manu})$.

Through substituting Eq. 3, the total profit in this period can be expressed as

$$\pi_{total1} = \pi_{oem1} + \pi_{pgc1} = q_{n1}(p_1 - c_{ntr} - c_{manu}) + Q_{PG}R_{engy}$$
$$= \begin{pmatrix} -\frac{M_{EV}}{C_n\delta_m}p_1^2 + \left(\frac{M_{EV}(c_{manu}+c_{ntr})}{C_n\delta_m} + M_{EV} + Q_{PG}\right)p_1 \\ -(c_{manu}+c_{ntr})(M_{EV}+Q_{PG}) + Q_{PG}R_{engy} \end{pmatrix} \tag{4}$$

As $-\frac{M_{EV}}{C_n\delta_m} < 0$, the maximum profit will be achieved when $\frac{\partial \pi_{oem1}}{\partial p_1} = 0$, so the optimal price for the EVB in period 1 is

$$p_1^* = \frac{c_{manu}M_{EV} + c_{ntr}M_{EV} + C_nM_{EV}\delta_m + C_n\delta_mQ_{PG}}{2M_{EV}} \tag{5}$$

With Eq. 2, we have the optimal total quantity of batteries made by natural materials:

$$q_1^* = q_{n1}^* = \frac{1}{2}\left(-\frac{M_{EV}(c_{manu}+c_{ntr})}{C_n\delta_m} + M_{EV} + Q_{PG}\right) \tag{6}$$

The EVBs made the raw materials are

$$q_{EV1}^* = \frac{1}{2}\left(-\frac{M_{EV}(c_{manu}+c_{ntr})}{C_n\delta_m} + M_{EV} + Q_{PG}\right) - Q_{PG} \tag{7}$$

3.2. Period 2

Period 2, as the later EV development stage, is the period that will be mainly studied in this study. As described before, θ of EVBs in period 1 reach their first end of life, which is $q_{oldorl2} = \theta q_{EV1}$. We then define the remaining power capacity(also be considered as quality of these batteries) for these returned batteries obeys the uniform distribution in $[\alpha_L, \alpha_H]$. These returned batteries will be divided into two types, β of them will be sorted as high-quality batteries and the others are low-quality batteries (it is easy to find that $\beta = \frac{\alpha_H-\alpha}{\alpha_H-\alpha_L}$). It can be found that the quality for high-quality batteries is uniform distributed in $[\alpha_L + \alpha(\alpha_H - \alpha_L), \alpha_H]$. Those low-quality returns ($q_{l2} = (1-\beta)q_{oldorl2}$) will be recycled to the battery material directly, while the high-quality returns ($q_{h2} = \beta q_{oldorl2}$) will be sorted again. Among, $\gamma(0 \le \gamma \le 1)$ of them are reusable batteries which will be reused by the PGC and the others $(1-\gamma)$ will go for remanufcturing directly. All these un-reusable batteries will be remanufactured to recycled materials for new battery manufacturing. Moreover, all new batteries used by the PGC in period 1 will all be recycledto materials as well. We define the remanufacturing rate for all these returns as λ, therefore the new batteries made by the used batteries are described as $q_{old2} = \lambda(q_{l2} + (1-\gamma)q_{h2} + Q_{PG})$.

Moreover, in commercial transactions with returned batteries in period 2, for simplicity of the model, we assume that the price of returned batteries is positively correlated with the quality. Therefore, we set the price of returned batteries $p_{2collect} = p_1(\alpha_L + \alpha_H)/2$ and we also define the price of selling reusable batteries to the PGC as $p_{su2} = p_1 Q_{tyu}$, where Q_{tyu} is the average quality of reusable batteries. Since secondary usable batteries are all from returned batteries, their quality must be somewhere between α_L and α_H ($\alpha_L < Q_{tyu} < \alpha_H$). For those batteries that were used by the PGC in period 1, they will be sold to the remanufacturer as a non-reusable item with fixed price $p_{dsc2} = p_1/N_d$, where N_d is a parameter about the residual value. Moreover, we have the electricity provided by all these reusable batteries, which will be reused by the PGC, is $Q_{tyu}q_{su2}$. With total PGC power demand Q_{PG} in both periods, the demanded quantity for new batteries by the PGC could be $q_{PG2} = Q_{PG} - Q_{tyu}q_{su2}$. Q_{tyu}, quality of reusable batteries, is described as $Q_{tyu} = \frac{1}{2}(\alpha_H(-\alpha\rho + \alpha + \rho + 1) + (\alpha - 1)\alpha_L(\rho - 1))$. The proof can be shown in Appendix B. For example, when $\rho = 1$, the quality of reusable batteries is α_H and when $\rho = 0$, the quality of them is $\frac{\alpha\alpha_H - \alpha\alpha_L + \alpha_H + \alpha_L}{2}$.

Similar to period 1, the entire demand for the EV depends on market size and EV price in period 2:

$$q_{EV2} = M_{EV}(1 - p_{EV2}/C_n) = M_{EV}(1 - \frac{p_2}{C_n\delta_m}) \tag{8}$$

With $q_2 = q_{EV2} + q_{PG2}$, the quantity of batteries required in this period is

$$q_2 = M_{EV}(1 - \frac{p_2}{C_n\delta_m}) + Q_{PG} - \gamma q_{h2}Q_{tyu} \tag{9}$$

And we can solve the battery price in this period by inversing Eq. 9:

$$p_2 = C_n\delta_m\left(1 - \frac{(q_2 - Q_{PG} + \gamma q_{h2}Q_{tyu})}{M_{EV}}\right) \tag{10}$$

In addition, q_2 can also be expressed to $q_2 = q_{n2} + q_{old2}$, this is because, in this period, there are two sources of raw materials for new batteries: natural resources and used batteries (from the returned EVBss and discarded PGC batteries in period 1). Therefore, in this period, the need for the batteries made by the natural material is

$$q_{n2} = q_2 - \lambda(q_{l2} + (1-\gamma)q_{h2} + Q_{PG}) \tag{11}$$

Combing Eq. 10, Eq. 11, Q_{PG} and q_{old2}, the EVB price could be expressed as

$$p_2 = C_n\delta_m\left(1 - \frac{\theta q_{EV1}(\lambda + \alpha\gamma(Q_{tyu} - \lambda)) + q_{n2} + (\lambda - 1)Q_{PG}}{M_{EV}}\right) \tag{12}$$

In this period, there are four parties in the CLSC, battery OEM, EBR and PGC and the government. Now, we discuss the profit these four parties. Firstly, in terms of OEM, the profit is the revenue of selling new batteries plus the revenue of selling the used batteries to the EBR minus the cost of buying battery materials then minus the battery manufacturing cost and minus the environment protection cost:

$$\pi_{oem2} = q_2(p_2 - c_{manu}) - q_{n2}(C_{envir} + c_{ntr}) - c_{ntr}q_{old2} + p_{collect2}q_{oldorl2} \tag{13}$$

The detailed formula can be seen in Eq. A.1 of Appendix A. Secondly, the profit for the EBR is the revenue of selling battery materials made from the used batteries to the OEM and plus the revenue of selling reusable batteries to the PGC minus the cost of purchasing the used batteries and minus the remanufacturing cost:

$$\pi_{ebr2} = q_{old2}(c_{ntr} - c_{remanu}) - p_{collect2}q_{oldorl2} - p_{dsc2}Q_{PG} + p_{su2}q_{su2} \tag{14}$$

Thirdly, the PGC's profit is the revenue in operating the batteries plus the revenue of selling the discarded batteries in period 1 and then minus the cost of buying the new batteries and reusable batteries plus the subsidy given by the government:

$$\pi_{pgc2} = p_{dsc2}Q_{PG} + Q_{PG}R_{engy} - p_2q_{PG2} - p_{su2}q_{su2} + q_{su2}s_{su2} \tag{15}$$

The detailed formula of π_{pgc2} can be seen in Eq. A.3 of Appendix A. And lastly, the government's profit can be thought as social welfare which is the profit of OEM, EBR and PGC then plus the environment protection charged from the OEM and minus the subsidy paid to the PGC:

$$\pi_{gvnmt} = \pi_{ebr2} + \pi_{oem2} + \pi_{pgc2} + C_{envir}q_{n2} - q_{su2}s_{su2} \tag{16}$$

The detailed formula of π_{gvnmt} can be seen in Eq. A.4 of Appendix A.

In order to promote RESC, we need to maximize the total profit for the EBR and PGC:

$$\begin{aligned}\pi_{re2} &= \pi_{ebr2} + \pi_{pgc2} \\ &= \left(\begin{array}{l} \frac{\alpha^2\gamma^2 C_n\delta_m\theta^2 q_{EV1}^2 Q_{tyu}(\lambda - Q_{tyu})}{M_{EV}}\gamma^2 \\ + \frac{\left(\begin{array}{l} \alpha\theta q_{EV1}(C_n\delta_m Q_{tyu}(M_{EV} - q_{n2} + 2Q_{PG}) \\ -C_n\delta_m\lambda(\theta q_{EV1}Q_{tyu} + Q_{PG}Q_{tyu} + Q_{PG}) \\ +\lambda M_{EV}(c_{remanu} - c_{ntr}) + \eta M_{EV} p_1 Q_{tyu}) \end{array} \right)}{M_{EV}}\gamma \\ +C_{re2} \end{array} \right)\end{aligned} \tag{17}$$

where C_{re2} is described in Eq. A.5. As can be seen, π_{re2} is a quadratic function on γ and we also have $0 \leq \gamma \leq 1$. When $(\lambda - Q_{tyu}) \neq 0$, it is easy to find that the equation of π_{re2} above has extreme value when

$$\gamma = K_1 = \frac{\left(\begin{array}{l} C_n\delta_m Q_{tyu}(M_{EV} - q_{n2} + 2Q_{PG}) - C_n\delta_m\lambda(\theta q_{EV1}Q_{tyu} + Q_{PG}Q_{tyu} + Q_{PG}) \\ +\lambda M_{EV}(c_{remanu} - c_{ntr}) + \eta M_{EV} p_1 Q_{tyu} \end{array} \right)}{2\alpha C_n\delta_m\theta q_{EV1}Q_{tyu}(Q_{tyu} - \lambda)} \tag{18}$$

As can be seen in Eq. 17 again, it is obvious that $\left(\frac{\alpha^2\gamma^2 C_n\delta_m\theta^2 q_{EV1}^2 Q_{tyu}}{M_{EV}}\right) > 0$. Therefore, based on quadratic function correlation properties, there are three possibilities for $(\lambda - Q_{tyu})$, which are $\lambda > Q_{tyu}$, $\lambda < Q_{tyu}$ and $\lambda = Q_{tyu}$, this can be considered as the relationship between used batteries remanufcaturing rate and average quality of reusable batteries. All these three relationships are discussed below.

1) Remanufacturing rate is greater than quality of reusable batteries ($\lambda > Q_{tyu}$):
   In this situation, π_{re2} has minimum value in the entire real number definition field. In order to achieve the maximum value in $\gamma^* \in [0,1]$, obviously, when $K_1 \leq \frac{1}{2}$, $\gamma^* = 1$, else when $K_1 > \frac{1}{2}$, $\gamma^* = 0$.
2) Quality of reusable batteries is greater than remanufacturing rate ($\lambda < Q_{tyu}$):
   In this situation, π_{re2} has maximum value in the entire real number definition domain. It is easy to find that, to achieve the maximum value in $\gamma^* \in [0,1]$ in this condition, if $K_1 \leq 0$,

$\gamma^* = 0$; else if $K_1 \geq 1$, $\gamma^* = 1$; else when $0 < K_1 < 1$, $\gamma^* = K_1$.

3) Quality of reusable batteries is equal to remanufacturing rate ($\lambda = Q_{tyu}$):

In this situation, π_{re2} is degenerated into

$$\pi_{re2} = \pi_{ebr2} + \pi_{pgc2}$$
$$= \left(\frac{\left(\begin{array}{l} \alpha\gamma\theta q_{EV1} Q_{tyu2} (C_n \delta_m (M_{EV} - q_{n2} + 2Q_{PG}) \\ -C_n \delta_m (\theta q_{EV1} Q_{tyu2} + Q_{PG} Q_{tyu2} + Q_{PG}) \\ +M_{EV} (c_{remanu} - c_{ntr}) + \eta M_{EV} p_1) \end{array} \right)}{M_{EV}} \gamma + \left(\begin{array}{l} \frac{\left(\begin{array}{l} Q_{tyu2} (\theta q_{EV1} + Q_{PG}) (C_n \delta_m Q_{PG} + c_{ntr} M_{EV} - c_{remanu} M_{EV}) \\ -C_n \delta_m Q_{PG} (M_{EV} - q_{n2} + Q_{PG}) + M_{EV} Q_{PG} R_{engy} \end{array} \right)}{M_{EV}} \\ -\frac{1}{2} \theta p_1 q_{EV1} (\alpha_H + \alpha_L) \end{array} \right) \right) \tag{19}$$

It is easy to find that $\frac{\alpha\gamma\theta q_{EV1} Q_{tyu2}}{4M_{EV}} > 0$. Therefore, we can conclude that if the formula $\left(\begin{array}{l} C_n \delta_m (M_{EV} - q_{n2} + 2Q_{PG}) + M_{EV} (c_{remanu} \\ -C_n \delta_m (\theta q_{EV1} Q_{tyu2} + Q_{PG} Q_{tyu2} + Q_{PG}) - c_{ntr}) + \eta M_{EV} p_1 \end{array} \right) < 0$, the optimal γ will be $\gamma^* = 0$, else, $\gamma^* = 1$.

Therefore, we are able to conclude two propositions below:

Proposition 1. If remanufacturing rate is greater or equal than quality of reusable batteries, the PGC will consider to use all the high-quality batteries for secondary use or use none of them.

Proposition 2. If remanufacturing rate is small than quality of reusable batteries, the PGC will consider to use all the high-quality batteries, or use none of them, or use a part of them for secondary use.

With propositions above, we can conclude that there are three possible values for γ^*, which are discussed in the following sub-sections below:

3.2.1. $\gamma^* = 0$

If $\gamma^* = 0$, the optimal choice for the RESC is that, no batteries will be sorted as reusable batteries. Therefore, all returned batteries will be recycled to material. Then π_{re2} can be expressed as

$$\pi_{re2} = \begin{pmatrix} \frac{C_n\delta_m Q_{PG}(\theta\lambda q_{EV1}+q_{n2}+(\lambda-1)Q_{PG})}{M_{EV}} - C_n\delta_m Q_{PG} \\ +\lambda(c_{ntr}-c_{remanu})(\theta q_{EV1}+Q_{PG}) \\ -\frac{1}{2}\theta p_1 q_{EV1}(\alpha_H+\alpha_L)+Q_{PG}R_{engy} \end{pmatrix} \tag{20}$$

With $\gamma^*=0$, π_{oem2} is updated to

$$\pi_{oem2} = \begin{pmatrix} -\frac{C_n\delta_m}{M_{EV}}q_{n2}^2 \\ +\begin{pmatrix} \frac{C_n\delta_m(M_{EV}-2\lambda(\theta q_{EV1}+Q_{PG})+Q_{PG})}{M_{EV}} \\ -C_{envir}-c_{manu}-c_{ntr} \end{pmatrix} q_{n2} \\ +C_{oem21} \end{pmatrix} \tag{21}$$

where C_{oem21} is described in Eq. A.6 of Appendix A. As $-\frac{C_n\delta_m}{M_{EV}}<0$, we have the maximum q_{n2}:

$$q_{n2}^* = \frac{\begin{pmatrix} -C_{envir}M_{EV}-c_{manu}M_{EV}+C_n\delta_m M_{EV}-2C_n\delta_m\theta\lambda q_{EV1} \\ -2C_n\delta_m\lambda Q_{PG}+C_n\delta_m Q_{PG}-c_{ntr}M_{EV} \end{pmatrix}}{2C_n\delta_m} \tag{22}$$

With $\gamma^*=0$ and q_{n2}^* above, the profit for the government is

$$\pi_{gvnmt} = \frac{1}{4}\begin{pmatrix} -\frac{C_{envir}^2 M_{EV}}{C_n\delta_m}-2C_{envir}Q_{PG}+\frac{c_{manu}^2 M_{EV}}{C_n\delta_m}+\frac{2c_{manu}c_{ntr}M_{EV}}{C_n\delta_m}-2c_{manu}(M_{EV}+2Q_{PG}) \\ +\frac{c_{ntr}^2 M_{EV}}{C_n\delta_m}+C_n\delta_m M_{EV}-\frac{C_n\delta_m Q_{PG}^2}{M_{EV}}+4\lambda(c_{ntr}-c_{remanu})(\theta q_{EV1}+Q_{PG}) \\ -2c_{ntr}M_{EV}-4c_{ntr}Q_{PG}+4Q_{PG}R_{engy} \end{pmatrix} \tag{23}$$

In this case, η is independent of the relevant parameters. And the government does not need to provide the subsidy to the supply chain.

3.2.2. $\gamma^*=1$

If $\gamma^*=1$, all high-quality batteries will be reused for the PGC as the optimal decision by the RESC. Therefore, all returned batteries will be recycled to material. And π_{re2} can be expressed as

$$\pi_{re2} = \begin{pmatrix} \alpha\theta p_1 q_{EV1}Q_{tyu}\eta \\ +\frac{C_n\delta_m(Q_{PG}-\alpha\theta q_{EV1}Q_{tyu})(\theta q_{EV1}(-\alpha\lambda+\lambda+\alpha Q_{tyu})+q_{n2}+(\lambda-1)Q_{PG})}{M_{EV}} \\ -C_n\delta_m Q_{PG}+\lambda(c_{ntr}-c_{remanu})(Q_{PG}-(\alpha-1)\theta q_{EV1}) \\ +Q_{PG}R_{engy}+\alpha C_n\delta_m\theta q_{EV1}Q_{tyu}-\frac{1}{2}\theta p_1 q_{EV1}(\alpha_H+\alpha_L) \end{pmatrix} \tag{24}$$

With $\gamma^* = 1$, π_{oem2} is updated to

$$\pi_{oem2} = \begin{pmatrix} -\frac{C_n\delta_m}{M_{EV}} q_{n2}^2 \\ + \frac{\begin{pmatrix} c_{manu}M_{EV} - C_n\delta_m M_{EV} + 2C_n\delta_m\lambda(\theta q_{EV1} - \alpha\theta q_{EV1} + Q_{PG}) \\ +C_{envir}M_{EV} + \alpha C_n\delta_m\theta q_{EV1}Q_{tyu} - C_n\delta_m Q_{PG} + c_{ntr}M_{EV} \end{pmatrix}}{M_{EV}} q_{n2} \\ +C_{oem22} \end{pmatrix} \tag{25}$$

where C_{oem22} is described in Eq. A.7 of Appendix A. As $-\frac{C_n\delta_m}{M_{EV}} < 0$, we have the optimal q_{n2}:

$$q_{n2}^* = \frac{\begin{pmatrix} -C_{envir}M_{EV} - c_{manu}M_{EV} + C_n\delta_m M_{EV} + 2\alpha C_n\delta_m\theta\lambda q_{EV1} - 2C_n\delta_m\theta\lambda q_{EV1} \\ -\alpha C_n\delta_m\theta q_{EV1}Q_{tyu} - 2C_n\delta_m\lambda Q_{PG} + C_n\delta_m Q_{PG} - c_{ntr}M_{EV} \end{pmatrix}}{2C_n\delta_m} \tag{26}$$

With $\gamma^* = 1$ and q_{n2}^* above, the profit for the government is

$$\pi_{gvnmt} = \frac{1}{4} \begin{pmatrix} -\frac{C_{envir}^2 M_{EV}}{C_n\delta_m} + 2\alpha C_{envir}\theta q_{EV1}Q_{tyu} - 2C_{envir}Q_{PG} + \frac{c_{manu}^2 M_{EV}}{C_n\delta_m} \\ +c_{manu}\left(M_{EV}\left(\frac{2c_{ntr}}{C_n\delta_m} - 2\right) + 4\alpha\theta q_{EV1}Q_{tyu} - 4Q_{PG}\right) + \frac{c_{ntr}^2 M_{EV}}{C_n\delta_m} \\ +C_n\delta_m M_{EV} + \frac{4M_{EV}Q_{PG}R_{engy} - C_n\delta_m(Q_{PG} - \alpha\theta q_{EV1}Q_{tyu})^2}{M_{EV}} \\ -2c_{ntr}(M_{EV} - 2\alpha\theta q_{EV1}Q_{tyu} + 2Q_{PG}) + 4c_{ntr}\lambda(Q_{PG} - (\alpha-1)\theta q_{EV1}) \\ -4c_{remanu}\lambda(Q_{PG} - (\alpha-1)\theta q_{EV1}) \end{pmatrix} \tag{27}$$

Then, as can be found in Eq. 24, the higher η, the more profit for the RESC, but it will not affect other parameters, e.g., the profit for the OEM (π_{oem2}), the quantity of batteries made from raw natural material (q_{n2}) and the profit for the government (π_{gvnmt}). In this case, the government still does not need to pay the subsidy to the supply chain.

3.2.3. $0 < \gamma^* < 1$

In this case, according to Eq. 17, the optimal γ^* will be achieved when $\frac{\pi_{re2}}{\partial\gamma} = 0$:

$$\gamma^* = \left(\frac{C_n\delta_m Q_{tyu}(M_{EV} - q_{n2} + 2Q_{PG}) - C_n\delta_m\lambda(\theta q_{EV1}Q_{tyu} + Q_{PG}Q_{tyu} + Q_{PG}) + \lambda M_{EV}(c_{remanu} - c_{ntr}) + \eta M_{EV}p_1Q_{tyu}}{2\alpha C_n\delta_m\theta q_{EV1}Q_{tyu}(Q_{tyu} - \lambda)} \right) \tag{28}$$

By substituting γ^* above, π_{oem2} can be expressed to:

$$\pi_{oem2} = \left(\begin{array}{l} \frac{C_n\delta_m(\lambda-2Q_{tyu})}{4M_{EV}(Q_{tyu}-\lambda)} q_{2n}^2 \\ + \frac{\left(\begin{array}{l} \lambda Q_{tyu}(M_{EV}(2C_{envir}+c_{manu}+2c_{ntr}-c_{remanu}+\eta p_1) \\ -2C_n\delta_m(\theta q_{EV1}Q_{tyu}+Q_{PG}(Q_{tyu}-1))) - M_{EV}Q_{tyu}^2(2C_{envir}+2c_{manu} \\ -C_n\delta_m+2c_{ntr}+\eta p_1)+\lambda^2(C_n\delta_m(\theta q_{EV1}Q_{tyu}+Q_{PG}(Q_{tyu}-1)) \\ -c_{ntr}M_{EV}+c_{remanu}M_{EV}) \end{array} \right)}{2M_{EV}Q_{tyu}(Q_{tyu}-\lambda)} q_{2n} \\ +C_{2oem} \end{array} \right) \tag{29}$$

Where C_{2oem} is shown in Eq. A.8. It is also easy to find that $\frac{C_n\delta_m(\lambda-2Q_{tyu})}{4M_{EV}(Q_{tyu}-\lambda)} < 0$. Therefore, the optimal q_{n2} is

$$q_{n2}^* = \frac{\left(\begin{array}{l} \lambda Q_{tyu}(M_{EV}(2C_{envir}+c_{manu}+2c_{ntr}-c_{remanu}+\eta p_1) \\ -2C_n\delta_m(\theta q_{EV1}Q_{tyu}+Q_{PG}(Q_{tyu}-1))) \\ -M_{EV}Q_{tyu}^2(2C_{envir}+2c_{manu}-C_n\delta_m+2c_{ntr}+\eta p_1) \\ +\lambda^2(C_n\delta_m(\theta q_{EV1}Q_{tyu}+Q_{PG}(Q_{tyu}-1))-c_{ntr}M_{EV}+c_{remanu}M_{EV}) \end{array} \right)}{C_n\delta_m Q_{tyu}(2Q_{tyu}-\lambda)} \tag{30}$$

Through substituting Eq. 30 into Eq. 28, γ^* can be updated to

$$\gamma^* = \frac{\left(\begin{array}{l} -\lambda Q_{tyu}(2C_{envir}M_{EV}+c_{manu}M_{EV}+C_n\delta_m M_{EV}+6C_n\delta_m Q_{PG}+4c_{ntr}M_{EV} \\ -3c_{remanu}M_{EV}+2\eta M_{EV}p_1)+Q_{tyu}^2(2C_{envir}M_{EV}+2c_{manu}M_{EV}+C_n\delta_m M_{EV} \\ +4C_n\delta_m Q_{PG}+2c_{ntr}M_{EV}+3\eta M_{EV}p_1)+2\lambda^2(C_n\delta_m Q_{PG}+c_{ntr}M_{EV}-c_{remanu}M_{EV}) \end{array} \right)}{2\alpha C_n\delta_m\theta q_{EV1}Q_{tyu}\left(\lambda^2+2Q_{tyu}^2-3\lambda Q_{tyu}\right)} \tag{31}$$

Now, we discuss the profit for the government. In this stage, the government will decide the optimal subsidy given to the PGC. We assume that the amount of subsidy is defined to $s_{su2} = \eta p_{su2}; 0 < \eta < 1$. With q_{n2}^* and γ^* in Eq. 30, Eq. 31 and C_{gvnmt} described in Eq. A.9, the profit for the government could be expressed to

$$\pi_{gvnmt} = \begin{pmatrix} -\frac{M_{EV} p_1^2 Q_{tyu}^2}{4C_n \delta_m (\lambda - 2Q_{tyu})^2} \eta^2 \\ + \frac{\begin{pmatrix} M_{EV} p_1 (\lambda Q_{tyu}^2 (-4C_{envir} - 7c_{manu} + C_n \delta_m - 12c_{ntr} + 5c_{remanu}) \\ + Q_{tyu}^3 (2C_{envir} + 6(c_{manu} + c_{ntr}) - C_n \delta_m) \\ + 2\lambda^2 Q_{tyu} (C_{envir} + c_{manu} + 4c_{ntr} - 3c_{remanu}) + 2\lambda^3 (c_{remanu} - c_{ntr})) \end{pmatrix}}{2C_n \delta_m (Q_{tyu} - \lambda)(\lambda - 2Q_{tyu})^2} \eta \\ + C_{gvnmt} \end{pmatrix} \quad (32)$$

As can be found $-\frac{M_{EV} p_1^2 Q_{tyu}^2}{4C_n \delta_m (\lambda - 2Q_{tyu})^2} < 0$. Therefore, maximum π_{gvnmt} is achieved when

$$\eta = \frac{\begin{pmatrix} \lambda Q_{tyu}^2 (-4C_{envir} - 7c_{manu} + C_n \delta_m - 12c_{ntr} + 5c_{remanu}) \\ + Q_{tyu}^3 (2C_{envir} + 6(c_{manu} + c_{ntr}) - C_n \delta_m) \\ + 2\lambda^2 Q_{tyu} (C_{envir} + c_{manu} + 4c_{ntr} - 3c_{remanu}) + 2\lambda^3 (c_{remanu} - c_{ntr}) \end{pmatrix}}{p_1 Q_{tyu}^2 (Q_{tyu} - \lambda)} \quad (33)$$

Here, η also satisfies the condition of $0 < \eta < S_L$. So we have the optimal γ^*:

$$\eta^* = \begin{cases} 0, & \eta \leq 0 \\ \eta, & 0 < \eta < S_L \\ S_L, & \eta \geq S_L \end{cases} \quad (34)$$

Therefore, q_{n2}^* can be updated to

$$q_{n2}^* = \begin{pmatrix} \frac{M_{EV} p_1}{2\alpha C_n \delta_m \theta q_{EV1} Q_{tyu} - 2\alpha C_n \delta_m \theta \lambda q_{EV1}} \eta \\ + \frac{C_n \delta_m (Q_{tyu}(M_{EV} - q_{n2} + 2Q_{PG}) - \lambda(\theta q_{EV1} Q_{tyu} + Q_{PG} Q_{tyu} + Q_{PG})) + \lambda M_{EV}(c_{remanu} - c_{ntr})}{2\alpha C_n \delta_m \theta q_{EV1} Q_{tyu} (Q_{tyu} - \lambda)} \end{pmatrix} \quad (35)$$

Then, with Eq. 28, we also have

$$\gamma^* = \begin{pmatrix} \frac{M_{EV} p_1}{2\alpha C_n \delta_m \theta q_{EV1} Q_{tyu} - 2\alpha C_n \delta_m \theta \lambda q_{EV1}} \eta - \frac{1}{2\alpha \theta q_{EV1} Q_{tyu} - 2\alpha \theta \lambda q_{EV1}} q_{n2} \\ - \frac{\begin{pmatrix} C_n \delta_m \theta \lambda q_{EV1} Q_{tyu} - C_n \delta_m M_{EV} Q_{tyu} + C_n \delta_m \lambda Q_{PG} \\ + C_n \delta_m \lambda Q_{PG} Q_{tyu} - 2C_n \delta_m Q_{PG} Q_{tyu} + c_{ntr} \lambda M_{EV} - c_{remanu} \lambda M_{EV} \end{pmatrix}}{2\alpha C_n \delta_m \theta q_{EV1} Q_{tyu}^2 - 2\alpha C_n \delta_m \theta \lambda q_{EV1} Q_{tyu}} \end{pmatrix} \quad (36)$$

To summarize, based on the backward induction, and with the basic preconditions $\lambda < Q_{tyu}$ and $0 < \gamma^* < 1$, the government first decides the subsidy. With Eq. 33 and Eq. 34, if $\eta \leq 0$, the government will not pay the subsidy ($\eta^* = 0$) and if $\eta \geq S_L$, the government will pay his maximum subsidy, that is $\eta^* = S_L$. Otherwise, the optimal subsidy for the government is $\eta^* = \eta$.

The optimal value of q_{n2}^* and γ^* for these three situations are described below:

1) The situation when $\eta^* = 0$

We have optimal quantity of batteries made by the OEM (q_{n2}^*) and the reusable batteries using rate γ^*

$$q_{n2}^* = \frac{\begin{pmatrix} \lambda Q_{tyu}(M_{EV}(2C_{envir} + c_{manu} + 2c_{ntr} - c_{remanu}) \\ -2C_n\delta_m(\theta q_{EV1}Q_{tyu} + Q_{PG}(Q_{tyu} - 1))) \\ +M_{EV}Q_{tyu}^2(C_n\delta_m - 2(C_{envir} + c_{manu} + c_{ntr})) \\ +\lambda^2(C_n\delta_m(\theta q_{EV1}Q_{tyu} + Q_{PG}(Q_{tyu} - 1)) - c_{ntr}M_{EV} + c_{remanu}M_{EV}) \end{pmatrix}}{C_n\delta_m Q_{tyu}(2Q_{tyu} - \lambda)} \tag{37}$$

and

$$\gamma^* = \frac{\begin{pmatrix} -\lambda Q_{tyu}(M_{EV}(2C_{envir} + c_{manu} + 4c_{ntr} - 3c_{remanu}) + C_n\delta_m(M_{EV} + 6Q_{PG})) \\ +Q_{tyu}^2(2M_{EV}(C_{envir} + c_{manu} + c_{ntr}) + C_n\delta_m(M_{EV} + 4Q_{PG})) \\ +2\lambda^2(C_n\delta_m Q_{PG} + c_{ntr}M_{EV} - c_{remanu}M_{EV}) \end{pmatrix}}{2\alpha C_n\delta_m\theta q_{EV1}Q_{tyu}\left(\lambda^2 + 2Q_{tyu}^2 - 3\lambda Q_{tyu}\right)} \tag{38}$$

2) The situation when $\eta^* = S_L$

We have optimal q_{n2}^* and optimal γ^*

$$q_{n2}^* = \frac{\begin{pmatrix} \lambda Q_{tyu}(M_{EV}(2C_{envir} + c_{manu} + 2c_{ntr} - c_{remanu} + p_1S_L) \\ -2C_n\delta_m(\theta q_{EV1}Q_{tyu} + Q_{PG}(Q_{tyu} - 1))) \\ -M_{EV}Q_{tyu}^2(2C_{envir} + 2c_{manu} - C_n\delta_m + 2c_{ntr} + p_1S_L) \\ +\lambda^2(C_n\delta_m(\theta q_{EV1}Q_{tyu} + Q_{PG}(Q_{tyu} - 1)) - c_{ntr}M_{EV} + c_{remanu}M_{EV}) \end{pmatrix}}{C_n\delta_m Q_{tyu}(2Q_{tyu} - \lambda)} \tag{39}$$

and

$$\gamma^* = \frac{\begin{pmatrix} -\lambda Q_{tyu}(M_{EV}(2C_{envir}+c_{manu}+4c_{ntr}-3c_{remanu}+2p_1S_L)+C_n\delta_m(M_{EV}+6Q_{PG})) \\ +Q_{tyu}^2(2M_{EV}(C_{envir}+c_{manu}+c_{ntr})+C_n\delta_m(M_{EV}+4Q_{PG})+3M_{EV}p_1S_L) \\ +2\lambda^2(C_n\delta_m Q_{PG}+c_{ntr}M_{EV}-c_{remanu}M_{EV}) \end{pmatrix}}{2\alpha C_n\delta_m\theta q_{EV1}Q_{tyu}\left(\lambda^2+2Q_{tyu}^2-3\lambda Q_{tyu}\right)} \tag{40}$$

3) The situation when $\eta^* = \eta$

We have optimal q_{n2}^* and γ^* as

$$q_{n2}^* = \frac{\begin{pmatrix} \lambda Q_{tyu}(M_{EV}(2C_{envir}+2c_{manu}+5c_{ntr}-3c_{remanu}) \\ +C_n\delta_m(-\theta q_{EV1}Q_{tyu}+Q_{PG}(-Q_{tyu})+Q_{PG})) \\ +M_{EV}Q_{tyu}^2(-2C_{envir}-4(c_{manu}+c_{ntr})+C_n\delta_m)+2\lambda^2M_{EV}(c_{remanu}-c_{ntr}) \end{pmatrix}}{C_n\delta_m Q_{tyu}^2} \tag{41}$$

and

$$\gamma^* = \frac{\begin{pmatrix} \lambda Q_{tyu}^2(C_n\delta_m(M_{EV}-4Q_{PG})-M_{EV}(8C_{envir}+13c_{manu}+22c_{ntr}-9c_{remanu})) \\ +2\lambda^2Q_{tyu}(2M_{EV}(C_{envir}+c_{manu}+4c_{ntr}-3c_{remanu})+C_n\delta_m Q_{PG}) \\ +Q_{tyu}^3(4C_{envir}M_{EV}+10M_{EV}(c_{manu}+c_{ntr})-C_n\delta_m(M_{EV}-2Q_{PG})) \\ +4\lambda^3M_{EV}(c_{remanu}-c_{ntr}) \end{pmatrix}}{2\alpha C_n\delta_m\theta q_{EV1}Q_{tyu}^2(Q_{tyu}-\lambda)^2} \tag{42}$$

4. Numerical experiment, analysis and discussion

As can be concluded from Section 3, the relationship among α, α_H and λ is crucial for SC and government decision-making. We will mainly discuss the relationship that remanufacturing rate is lower than the quality of reusable batteries ($\lambda < Q_{tyu}$). We list all initial values regarding all input parameters in Table 2 below. Initial values involving money are measured in pound sterling (£).

Table 2: Initial values of notations

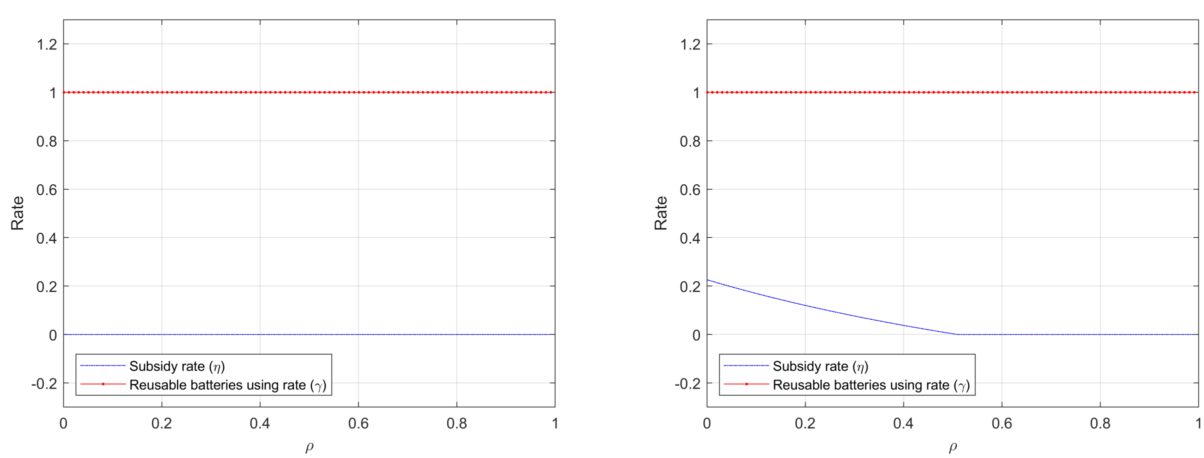
$\theta = 0.6$	$\delta_m = 0.3$	$\lambda = 0.7$	$N_d = 5$	$M_{EV} = 1000000$
$R_{engy} = 5$	$c_{ntr} = 3000$	$c_{manu} = 1500$	$c_{remanu} = 1000$	$C_{envir} = 250$
$C_n = 100000$	$Q_{PG} = 20000$	$\alpha_H = 0.85$	$\alpha_L = 0.55$	$\alpha = 0.6$
$S_L = 0.5$	$\rho = 0.3$			

Among, specifically, parameters related to supply chain battery manufacturing (i.e., θ, α, λ, N_d, c_{ntr}, c_{manu}, c_{remanu}, C_{envir}, M_{EV}, C_n, etc.) are referenced from Lambert (2019); International Energy Agency (2019); Gu et al. (2018), some parameters about batteries return, secondary use and remanufacturing (c_{remanu}, Q_{PG}, ρ) are based on research or report of Richa et al. (2014); International Energy Agency (2020). Furthermore, we assume the ceiling of government subsidy is $S_L = 0.5$, which means that the maximum subsidy that government pays to the RESC is half of price of used batteries bought by the secondary user. On the basis of McIntire-Strasburg (2015), we set the quality of returned batteries is between $\alpha_L = 0.55$ and $\alpha_H = 0.85$.

With the initial values above and Eq. 5, 6 and 7, we have $p_1 = 20250$, $q_1 = q_{n1} = 525000$ and $q_{EV1} = 325000$ in period 1.

In period 2, with $\alpha = 0.6$ and Eq. 34, we have the optimal $\eta^* = 0.0763$, which means that the optimal subsidy is $s^*_{su2} = 1248.4$. In this case, the PGC will use all the reusable batteries, that is $\gamma^* = 1$. Additionally, the quantity of new batteries made by the raw natural material is $q_{n2} = 627640$, and the quantity of new batteries made by the used batteries is $q_{old2} = 194600$ calculated Eq. 10, Eq. 11 and Eq. 12. Therefore, the total quantity is $q_2 = 822240$ and the battery selling price is $p_2 = 8496.8$.

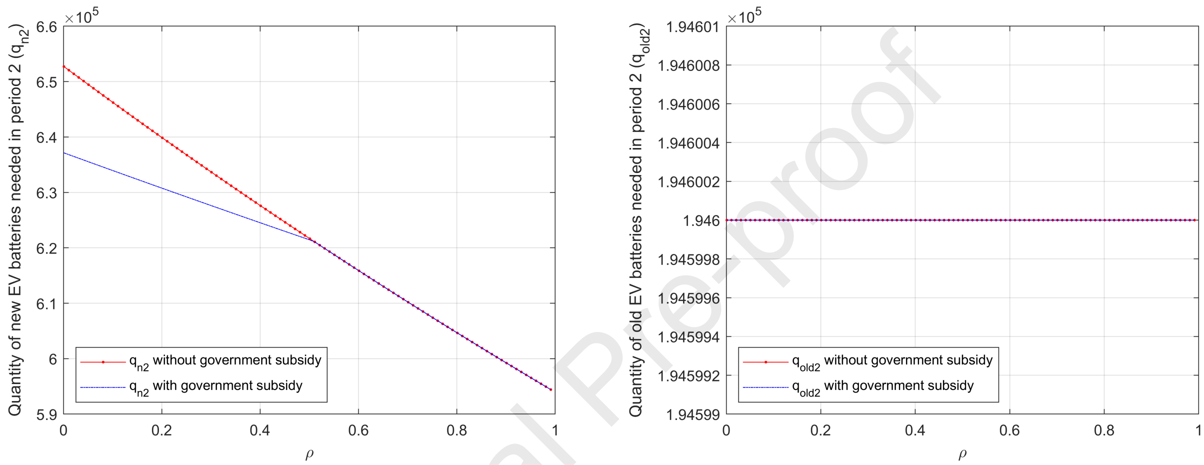
Now we are able to discuss the relationship between used batteries' quality by clearing the initialization of $\rho = 0.3$ in Table 2. We illustrate the relationship between α and η and the relationship between ρ and γ in Fig. 2, the relationship between ρ and (re)manufacturing quantity in Fig. 3, the relationship between ρ and p_2 and the relationship between ρ and π_{gvnmt} in Fig. 4 and 5.



(a) Without government subsidy (b) With government subsidy

Fig. 2: Relationship between ρ and η,γ

Fig. 2 shows the relationship between ρ, subsidy rate η and reusable battery using rate γ. Fig 2(a) shows optimal η and γ if the government does not provide the subsidy and Fig. 2(b) shows optimal η and γ if government provides the subsidy to the SC. Regardless of whether the government subsidizes the SC or not, the PGC will use all the high-quality batteries for secondary use ($\gamma = 1$). Meanwhile, in the case of the government subsidizing the SC, to achieve the maximum social welfare, when $\rho < 0.51$, the government should pay the subsidy. When $\rho \geq 0.51$, the government does not need to provide subsidies to the SC.

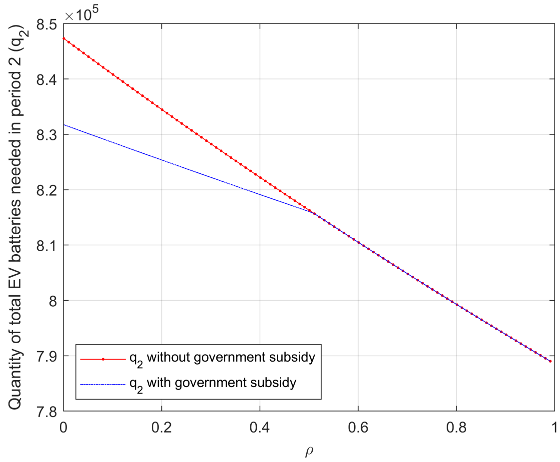


(a) Without government subsidy (b) With government subsidy

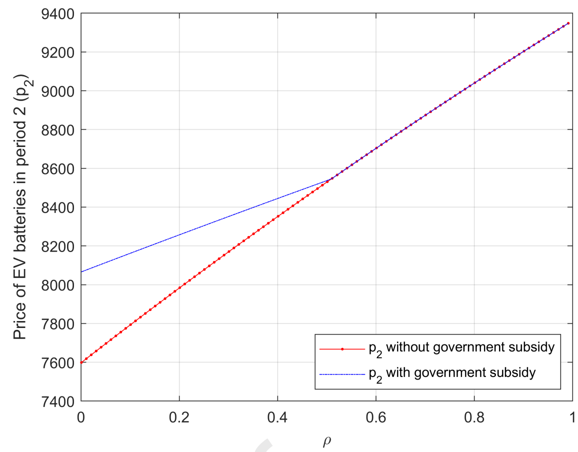
Fig. 3: Relationship between ρ and q_{n2}, q_{old2}

Now, it seems that it does not matter to SC whether the government provides subsidy or not. As can be seen in Fig. 3(a), when $\rho < 0.51$, with the increasing ρ, provision of optimal subsidy will decrease the quantity of new batteries made by the natural raw materials (q_{n2}). And in this case, the optimal q_{n2} is smaller when subsidy is given than when it is not. Moreover, as the optimal γ^* is fixed at 1, whatever the value ρ takes, q_{old2} is fixed in this discussion.

Since the overall market demand, q_2, equals the sum of q_{n2} and q_{old2}, the overall market demand will also decrease. When $\rho < 0.51$, q_2 is also smaller with subsidy than without subsidy as can be seen in Fig. 4(a). Contrary to q_2, the price of batteries in period 2, p_2, is higher with subsidy than without subsidy, which is shown in Fig. 4(b).



(a) Without government subsidy



(b) With government subsidy

Fig. 4: Relationship between ρ and q_2, p_2

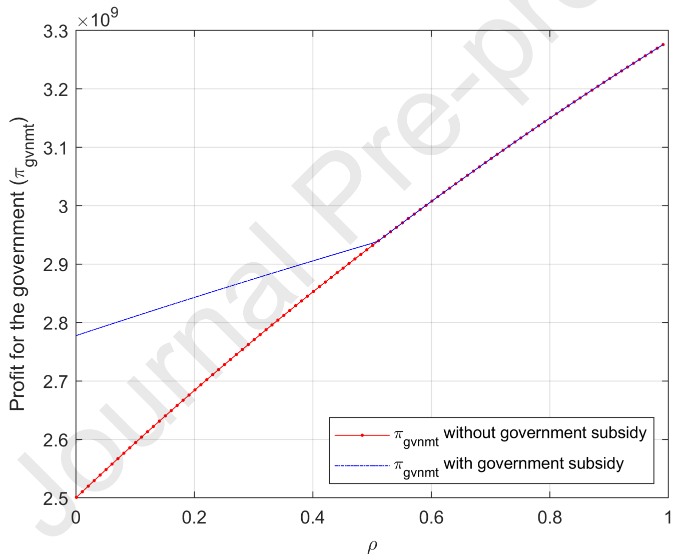
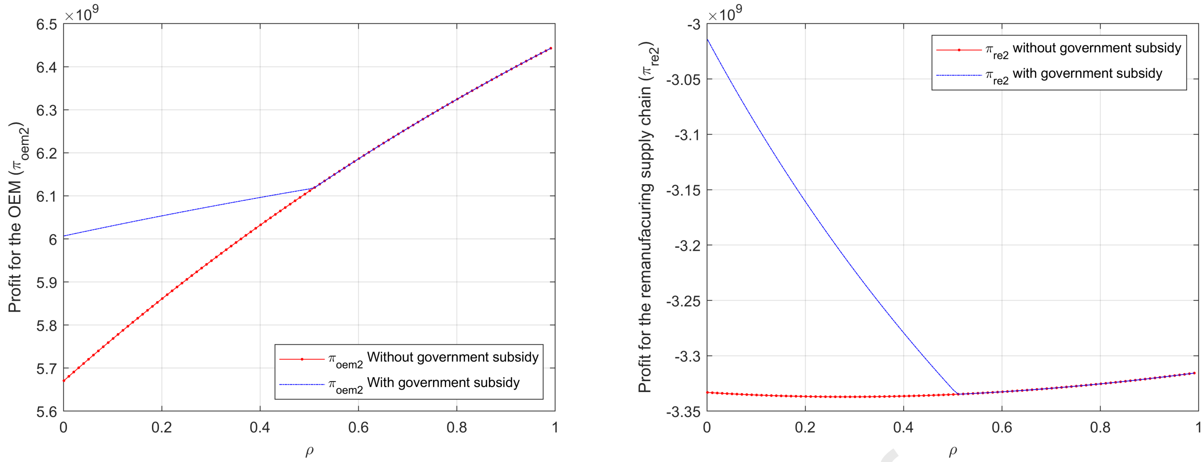


Fig. 5: Relationship between ρ and π_{gvnmt}

Regarding to the profit for the government π_{gvnmt} (also be considered as the social welfare) shown in Fig 5, with paying the subsidy ($\rho < 0.51$), the profit is higher. Also, with the increasing ρ, π_{gvnmt} is increasing no matter providing the subsidy or not.



(a) Profit for the OEM (b) Profit for the RESC

Fig. 6: Relationship between ρ and π_{oem2}, π_{re2}

Based on the premise of maximizing the welfare of society (π_{gvnmt}) as a whole in 5 before, we now observe the profit for the OEM and RESC (including PGC and EBR) separately. As can be seen in Fig. 6(a) and 6(b), with subsidies, profits for OEM and RESE are greater or equal than without. With the increasing quality of reused batteries (ρ), the profit for the OEM is increasing as well. The profit for the RESC is negative at all times. When $\rho < 0.51$, the profit is decreasing rapidly in the case that without subsidy. Then, when $\rho > 0.51$, the government will not provide the subsidy and the profit is slowly increasing. Thus, we can argue that providing subsidies is good for OEMs when ρ is small, but not for the RESC.

Therefore, to summarize this numerical experiment, with the target to achieve the maximum total profit of SC in period 2, the government need to pay the subsidy when the quality of reused batteries is low ($\rho < 0.51$) and the optimal subsidy ratio can be found in Fig. 2(b). With the provision of subsidy, the profits for the whold CLSC, OEM and RESC are all higher than without the subsidy, as well as the battery price. But the quantity demand of batteries (q_2) would decrease, if subsidies were provided. Furthermore, with the increasing ρ, which is the quality of reused batteries, new batteries made by the raw natural materials is decreasing but the new battery price is increasing . The profit for the government and the profit for the OEM are increasing, too.

5. Conclusions

In this study, we propose a two-period electric vehicle battery closed-loop supply chain model to describe the processes of EVB manufacturing, return, sorting, secondary use and remanufacturing process. Different from other products, EVBs should be disassembled from EVs when their capacity falls to 70%∼80%. But they can be reused for other purposes. Unlike existing studies, this research article discusses the situation and conditions regarding the proportion of returned batteries that are secondary used for other purposes as well as the government optimal incentive policy for the supply chain.

The main conclusions are summarized below:

(1) Based on the different relationships between the quality of reused batteries (Q_{tyu}) and the remanufacturing rate for recycled batteries (λ), government will choose to subsidize or not subsidize the RESC. When the quality of reusable batteries is lower than the discarded battery remanufacturing rate, the government does not need to subsidize. Otherwise, the government will consider subsidizing the RESC. Based on the parameters in Eq. 33, if $\eta \leq 0$, a subsidy is not needed; otherwise, a subsidy is necessary. Based on Eq. 34, the government will find the optimal subsidy amount.

(2) The secondary user, PGC, has three options: (i) accept all high-quality used batteries for secondary use; (ii) refuse all high-quality batteries; or (iii) accept a portion of high-quality used batteries. We also discuss and provide the range of these three different conditions by mathematical expressions. Under the condition that the quality of reusable batteries is smaller than the used battery remanufacturing rate, the PGC will go for option (i) or (ii), which depends on Eq. 18. Otherwise, the PGC will have 3 options for battery secondary use depending on Eq. 18 as well.

(3) With a numerical case study as an experiment, we have discussed the optimal decisions by the OEM, PGC and EBR. The optimal subsidy paid by the government is also given. Moreover, analysis of trends for ρ, η and decision parameters are discussed. As seen, with lower ρ, government subsidy to the RESC will increase the EV battery price and decrease the demand for the EVBs. In addition, we have a counter-intuitive finding here, that is, with the government subsidy, high quality of reusable batteries will detriment the profit of RESC.

This study extends the research area related to the CLSC of EV and EV batteries and fills relevant gaps. It is also useful for entities within the CLSC to better understand the relationships among them in order to make better decisions. However, we did not consider the potential environmental impact of used EVB remanufacturing and secondary use, which will be one of our future research directions.

Funding

This research is funded by project supported by the National Science Foundation (Grant No. 71901121, 71972101, 71931006, 72071113); and Support by Fundamental Research Funds for the Central Universities (Grant No. 30919013202)

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Appendix A. Related expressions

1) π_{oem2} in Eq. 13

$$\pi_{oem2} = \left(\begin{array}{l} -\frac{\left(\begin{array}{l} (\lambda(\theta q_{EV1}(1-\alpha\gamma)+Q_{PG})+q_{n2})(c_{manu}M_{EV} \\ +C_n\delta_m(-M_{EV}+\theta q_{EV1}(\lambda+\alpha\gamma(Q_{tyu}-\lambda)) \\ +q_{n2}+(\lambda-1)Q_{PG})+c_{ntr}M_{EV}) \end{array} \right)}{M_{EV}} \\ -C_{envir}q_{n2}+\frac{1}{2}\theta p_1 q_{EV1}(\alpha_H+\alpha_L) \end{array} \right) \tag{A.1}$$

2) π_{ebr2} in Eq. 14

$$\pi_{ebr2} = \left(\begin{array}{l} \lambda(c_{ntr}-c_{remanu})(-\alpha\gamma\theta q_{EV1}+\theta q_{EV1}+Q_{PG}) \\ -\frac{p_1 Q_{PG}}{N_d}-\frac{1}{2}\theta p_1 q_{EV1}(\alpha_H+\alpha_L-2\alpha\gamma Q_{tyu}) \end{array} \right) \tag{A.2}$$

3) π_{pgc2} in Eq. 15

$$\pi_{pgc2} = \left(\begin{array}{l} \frac{C_n\delta_m(Q_{PG}-\alpha\gamma\theta q_{EV1}Q_{tyu})(-M_{EV}+\theta q_{EV1}(\lambda+\alpha\gamma(Q_{tyu}-\lambda))+q_{n2}+(\lambda-1)Q_{PG})}{M_{EV}} \\ +\frac{p_1 Q_{PG}}{N_d}+\alpha\gamma\eta\theta p_1 q_{EV1}Q_{tyu}-\alpha\gamma\theta p_1 q_{EV1}Q_{tyu}+Q_{PG}R_{engy} \end{array} \right) \tag{A.3}$$

4) π_{gvnmt} in Eq. 16

$$\pi_{gvnmt} = \left(\begin{array}{l} \frac{\left(\begin{array}{l} -c_{manu}M_{EV}(\lambda(-\alpha\gamma\theta q_{EV1}+\theta q_{EV1}+Q_{PG})+q_{n2}) \\ +\lambda(\theta q_{EV1}(1-\alpha\gamma)+Q_{PG})(C_n\delta_m(M_{EV}-2\alpha\gamma\theta q_{EV1}Q_{tyu}-2q_{n2}+2Q_{PG}) \\ -c_{remanu}M_{EV})+C_n\delta_m(\alpha\gamma\theta q_{EV1}Q_{tyu}+q_{n2}-Q_{PG})(M_{EV}-\alpha\gamma\theta q_{EV1}Q_{tyu} \\ -q_{n2}+Q_{PG})-C_n\delta_m\lambda^2(\theta q_{EV1}(1-\alpha\gamma)+Q_{PG})^2-c_{ntr}M_{EV}q_{n2} \end{array} \right)}{M_{EV}} \\ +Q_{PG}R_{engy} \end{array} \right) \tag{A.4}$$

5) C_{re2} in Eq. 17

$$C_{re2} = \begin{pmatrix} -\frac{1}{2}\theta p_1 q_{EV1}(\alpha_H + \alpha_L) \\ + \frac{\begin{pmatrix} \lambda(\theta q_{EV1} + Q_{PG})(C_n\delta_m Q_{PG} + c_{ntr}M_{EV} - c_{remanu}M_{EV}) \\ -C_n\delta_m Q_{PG}(M_{EV} - q_{n2} + Q_{PG}) + M_{EV}Q_{PG}R_{engy} \end{pmatrix}}{M_{EV}} \end{pmatrix} \tag{A.5}$$

6) C_{oem21} in Eq. 21

$$C_{oem21} = \begin{pmatrix} \frac{1}{2}\theta p_1 q_{EV1}(\alpha_H + \alpha_L) \\ -\frac{\lambda(\theta q_{EV1}+Q_{PG})(c_{manu}M_{EV} - C_n\delta_m(M_{EV}+Q_{PG}) + C_n\delta_m\lambda(\theta q_{EV1}+Q_{PG}) + c_{ntr}M_{EV})}{M_{EV}} \end{pmatrix} \tag{A.6}$$

7) C_{oem22} in Eq. 25

$$C_{oem22} = \frac{\begin{pmatrix} -2\lambda(Q_{PG} - (\alpha-1)\theta q_{EV1})(c_{manu}M_{EV} - C_n\delta_m(M_{EV} - \alpha\theta q_{EV1}Q_{tyu} + Q_{PG}) \\ +c_{ntr}M_{EV}) - 2C_n\delta_m\lambda^2(Q_{PG} - (\alpha-1)\theta q_{EV1})^2 + \theta M_{EV}p_1 q_{EV1}(\alpha_H + \alpha_L) \end{pmatrix}}{2M_{EV}} \tag{A.7}$$

8) C_{2oem} in Eq. 29

$$C_{2oem} = \frac{\begin{pmatrix} 2C_n\delta_m M_{EV}(\lambda(\lambda Q_{tyu}(c_{manu} + 2c_{ntr} - c_{remanu})(\theta q_{EV1}Q_{tyu} + Q_{PG}(Q_{tyu}-1)) \\ +Q_{tyu}^2(c_{manu} + c_{ntr})(M_{EV} - 2\theta q_{EV1}Q_{tyu} - 2Q_{PG}Q_{tyu} + 2Q_{PG}) \\ -\lambda^2(c_{ntr} - c_{remanu})(\theta q_{EV1}Q_{tyu} + Q_{PG}(Q_{tyu}-1))) + p_1 Q_{tyu}(Q_{tyu} - \lambda) \\ \cdot(-\eta\lambda Q_{tyu}(\theta q_{EV1} + Q_{PG}) + \theta q_{EV1}Q_{tyu}(\alpha_H + \alpha_L) + \eta\lambda Q_{PG})) \\ +\lambda M_{EV}^2(\lambda(c_{remanu} - c_{ntr}) + \eta p_1 Q_{tyu})(2c_{manu}Q_{tyu} - c_{ntr}\lambda + 2c_{ntr}Q_{tyu} \\ +c_{remanu}\lambda + \eta p_1 Q_{tyu}) - C_n^2\delta_m^2\lambda(M_{EV}Q_{tyu} - (2Q_{tyu} - \lambda)(\theta q_{EV1}Q_{tyu} \\ +Q_{PG}(Q_{tyu}-1)))(Q_{tyu}(M_{EV} - \lambda(\theta q_{EV1} + Q_{PG})) + \lambda Q_{PG}) \end{pmatrix}}{4C_n\delta_m M_{EV}Q_{tyu}^2(Q_{tyu} - \lambda)} \tag{A.8}$$

9) C_{gvnmt} in Eq. 32

$$C_{gvnmt} = \frac{\left(\begin{array}{l} -4C_{envir}^2 M_{EV} Q_{tyu}(Q_{tyu}-\lambda)^3 + 4C_{envir} M_{EV} Q_{tyu}(Q_{tyu}-\lambda) \\ \cdot(-\lambda Q_{tyu}(c_{manu}+C_n\delta_m+4c_{ntr}-3c_{remanu})+Q_{tyu}^2(2(c_{manu}+c_{ntr}) \\ +C_n\delta_m)+2\lambda^2(c_{ntr}-c_{remanu}))+\lambda^2 Q_{tyu}^2(7c_{manu}^2 M_{EV}+2c_{manu}M_{EV} \\ \cdot(-4C_n\delta_m+18c_{ntr}-11c_{remanu})+5C_n^2\delta_m^2 M_{EV}-4c_{ntr}(C_n\delta_m(M_{EV} \\ +8\theta q_{EV1}Q_{tyu}+8Q_{PG}(Q_{tyu}-1))+11c_{remanu}M_{EV})-4C_n c_{remanu}\delta_m M_{EV} \\ +32C_n c_{remanu}\delta_m\theta q_{EV1}Q_{tyu}-32C_n c_{remanu}\delta_m Q_{PG}+32C_n c_{remanu}\delta_m Q_{PG}Q_{tyu} \\ +20C_n\delta_m Q_{PG}R_{engy}+40c_{ntr}^2 M_{EV}+11c_{remanu}^2 M_{EV}) \\ +\lambda^3 Q_{tyu}(-c_{manu}^2 M_{EV}+2c_{manu}M_{EV}(C_n\delta_m-4c_{ntr}+3c_{remanu}) \\ -C_n^2\delta_m^2 M_{EV}+4c_{ntr}(5C_n\delta_m(\theta q_{EV1}Q_{tyu}+Q_{PG}(Q_{tyu}-1))+8c_{remanu}M_{EV}) \\ +2C_n c_{remanu}\delta_m M_{EV}-20C_n c_{remanu}\delta_m\theta q_{EV1}Q_{tyu}+20C_n c_{remanu}\delta_m Q_{PG} \\ -20C_n c_{remanu}\delta_m Q_{PG}Q_{tyu}-4C_n\delta_m Q_{PG}R_{engy}-20c_{ntr}^2 M_{EV}-13c_{remanu}^2 M_{EV}) \\ +\lambda Q_{tyu}^3(-16c_{manu}^2 M_{EV}+2c_{manu}M_{EV}(5C_n\delta_m-26c_{ntr}+10c_{remanu}) \\ +4c_{ntr}(2C_n\delta_m(M_{EV}+2\theta q_{EV1}Q_{tyu}+2Q_{PG}(Q_{tyu}-1))+5c_{remanu}M_{EV}) \\ -C_n\delta_m(7C_n\delta_m M_{EV}-2c_{remanu}(M_{EV}-8\theta q_{EV1}Q_{tyu}-8Q_{PG}Q_{tyu}+8Q_{PG}) \\ +32Q_{PG}R_{engy})-36c_{ntr}^2 M_{EV})+Q_{tyu}^4(-4C_n\delta_m(M_{EV}(c_{manu}+c_{ntr})-4Q_{PG}R_{engy}) \\ +12M_{EV}(c_{manu}+c_{ntr})^2+3C_n^2\delta_m^2 M_{EV})+4\lambda^4(c_{ntr}-c_{remanu})(C_n\delta_m(-\theta q_{EV1}Q_{tyu} \\ +Q_{PG}(-Q_{tyu})+Q_{PG})+c_{ntr}M_{EV}-c_{remanu}M_{EV}) \end{array}\right)}{4C_n\delta_m Q_{tyu}(Q_{tyu}-\lambda)(\lambda-2Q_{tyu})^2} \quad \text{(A.9)}$$

Appendix B. Proof for Q_{tyu}

Q_{tyu} is defined as the quality of secondary usable batteries. Based on the model description and Fig. 1 and schematic diagram below, with the quality demarcation between low-quality and high-quality batteries, α $(0 \le \alpha \le 1)$, the quality of high-quality batteries is in $[\alpha_L + \alpha(\alpha_H - \alpha_L), \alpha_H]$. So the average quality of high-quality batteries is $\frac{1}{2}(\alpha_L + \alpha(\alpha_H - \alpha_L) + \alpha_H)$. If normalized this interval to $[0,1]$, and with the quality demarcation between high-quality and secondary usable batteries (ρ; $0 \le \rho \le 1$), we have the lowest quality of secondary usable batteries is $\alpha_L + \alpha(\alpha_H - \alpha_L) + \rho(\alpha_H - (\alpha_L + \alpha(\alpha_H - \alpha_L)))$. And the quality of secondary usable batteries is in $[\alpha_L + \alpha(\alpha_H - \alpha_L) + \rho(\alpha_H - (\alpha_L + \alpha(\alpha_H - \alpha_L))), \alpha_H]$. Therefore, the average quality of secondary usable batteries is $Q_{tyu} = \frac{\alpha_L+\alpha(\alpha_H-\alpha_L)+\rho(\alpha_H-(\alpha_L+\alpha(\alpha_H-\alpha_L)))+\alpha_H}{2} = \frac{1}{2}(\alpha_H(\alpha+\rho-\alpha\rho+1)+(\alpha-1)\alpha_L(\rho-1))$.

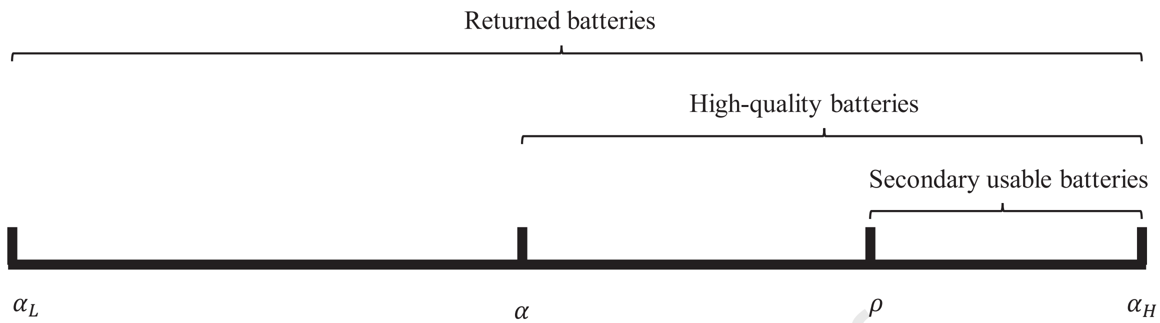

Fig. B.7: Schematic diagram of returned batteries' quality