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Yuki Yoneda, Etsuko Kusakawa

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Yuki Yoneda

Department of Electrical and Electronic Engineering,
College of Engineering,
Osaka Prefecture University,
Sakai, Osaka, 599-8531, Japan
Email: yuki.yoneda.opu@gmail.com

Etsuko Kusakawa*

Department of Electrical and Electronic Engineering,
College of Engineering,
Osaka Metropolitan University,
Sakai, Osaka, 599-8531, Japan
Email: n21119c@omu.ac.jp
*Corresponding author

Abstract: This paper proposes the optimal operation of a two-period closed-loop supply chain (CLSC) considering quality of used batteries, their secondary use and recycling into materials, and government subsidy for: 1) secondary use (model I); 2) collection and dismantling of used batteries (model II); 3) makes social welfare (SW) evaluation for the optimal operation in CLSC (model III). First period involves production and sales of new EV battery. Second period does secondary use and recycling of used batteries with quality classifications: high, medium and low. CLSC consists of a battery manufacturer (Stackelberg leader), a third party, a power grid company, and a vehicle manufacturer. Numerical analysis compares the optimal operation and SW for each model. Sensitivity analysis clarifies how collection rate, quality classification and recycling rate of used batteries and each government subsidy affect the optimal operation and SW in CLSC.

Keywords: closed-loop supply chain; CLSC; secondary use of electric vehicle batteries; remanufacturing; government subsidy; social welfare.

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Biographical notes: Yuki Yoneda earned his Master's in Electrical and Electronic Engineering in 2022 from Osaka Prefecture University, Japan. His research interest is supply chain management including green closed-loop supply chain.

Etsuko Kusakawa is an Associate Professor at the Course of Electrical and Electronic Engineering, College of Engineering in Osaka Metropolitan University, Japan. She earned her PhD in Industrial Engineering in 2001 from Osaka Prefecture University in Japan. Her research interests are supply chain management including closed-loop supply chain, green supply chain, dual supply chain, food supply chain and quality control. She is the corresponding author of this paper. She has published research articles in *Industrial Engineering & Management System* and *International Journal of E-Business Development*.

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1 Introduction

Since the industrial revolution, the increase in greenhouse gas emissions has caused climate change, with serious consequences worldwide (Krass et al., 2013; Hong and Guo, 2019; Ding et al., 2020; Gong et al., 2020; Gu et al., 2021). Pollutants contaminate the water and air environment, and the unplanned consumption of mineral and energy resources not only destroys the environment but also sometimes causes conflicts due to competition. In order to cope with resource depletion and disposal problems, companies need to collect used products, recycle them into parts, etc. and reuse them in product manufacturing, etc. (He et al., 2019; Wang et al., 2019; Gu et al., 2021).

In addition, carbon neutrality is a global issue (Krass et al., 2013; Xiong et al., 2016; Yi and Li, 2018). The electrification of automobiles is considered essential for reducing CO₂ emissions in the transportation sector (Ding et al., 2020; Gong et al., 2020; Gu et al., 2021). In recent years, with the spread of electric vehicles, it has become necessary to make effective use of used batteries, and secondary use (Gu et al., 2021) of used batteries and use of recycled resources (Ding et al., 2020; Gong et al., 2020). Currently, 4R Energy Corporation (<https://www.4r-energy.com/>) is one of the companies in Japan that disassembles used EV batteries for secondary use. Used EV batteries can be disassembled, inspected, and classified by quality for secondary use, as they have the capacity to store 60–80% of the power of a new battery (Gu et al., 2021). They are classified into three types according to quality: electric vehicle batteries, storage batteries, and materials (Gu et al., 2021). VOLTA Corporation (<https://www.env-volta.jp/>) is one of the companies in Japan that is currently recycling used lithium-ion batteries, such as those used in electric vehicles. Although used batteries are often incinerated, the company collects cobalt, nickel, and lithium from used batteries and sells them.

Based on the above research background, this paper discusses the optimal operation of a two-period closed-loop supply chain (CLSC) consisting of first period to produce and sell new batteries for electric vehicles and second period to make secondary use and recycling of used batteries. When considering the optimal operation of such a two-period CLSC, the following questions may be raised by planners and researchers for the construction and the decision-making of the optimal operation of a two-period CLSC:

- RQ1 How are used batteries classified in terms of quality?
- RQ2 When used batteries are classified as high-quality, medium-quality and low-quality, how do these classifications affect the quantity of secondary use of medium-quality batteries and the quantity recycled into materials?
- RQ3 How does the classification of used batteries into high-quality, medium-quality and low-quality affect the profits of a battery manufacturer, a third party, a power grid company and a vehicle manufacturer and social welfare (SW)?
- RQ4 How do government subsidies for the sale of reusable batteries, the purchase of reusable batteries, and the collection and dismantling of used batteries affect the optimal decision for the secondary use rate, the profit of each member, and SW in a CLSC?

In order to solve the above problems from RQ1 to RQ4, this paper presents the optimal operation of a two-period CLSC consisting of first period to produce and sell new batteries for electric vehicles and second period to reuse used batteries, considering the quality classification of used batteries, recovery of batteries from the government, disassembly, and government subsidies for the purchase and sale. This paper considers the following three government subsidy models. This paper considers the following three subsidy models by the government. Model I where the government gives a subsidy η only to a power grid company who purchases secondary use batteries. Model II where the government gives subsidies $(\delta_c, \delta_d, \eta_{th})$ to a third party who collects, dismantles, and sells secondary use of used batteries. Model III where the government gives a subsidy η to a power grid company who purchases secondary use batteries, and subsidies $\eta, \delta_c, \delta_d, \eta_{th}$ to a third party who collects dismantles used batteries, and sells secondary use batteries.

In the two-period CLSC, this paper also classifies the quality of used batteries and consider a two-period CLSC where high-quality batteries are sold as electric vehicle batteries, medium-quality batteries are sold as batteries for power storage, and low-quality batteries are sold as recycled materials.

In this paper, based on Gu et al. (2021), in models I–III in the second period, a battery manufacturer pays the environmental pollution cost to the government for the batteries quantity manufactured using new materials, and this cost is the government revenue.

As the optimal operation of the two-period CLSC, in the first period, the battery manufacturer determines the optimal price p_1 of the battery in the first period. In the second period, a third party is the Stackelberg leader and a battery manufacturer is the Stackelberg follower. As to Models I–III, the third party determines the optimal secondary use rate γ of medium-quality batteries, and the battery manufacturer determines the optimal battery price p_2 in the second period using the backward induction method which is the decision method in Stackelberg game model (Yi and Li, 2018). This paper evaluates the optimal operation of CLSC only in the second period using SW (Krass et al., 2013; Nielsen et al., 2019; Xue et al., 2019; Hong and Guo, 2019; He et al., 2019; Wang et al., 2019; Liu and Xiao, 2020) as social evaluation. The evaluation of SW in the second period includes the total profit of CLSC as the sum of the profits of a battery manufacturer, a third party, a power grid company and a vehicle manufacturer, consumers surplus and the environmental impact (EI) in the period.

Table 1 The comparison of the contributions of this paper with those of previous papers

Assumption Authors	CLSC model						Stackelberg		Social welfare		
	Collection of used batteries	Dismantling	Recycling	Secondary use	Quality classification	Government subsidy		game model	Profit of CLSC members	Consumer surplus	Environmental impact
						Collection	Dismantling				
Ding et al. (2020)	✓	✓	✓			✓	✓	✓	✓	✓	✓
Gong et al. (2020)	✓	✓	✓		High		✓	✓			
Gu et al. (2021)					Low			✓			
This paper	✓	✓	✓	✓	High		✓	✓	✓	✓	✓
					Medium						
					Low						

Numerical analysis first compares the optimal operations, profit and SW in models I, II and III, giving numerical examples. The optimal operations in each model are the battery price p_1 in the first period, the battery price p_2 and the secondary use rate of medium-quality batteries in the second period. Next, how the collection rate θ , the quality classification and recycling rate of used batteries and government subsidies for collection, dismantling and secondary use affect the optimal operation of the two-period CLSC, profits of each member and CLSC, consumer surplus (CS), EI and SW.

The rest of this paper is organised as follows. Section 2 shows literature review. Section 3 defines notation used in mathematical expressions of this paper. Section 4 provides model descriptions, model assumptions, and formulates the profits of a battery manufacturer, a third party, a power grid company and a vehicle manufacturer in a two-period CLSC, and finally describes social welfare to evaluate the optimal operation in two period addressed in this paper. Section 5 describes the decision procedures for the optimal operations in two-period CLSC. Section 6 conducts numerical analyses, shows the comparison of the optimal operation in models I, II and III and the results of sensitivity analysis. Section 7 provides conclusions including research finding and managerial insights in this paper.

2 Literature review

In the academic researches, the previous papers address the government subsidy policy to promote the collection (Ding et al., 2020; Gu et al., 2021), disassembly (Ding et al., 2020; Gu et al., 2021), and secondary use (Gu et al., 2021) of used products.

In a previous study that introduced collection and dismantling subsidies in a CLSC including battery remanufacturing, Ding et al. (2020) studied a CLSC with a battery manufacturer, a vehicle manufacturer and a third party. A vehicle manufacturer and a third party determine whether to collect used batteries, and the third party dismantle the used batteries. The government determines whether to provide collection and dismantling subsidies of the used batteries, considering SW including the profits of all CLSC members, CS and EI in CLSC. Both collection and dismantling subsidies increases the profits of a vehicle manufacturer and a third party in most cases. This previous paper showed that both these subsidies promoted the collection of used batteries and improved the EI and SW evaluation.

In a previous study that introduced purchase and dismantling subsidies in a CLSC with remanufacturing, Gong et al. (2020) studied whether subsidies increased the effort level on remanufacturing of each member in a CLSC with a manufacturer and a dismantler, and how dismantling subsidies affected the profit of each member. This previous paper considered that a single dismantler collected and dismantled used products, the government provided dismantling subsidies of used given to a manufacturer and a dismantler and purchasing subsidies of remanufacturing products to consumers. This previous paper showed that only purchase subsidy could not improve collection and disassembly efforts, and only disassembly subsidy could not to improve disassembly efforts.

In a previous study on the reuse of used EV batteries, Gu et al. (2021) presented a two-period CLSC in which made secondary used as storage batteries considering the quality of used batteries before the used batteries were remanufacturing or recycling as

materials. This previous paper addressed a two-period CLSC with a battery manufacturer, a third party and a power grid company. In this previous paper, the battery manufacturer paid the government an environmental pollution fee for the quantity of batteries manufactured using new materials, and the environmental pollution fee was as income for the government. The government subsidy was provided to only the power grid company based on the quality of the secondary use batteries and the remanufacturing rate. The used batteries were classified into two types, high-quality and low-quality, and the high-quality batteries were sold to a power grid company as storage batteries, and the low-quality batteries were sold to a battery manufacturer as materials. This previous study clarified the effect of government subsidies and the CLSC for the secondary use of used batteries. This previous paper showed that the government subsidy resulted in higher quality batteries for secondary use, but a smaller sum of profits of the power grid company and the battery manufacturer. Thus, the government subsidies were not working effectively in terms of profit of each member in CLSC in this previous paper.

In summary, the previous studies (Ding et al., 2020; Gong et al., 2020; Gu et al., 2021) did not considered the following issues:

- The government provided the collection and dismantling subsidies, but did not provide subsidies to the seller of secondary use batteries, subsidies to the buyer of secondary use batteries, and subsidies for collection and dismantling of used batteries.
- The government provided the dismantling subsidy of used batteries to a dismantler and the purchase subsidy of the remanufactured batteries to consumers, but those subsidies could not improve efforts of collection and dismantling of used batteries. The optimal operation in a CLSC is not evaluated by using SW including the profits of all members, CS and EI in CLSC.
- The qualities of used batteries were classified as high-quality and low-quality, and secondary use batteries. The government provided only subsidy only to a power grid company for purchase of secondary use batteries. The secondary use batteries as batteries for electric vehicles were not considered. The government subsidy to a third party to sell the secondary use batteries was not considered. The optimal operation in a CLSC is not evaluated by using SW including the profits of all members, CS and EI in CLSC.

Table 1 shows the comparison of the contributions of this paper with those of previous papers.

This paper is expected to make a significant contribution to policy makers and researchers to show a managerial guideline for the establishment, the optimal operation and the SW evaluation of a CLSC with a battery manufacturer, a third party, a power grid company, a vehicle manufacturer, consumers and the government under government subsidies to a third party to collect and dismantle used batteries and sell secondary use batteries, a power grid company to purchase secondary use batteries.

3 Notation

The model symbols used in this paper are defined below.

- c_{ntr} is the unit cost of new materials in batteries production ($c_{ntr} > 0$).
- c_{manu} is the unit production cost of batteries ($c_{manu} > 0$).
- a is the potential demand for EV battery ($a > 0$).
- β is the sensitivity of demand of EV battery in the unit sales price of EV battery ($\beta > 0$).
- Q_{PG} is the quantity of batteries required by a power grid company in the first and second periods, respectively ($Q_{PG} > 0$).
- q_{ev1} is the demand of EV battery ($q_{ev1} > 0$).
- p_{1c} is the unit purchase price of batteries by consumers ($p_{1c} > 0$).
- n_{evp} is the ratio of EV battery sales price to the unit purchase price of EV battery for a vehicle manufacturer ($n_{evp} > 0$).
- R_{engv} is the unit operating revenue of batteries of a power grid company ($R_{engv} > 0$).
- π_{P1} is the profit of a power grid company ($\pi_{P1} > 0$).
- π_{M1} is the profit of a battery manufacturer ($\pi_{M1} > 0$).
- π_{N1} is the profit of a vehicle manufacturer ($\pi_{N1} > 0$).
- η is the percentage of government subsidy for the purchase cost of secondary use batteries ($0 \leq \eta \leq 1$).
- δ_c is the degree of government subsidy for the collection cost of used batteries ($0 \leq \delta_c \leq 1$).
- δ_d is the percentage of government subsidy for the cost of dismantling used batteries ($\delta_d \geq 0$).
- η_{th} is the degree of government subsidy to a third party for sales quantity of secondary use batteries ($\eta_{th} \geq 0$).
- q_{oldor2} is the quantity of EV batteries collected from consumers ($q_{oldor2} > 0$).
- $p_{collect2}$ is the unit purchase price of used batteries ($p_{collect2} > 0$).
- e_c is the unit collection efforts cost of a third party ($e_c > 0$).
- k is the parameter for collection effort of used batteries by a third party ($k > 0$).
- θ is the collection rate of used batteries by a third party ($\theta \geq 0$).
- cd is the unit dismantling and inspection cost of collected used batteries ($cd > 0$).
- β_1 is the percentage of high-quality batteries among collected used batteries ($0 \leq \beta_1 \leq 1$).
- β_2 is the percentage of medium-quality batteries among collected used batteries ($0 \leq \beta_2 \leq 1$).
- β_3 is the percentage of low-quality batteries among those collected used batteries ($0 \leq \beta_3 \leq 1$).

- p_{dsc2} : the unit purchase price of batteries that a third party buys from a power grid company ($p_{dsc2} > 0$).
- dc : discount rate of secondary use batteries to new batteries ($0 \leq dc \leq 1$).
- c_{envir} is the unit environmental pollution cost of batteries from new materials ($c_{envir} > 0$).
- α_h is the ratio of the capacity of the highest quality batteries collected by a third party to new batteries ($0 \leq \alpha_h \leq 1$).
- α_l is the ratio of the capacity of the lowest quality batteries collected by a third party to new batteries ($0 \leq \alpha_l \leq 1$).
- α_{h2} is the smallest capacity of batteries in the high-quality batteries for secondary use ($0 < \alpha_{h2} < 1$).
- α_{m1} is the largest capacity of batteries among the medium-quality batteries used for secondary use ($0 < \alpha_{m1} < 1$).
- α_{m2} is the smallest capacity of batteries among the medium-quality batteries for secondary use ($0 < \alpha_{m2} < 1$).
- q_{h2} is the quantity of high-quality batteries among the collected used batteries ($q_{h2} > 0$).
- p_{qh2} is the unit sales price of high-quality batteries for secondary use in the second period ($p_{qh2} > 0$).
- Q_{htyu} is the discounted rate for high-quality batteries for secondary use as to quality ($0 < Q_{htyu} < 1$).
- q_{m2} is the quantity of medium-quality batteries within the collected used batteries in the second period ($q_{m2} > 0$).
- $q_{m\gamma2}$ is the quantity of medium-quality batteries within the collected used batteries ($q_{m\gamma2} > 0$).
- Q_{mtyu} is the discount rate for medium-quality batteries to be used secondarily based on quality ($0 < Q_{mtyu} < 1$).
- p_{qm2} is the unit sales price of medium-quality batteries for secondary use ($p_{qm2} > 0$).
- q_{l2} is the quantity of low-quality batteries in the collected used batteries ($0 < q_{l2} > 0$).
- α_{h1} is the largest capacity of batteries in the high-quality batteries for secondary use ($0 < \alpha_{h1} < 1$).
- λ is the remanufacturing rate of used batteries into materials ($0 < \lambda < 1$).
- q_{old2} is the quantity of recycled material in the second period ($q_{old2} > 0$).
- q_{repg2} is the batteries quantity purchased by a power grid company from a battery manufacturer ($q_{repg2} > 0$).
- q_{ev2} is the EV battery demand in the second period ($q_{ev2} > 0$).

- q_{reev2} is the batteries quantity purchased by a vehicle manufacturer from a battery manufacturer ($q_{reev2} > 0$).
- q_2 is the batteries quantity produced by a battery manufacturer ($q_2 > 0$).
- p_{dsc2} is the unit price of the battery material in the second period.
- N_d is the residual value of used batteries to new batteries ($N_d \geq 0$).
- q_{n2} is the battery quantity produced by a battery manufacturer using new materials ($q_{n2} > 0$).
- p_{2c} is the unit sales price of batteries purchased by consumers ($p_{2c} > 0$).
- π_{M2} is the profit of a battery manufacturer in the second period ($\pi_{M2} > 0$).
- π_{T2} is the profit of a third party in the second period ($\pi_{T2} > 0$).
- π_{N2} is the profit of a vehicle manufacturer in the second period ($\pi_{N2} > 0$).
- π_{P2} is the profit of a power grid company in the second period ($\pi_{P2} > 0$).
- CS_2 is the CS in the second period ($CS_2 > 0$).
- SW_2 is the SW in the second period ($SW > 0$).
- e_n is the unit EI of new batteries quantity q_{n2} in the second period produced from new materials ($e_n \leq 0$).
- e_{ue} is the unit EI of recycled materials quantity q_{old2} in the second period produced from used batteries ($e_{ue} \leq 0$).
- e_r is the unit EI of new batteries in the second period produced from recycled materials ($e_r \leq 0$).
- EI_2 is the EI in the second period ($EI_2 < 0$).
- Decision variables in CLSC are defined below.
- p_1 is the unit battery prices in the first period (a battery manufacturer) ($p_1 > 0$).
- p_2 is the unit battery price in the second period (a battery manufacturer) ($p_2 > 0$).
- γ is the secondary use rate of medium-quality batteries (a third party) ($0 \leq \gamma \leq 1$).

4 Model descriptions

This paper considers a two-period CLSC with first period for the production and sale of new batteries for electric vehicles and second period for the reuse of used batteries, including secondary use and recycling of used batteries. Figure 1 shows the operation flow of CLSC in the first period with production and sales a single type of new EV battery considered in this paper. The operational flow of CLSC in the first period in Figure 1 is described below. The numbers in Figure 1 correspond to the numbers in the following system operation flow of CLSC in the first period.

- 1 A battery manufacturer purchases new battery material at a unit cost c_{ntr} and manufactures batteries at a unit production cost c_{manu} . A battery manufacturer produces a single type of batteries and sells the batteries quantity Q_{pg} to a power grid company at the unit sales price p_1 . The battery manufacturer determines optimally the unit price p_1 of the battery in the first period.

Figure 1 Operational flow of CLSC in the first period (see online version for colours)

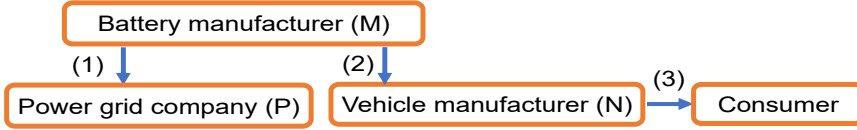
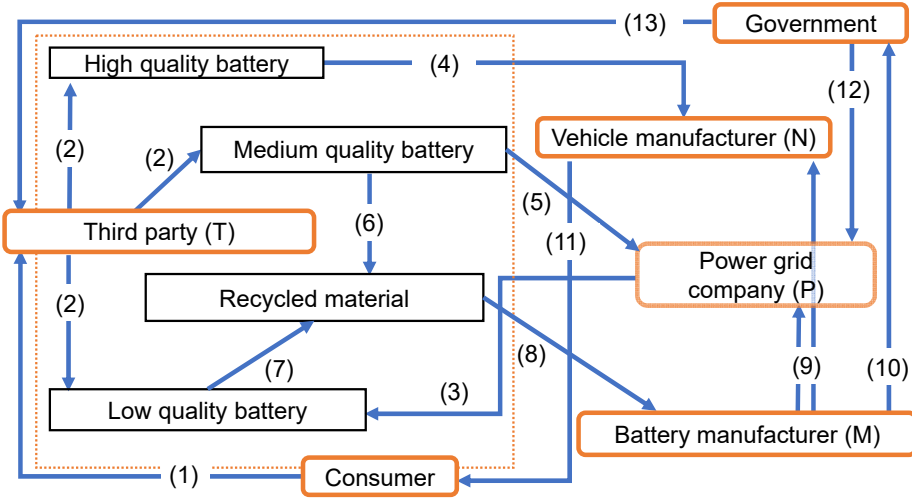


Figure 2 Operational flow of CLSC in the second period (see online version for colours)



- 2 The battery manufacturer produces the same single type of batteries and sells the batteries quantity q_{ev1} to a vehicle manufacturer at the unit sales price p_1 .
- 3 The vehicle manufacturer sells the batteries to consumers at the unit sales price p_{1c} .

Next, this paper discusses provides the following three government subsidy models: model I where the government gives a subsidy η only to a power grid company who purchases secondary use batteries. Model II where the government gives subsidies (δ_c , δ_d , η_{th}) to a third party who collects, dismantles, and sells secondary use of used batteries. Model III where the government gives a subsidy η to a power grid company who purchases secondary use batteries, and subsidies η , δ_c , δ_d , η_{th} to a third party who collects dismantles used batteries, and sells secondary use batteries.

Figure 2 shows the operation flow of CLSC in the second period with reuse of a single type of used EV batteries considered in this paper. The operation flow of CLSC in the second period in Figure 2 is described below. The numbers in Figure 2 correspond to the numbers in the following system operation flow of CLSC in the second period.

- 1 A third party collects a single type of used EV batteries from consumers and purchases the used EV battery quantity q_{oldor2} at the unit sales price $p_{collect2}$.
- 2 The third party dismantles and inspects the used EV batteries and classifies them as high-quality ones, medium-quality ones, or low-quality ones with ratio of β_1 , β_2 , and β_3 at the unit cost c_d (the answer of RQ1).
- 3 The third party buys the quantity of used batteries Q_{pg} from a power grid company at the unit sales price p_{dsc2} , and classifies all of them as low-quality batteries.
- 4 The third party sells the high-quality used batteries quantity q_{h2} to a vehicle manufacturer at the unit sales price p_{qh2} .
- 5 The third party sells the quantity of medium-quality used batteries q_{m2} to a power grid company at the unit sales price p_{qm2} for the secondary use at the ratio γ ($0 \leq \gamma \leq 1$). The third party determines optimally the secondary use at the ratio γ in the second period in the following range of γ : $0 \leq \gamma \leq 1$.
- 6 The third party recycles the medium-quality used batteries that has no secondary use into materials at the recycling rate λ ($0 \leq \lambda \leq 1$).
- 7 The third party recycles the quantity of low-quality used batteries q_{l2} into material at the recycling rate λ ($0 \leq \lambda \leq 1$).
- 8 The third party sells the quantity of material q_{old2} recycled in steps 6 and 7 to the battery manufacturer at the unit sales price c_{ntr} .
- 9 The battery manufacturer produces the battery quantity q_2 using both the materials purchased from the third party and new materials. q_{reev2} is the battery quantity sold to the vehicle manufacturer at the unit sales price p_2 and Q_{pg} is the battery quantity sold to the power grid company at the unit sales price p_2 . The battery manufacturer determines optimally the unit price p_2 of the battery in the second period.
- 10 The battery manufacturer pays the government environmental pollution cost C_{envir} for the quantity of new materials q_{n2} used in the production of EV battery.
- 11 The vehicle manufacturer sells the battery quantity q_{ev2} to consumers at the unit sales price p_{2c} .
- 12 In models I and III, the government provides the power grid company the subsidy ratio η for the secondary use of EV battery.
- 13 In models II and III, the government provides the subsidy ratio δ_c , δ_d for the collection and dismantling of used EV batteries and the subsidy ratio η_{th} for the sales quantity of secondary use of EV batteries to the third party.

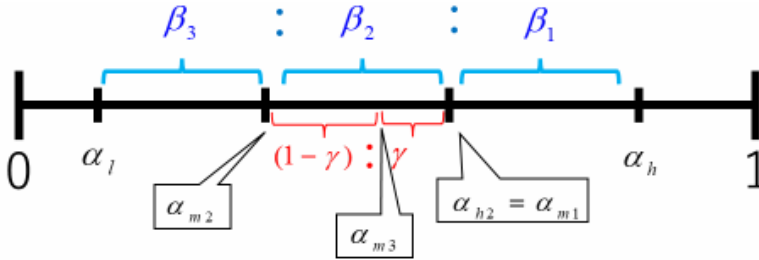
Model assumptions of a two-period CLSC are described below.

- 1 In the first and second periods, a power grid company purchases batteries from a battery manufacturer, and operates these batteries as storage batteries. The battery manufacturer earns the unit revenue R_{engv} of sales quantity of batteries.
- 2 In the first period, the demand of EV battery for the unit sales price p_1 is modelled as $q_{ev1} = a - \beta \times p_1$. a is the potential demand and β is the price sensitivity for p_1 . Similarly, in the second period, the demand for EV battery for the unit sales price p_2

is modelled as $q_{ev2} = a - \beta \times p_2$. a is the potential demand and β is the price sensitivity for p_2 . The quantity of battery required by the power grid company in the first and second periods is same and is denoted by Q_{PG} . The total battery demand in the first period is the sum of q_{ev1} and Q_{PG} as $q_1 = q_{ev1} + Q_{PG}$. The total battery demand in the second period is the sum of q_{ev2} and Q_{PG} as $q_2 = q_{ev2} + Q_{PG}$. The order quantity of batteries by a vehicle manufacturer q_{ev1} is equal to the sales quantity of batteries by a vehicle manufacturer to consumers q_{ev2} are equal to the quantity of batteries demanded.

- 3 The unit battery price p_{1c} that consumers purchase from the vehicle manufacturer in the first period is calculated as $p_{1c} = p_1 \times n_{evp}$, considering the sales profit rate n_{evp} (>1).
- 4 Assume that the collection effort cost e_c is incurred when a third party collects a used battery, and that the cost is calculated using the parameter k for the third party's collection effort as $e_c = (k/2) \times \theta^2$.

Figure 3 Capacity distribution of used batteries (see online version for colours)



- 5 A third party collects the quantity of used batteries q_{oldor2} ($= \theta q_{ev1}$) at collection rate θ . The collection effort cost e_c for collection rate θ is $e_c = (k/2) \times \theta^2$. k is a cost parameter for the third party's collection effort.
- 6 Batteries used by the power grid company in the first phase shall be collected by the third party and all shall be classified as low-quality batteries.
- 7 A third party collects a single type of used batteries Q_{PG} from a power grid company in the first period, and all used batteries are classified as low-quality used batteries.
- 8 The used batteries quantity with high-quality q_{h2} is $q_{h2} = \beta \times q_{oldor2}$. That with medium-quality q_{m2} is $q_{m2} = \beta_2 \times q_{oldor2}$. That with low-quality q_{l2} is $q_{l2} = \beta_3 \times q_{oldor2} + Q_{PG}$. The secondary use quantity in medium-quality used batteries q_{m2} is $q_{m2} = q_{m2}(\gamma) = \gamma \times \beta_2 \times q_{oldor2}$.

Figure 3 shows the capacity distribution of used batteries. In this paper, when collected used batteries are used as secondary use, the unit price of the secondary use batteries is determined using a standard value 1 of capacity of the unit new battery. The unit capacity of the collected used batteries follows the uniform distribution in the range [the minimum value α_l , the maximum value α_h] and α_l and α_h are between 0 and 1. The quality of used batteries is based on the capacity of used batteries. This paper assumes that a high-quality used battery has a high capacity, while a low-quality used battery has a low capacity. α_{h2} is the smallest capacity of batteries

among the high-quality batteries for secondary use ($0 < \alpha_{h2} < 1$). α_{m1} is the largest capacity of batteries among the medium-quality batteries used for secondary use ($0 < \alpha_{m1} < 1$). α_{m2} is the smallest capacity of batteries among the medium-quality batteries for secondary use ($0 < \alpha_{m2} < 1$). From Figure 3, the ratio of capacities of used batteries to capacities of new batteries is obtained as to the quality of the used batteries. From Figure 3, first, the ratios of the high-quality, medium-quality and low-quality in used batteries are investigated as β_1 , β_2 and β_3 . This paper assumes that α_{h2} is equal to α_{m1} . The distribution of β_1 is between α_{h2} and $\alpha_{h2} = \alpha_{m1}$. The distribution of β_2 is between $\alpha_{h2} = \alpha_{m1}$ and α_{m2} . The distribution of β_3 is between α_{m2} and α_l . The ratio of β_1 is obtained as the area of $\alpha_{h2} = \alpha_{m1}$ from α_{h2} in the distribution of β_1 . Similarly, the ratios of β_2 and β_3 are obtained. From the ratios of β_1 , β_2 and β_3 in Figure 3, the largest battery capacity α_{h2} and the smallest battery capacity α_{m2} of the medium-quality batteries for secondary are calculated as

$$\alpha_{h2} = \alpha_h - (\alpha_h - \alpha_l) \times \frac{\beta_1}{\beta_1 + \beta_2 + \beta_3} = \alpha_h - (\alpha_h - \alpha_l) \times \beta_1 \quad (1)$$

$$\alpha_{m2} = \alpha_h - (\alpha_h - \alpha_l) \times \frac{\beta_1 + \beta_2}{\beta_1 + \beta_2 + \beta_3} = \alpha_h - (\alpha_h - \alpha_l) \times (\beta_1 + \beta_2) \quad (2)$$

The calculation procedure of the smallest battery capacity α_{m3} of the medium-quality used batteries for secondary use are shown below. In this paper, the unit price of the medium-quality used batteries for secondary use is obtained as to the secondary use rate γ of the medium-quality used battery. From Figure 3, first the ratio of secondary use γ and the ratio of non-secondary use $1 - \gamma$ among medium-quality used batteries are obtained. The distribution of γ is between $\alpha_{h2} = \alpha_{m1}$ and α_{m3} . The distribution of $(1 - \gamma)$ is between α_{m2} and α_{m3} . The ratio of γ is obtained as the area of α_{m3} from $\alpha_{h2} = \alpha_{m1}$ in the distribution of γ . Similarly, the ratio of $(1 - \gamma)$ is obtained. Therefore, from Figure 3, the smallest battery capacity α_{m3} of the medium-quality used batteries for secondary use can be obtained as

$$\begin{aligned} \alpha_{m3} &= \alpha_{m3}(\gamma) = \alpha_{m2} + (\alpha_{h2} - \alpha_{m2}) \times (1 - \gamma) \\ &= (\alpha_l + (\alpha_h - \alpha_l) \times (1 - \beta_1)) \times (2 - \gamma) + (\alpha_l + (\alpha_h - \alpha_l) \times \beta_3) \times \gamma \end{aligned} \quad (3)$$

- 9 In this paper, the discount rate Q_{htyu} for a high-quality used batteries for secondary use is calculated as $Q_{htyu} = ((\alpha_h + \alpha_{h2})/2)^2 \times dc$, by multiplying the square of the average value of the largest capacity α_h and the smallest capacity α_{h2} of the high-quality used batteries by the discount rate dc of the secondary use battery for new batteries. The unit price of high-quality used batteries for secondary use p_{qh2} is obtained as $p_{qh2} = p_1 \times Q_{htyu}$, using the unit battery price p_1 in the first period and the discount rate Q_{htyu} for high-quality used batteries for used secondarily.
- 10 The discount rate Q_{mtyu} for a medium-quality used battery for secondary use is affected by the secondary use rate γ ($0 \leq \gamma \leq 1$) of the medium-quality used batteries. Therefore, the discount rate Q_{mtyu} varies as to model $k \in I, II, III$. In this paper, Q_{mtyu} is calculated as $Q_{mtyu} = Q_{mtyu}(\gamma) ((\alpha_{m1} + \alpha_{m3})/2)^2 \times dc$, by multiplying the square of the average value of the largest capacity α_{m1} and the smallest capacity α_{m2} of the medium-quality used batteries by the discount rate dc of the secondary use battery

for new batteries. The unit price of medium-quality used batteries for secondary use p_{qm2} is obtained as $p_{qm2} = p_{qm2}(\gamma) = p_1 \times Q_{mtyu}$, using the unit battery price p_1 in the first period and the discount rate Q_{mtyu} for medium-quality used batteries for used secondarily.

- 11 The quantity of batteries recycled by the third party as material q_{old2} for the secondary use rate γ of medium-quality used batteries in the second period and the recycling rate λ ($0 \leq \lambda \leq 1$) is obtained as $q_{old2} = q_{old2}(\gamma) = \lambda \times (q_{l2} + (1 - \gamma) \times q_{m2})$.
- 12 The unit price of the battery material p_{dsc2} in the second period is obtained as $p_{dsc2} = p_1/N_d$, considering the residual value N_d of the material of the used batteries to the unit price of the new battery p_1 .
- 13 The purchase quantity of batteries in the second period q_{reev2} by a vehicle manufacturer from a battery manufacturer is obtained as $q_{reev2} = q_{ev2} - q_{h2}$ by subtracting the purchase quantity of high-quality used batteries from the demand of EV battery in the second period.
- 14 The purchase quantity of batteries in the second period by a power grid company from a battery manufacturer for the secondary use rate γ of medium-quality used batteries q_{repg2} is obtained as $q_{repg2} = q_{repg2}(\gamma) = Q_{PG} - q_{my2}$, by subtracting the quantity of medium-quality used batteries q_{my2} in collected used batteries from the required quantity Q_{PG} of batteries of the power grid company.
- 15 The production quantity of batteries by a battery manufacturer q_2 in the second period for the secondary use rate of medium-quality used batteries γ is obtained as $q_2 = q_2(\gamma) = q_{reev2} + Q_{PG} - q_{my2}$ by subtracting the quantity of medium-quality used batteries in collected used batteries q_{my2} from the sum of the purchase quantity of batteries of a vehicle manufacturer from a battery manufacturer q_{reev2} and the required quantity of batteries of a power grid company Q_{PG} .
- 16 The production quantity of batteries using new materials by a battery manufacturer q_{n2} in the second period for the secondary use rate γ of medium-quality used batteries is obtained as $q_{n2} = q_{n2}(\gamma) = q_2 - q_{old2}$ by subtracting the production quantity of batteries using recycled materials q_{old2} from the production quantity of batteries in the second period q_2 . In this case, the production quantity of batteries using new materials by the battery manufacturer is q_{n2} . The battery manufacturer pays the environmental pollution cost to the government $q_{n2} \times c_{envir}$.
- 17 The unit battery price p_{2c} that consumers purchase from the vehicle manufacturer in the second period is calculated as $p_{2c} = p_2 \times n_{evp}$, with the sales profit rate n_{evp} (>1).
- 18 The EI e_n (≤ 0) is generated per unit of new battery q_{n2} manufactured from new materials. The EI e_r (≤ 0) is generated per q_{old2} unit of recycled material produced from used batteries. The EI e_{ue} (≤ 0) is generated by the use of the unit battery.

Based on the system operational flow of CLSC in Subsection 3.1 shown in Figure 1, the profits of a battery manufacturer, a power grid company and a vehicle manufacturer in CLSC in the first period are formulated below.

The profit of a battery manufacturer in the first period is formulated from the unit sales price p_1 , the unit cost of new battery material c_{ntr} and the unit cost of battery

production c_{manu} for the production quantity of EV battery ($q_{ev1} + Q_{PG}$) in the first period below.

$$\pi_{M1} = (p_1 - c_{ntr} - c_{manu}) \times (q_{ev1} + Q_{PG}) \quad (4)$$

The profit of a power grid company in the first period is formulated from the unit operational revenue of EV battery R_{engy} and the unit purchasing cost of EV battery p_1 for EV battery quantity Q_{PG} below.

$$\pi_{P1} = \pi_{PGC1}(p_1) = (R_{engy} - p_1) \times Q_{PG} \quad (5)$$

The profit of a vehicle manufacturer (N) in the first period is formulated from the unit sales price of EV battery p_{1c} and the unit purchasing cost of EV battery p_1 for the quantity of EV battery q_{ev1} below.

$$\pi_{N1} = \pi_{N1}(p_1) = (p_{1c} - p_1) \times q_{ev1} \quad (6)$$

Based on the system operation flow of CLSC in Subsection 3.1 shown in Figure 2 and the model assumptions in Subsection 3.2, the profits of a third party, a battery manufacturer, a power grid company and a vehicle manufacturer are formulated, as to models I, II and III.

The profit of a third party in model i ($i \in \{I, II, III\}$), π_{T2}^i , in the second period is obtained from sales of EV battery as secondary use of in high-quality and medium-quality batteries, sales of recycled materials, the effort cost of collection of used EV battery at unit cost e_c , the collection subsidy from G to T in models II and III at subsidy ratio δ_c , the purchasing cost of the quantity of used EV battery q_{oldor2} at unit cost $p_{collect2}$, the disassembly and inspection costs of used EV batteries at the unit cost c_d , the disassembly subsidy from G to T in models II and III at subsidy ratio δ_d and the subsidy for sales quantity of EV battery as secondary use at subsidy ratio η_{th} . The profit of a third party in the second period in model i ($i \in \{I, II, III\}$), π_{T2}^i , for the unit sales price p_2 and the ratio of secondary use in medium-quality EV battery γ is

$$\begin{aligned} \pi_{T2}^I = \pi_{T2}^I(p_2, \gamma) &= p_{qh2} \times q_{h2} + p_{qm2} \times q_{reev2} \\ &+ c_{ntr} \times q_{old2} - e_c - (p_{collect2} + c_d) \times q_{oldor2} \end{aligned} \quad (7)$$

$$\begin{aligned} \pi_{T2}^{II} = \pi_{T2}^{III} = \pi_{T2}^{II}(p_2, \gamma) &= \pi_{T2}^{III}(p_2, \gamma) \\ &= p_{qh2} \times q_{h2} + p_{qm2} \times q_{reev2} + c_{ntr} \times q_{old2} - e_c \times (1 - \delta_c) \\ &- (p_{collect2} + c_d - \delta_d) \times q_{oldor2} + (q_{myth2} + q_{h2}) \times \eta_{th}, \end{aligned} \quad (8)$$

where $q_{reev2} = q_{ev2} - q_{h2}$, $q_{h2} = \beta_1 q_{old2or2}$, $q_{oldor2} = \theta q_{ev1}$, $q_{old2} = \lambda(q_{I2} + (1 - \gamma)q_{m2})$, $q_{my2} = \gamma\beta_1 q_{oldor2}$.

The profit of a battery manufacturer in model i ($i \in \{I, II, III\}$), π_{M2}^i , in the second period is obtained from sales profit of EV battery (sales price of battery at p_2 in the second period-production cost of battery at unit cost c_{manu}) for the total quantity of the purchasing quantity of new EV battery q_{reev2} by a vehicle manufacturer and the purchasing quantity new EV battery q_{rep2} by a power grid company, the new material cost c_{ntr} for the production quantity of EV battery using materials, environmental pollution cost c_{envir} paid to the government for the quantity of new material used and

purchasing cost of recycled material from a third party below. The profit of a battery manufacturer in the second period in model i ($\in \{I, II, III\}$), π_{M2}^i , for the unit sales price p_2 and the ratio of secondary use in medium-quality EV battery γ is

$$\begin{aligned}\pi_{M2}^I &= \pi_{M2}^{II} = \pi_{M2}^{III} = \pi_{M2}^I(p_2, \gamma) = \pi_{M2}^{II}(p_2, \gamma) = \pi_{M2}^{III}(p_2, \gamma) \\ &= (p_2^k - c_{manu}) \times q_2^k - (c_{ntr} + c_{envir}) \times q_{n2} - c_{ntr} \times q_{old2} \\ &= (p_2 - c_{manu}) \times (q_{reev2} + q_{reg2}) - (c_{ntr} + c_{envir}) \\ &\quad \times (q_{reev2} + q_{reg2} - q_{old2}) - c_{ntr} \times q_{old2},\end{aligned}\tag{9}$$

where $q_2 = q_{reev2} + Q_{PG} - q_{m\gamma2}$, $q_{reg2} = Q_{PG} - q_{m\gamma2}$, $q_{n2} = q_2 - q_{old2}$.

The profit of a power grid company in model i ($\in \{I, II, III\}$), π_{p2}^i , in the second period is formulated from the unit operation revenue of EV battery R_{engy} , sales of used EV battery from the third party at the unit sales price p_{dsc2} , the purchasing cost of new batteries, the purchasing cost of battery as secondary use for the purchasing quantity of battery Q_{PG} and subsidy from the government for the sales quantity of battery as secondary use below. The profit of a power grid company in the second period in model i ($\in \{I, II, III\}$), π_{p2}^i , for the unit sales price p_2 and the ratio of secondary use in medium-quality EV battery γ is

$$\pi_{p2}^I = \pi_{p2}^{III} = (R_{engy} + p_{dsc2}) \times Q_{pg} - p_2 \times (Q_{PG} - q_{m\gamma2}) - p_{qm2} \times (1 - \eta) \times q_{m\gamma2}\tag{10}$$

$$\pi_{p2}^{II} = (R_{engy} + p_{dsc2}) \times Q_{pg} - p_2 \times (Q_{PG} - q_{m\gamma2}) - p_{qm2} \times q_{m\gamma2}\tag{11}$$

The profit of a vehicle manufacturer in model i , π_{N2}^i , in the second period is formulated from sales of EV battery, the purchasing cost of battery as secondary use and the purchasing cost of new battery in the second period below. The profit of a vehicle manufacturer in the second period in model i ($\in \{I, II, III\}$), π_{N2}^i , for the unit sales price p_2 and the ratio of secondary use in medium-quality EV battery γ is

$$\begin{aligned}\pi_{N2} &= \pi_{N2}(p_2, \gamma) = p_{2c} \times q_{ev2} - p_{qh2} \times q_{h2} - p_2 \times q_{reev2} \\ &= n_{evp} p_2 \times q_{ev2} - p_{qh2} \times q_{h2} - p_2 \times q_{reev2}\end{aligned}\tag{12}$$

The profit of CLSC in the second period in model i ($\in \{I, II, III\}$), π_{S2}^i , for the unit sales price p_2 and the ratio of secondary use in medium-quality EV battery γ is calculated as the sum of the profits of a third party, a battery manufacturer, a power grid company and a vehicle manufacturer in the second period, $\pi_{S2}^i = \pi_{T2}^i + \pi_{M2}^i + \pi_{p2}^i + \pi_{N2}^i$.

In previous studies on CLSC, the evaluation of the optimal operation of CLSCs has been mostly on the profit sides for the CLSC members and the whole CLSC. However, when operating a two-phase CLSC, which is the subject of this paper, it is necessary to consider consumers, governments, and the environment in addition to a battery manufacturers, a third party, a power grid company, and a vehicle manufacturer. Therefore, the evaluation of the optimal operation from this paper takes into account the aspects of the economy, the consumer satisfaction, and environment impact, that is, the aspects of the profits of CLSC members, the consumer satisfaction with the product price, and EI from production of EV batteries. This evaluation method has been used in

recent studies to evaluate the optimal operation of CLSC (Krass et al., 2013; Nielsen et al., 2019; Xue et al., 2019; Hong and Guo, 2019; He et al., 2019; Wang et al., 2019; Liu and Xiao, 2020).

To make social evaluation for the optimal operation in CLSC in the second period, this paper adopts the SW evaluation with the profit of CLSC, CS, and EI in the second period. SW for model i ($i \in \{I, II, III\}$), π_{SW2}^i , in the second period is calculated as

$$\pi_{SW2}^i (i \in \{I, II, III\}) = \pi_{S2}^i + CS^i - EI^i = \pi_{T2}^i + \pi_{M2}^i + \pi_{P2}^i + \pi_{N2}^i + CS^i - EI^i \quad (13)$$

This paper adopts CS CS_2^i ($i \in \{I, II, III\}$) in the second period to represent consumer satisfaction with the unit sales price p_2 in the second period. CS_2^i is calculated as

$$CS_2^i (i \in \{I, II, III\}) = \int_{p_2}^{p_0} q_{ev2} dp = p_2 \times (a - q_{ev2}) / 2, \quad (14)$$

using the demand of EV battery in the second period q_{ev2} ($= \alpha - \beta p_2$), p_0 (the unit sales price where q_{ev2} is zero) and the unit sales price p_2 in the second period actually paid by consumers.

This paper adopts the EI in the second period in each model EI_2^i ($i \in \{I, II, III\}$) calculating as sum of EI of

- 1 EI e_n and EI e_{ue} from use of EV battery for the production quantity of new EV battery q_{n2} from new materials.
- 2 EI e_r from production using recycled materials and EI e_{ue} from the use of EV battery for the production quantity of EV battery q_{old2} using recycled materials below.

$$EI_2^i = \varepsilon_1 (e_n + e_{ue}) \times q_{n2} + \varepsilon_2 (e_r + e_{ue}) \times q_{old2} \quad (15)$$

ε_1 and ε_2 are parameters that convert EIs of 1 and 2 into monetary values.

5 Decision procedure of optimal operation in CLSC

As the optimal operation of the two-period CLSC, firstly, in the first period, the battery manufacturer determines the optimal price p_1 of the battery in the first period.

In the first period, the battery manufacturer determines the optimal battery price p_1 to maximize the own profit π_{M1} . π_{M1} is concave for p_1 due to $\partial^2 \pi_{M1} / \partial p_1^2 = -2\beta$. Using software Mathematica, the battery manufacturer determines the optimal value p_1^* by solving the first order condition $\partial \pi_{M1} / \partial p_1 = 0$ in terms of p_1 . p_1^* is obtained as $p_1^* = (a + Q_{pg} + (c_{manu} + c_{ntr})\beta) / 2\beta$.

Secondly, in the second period, a third party is the Stackelberg leader and a battery manufacturer is the Stackelberg follower. In the second period, a third party who is the Stackelberg leader determines optimally the secondary use rate γ of the medium-quality used batteries in model i ($i \in \{I, II, III\}$) as γ^i to maximize the own profit π_{T2}^i . A battery manufacturer who is the Stackelberg follower determines optimally the battery price p_2 in the second period in model i ($i \in \{I, II, III\}$) as p_2^i to maximize the own profit π_{M2}^i . Using

the backward induction method (Yi and Li, 2018) in solution approach of Stackelberg game, the decision procedure is below.

- 1 In the second period, the battery manufacturer as the Stackelberg follower determines the tentative value of battery price p_2 in the second period in model i as ${}^t p_2^i$ to maximize the own profit π_{M2}^i . π_{M2} is concave for p_2 due to $\partial^2 \pi_{M2} / \partial p_2^2 = -2\beta$. Using software Mathematica, the battery manufacturer determines the tentative value of battery price p_2 in the second period in model i as ${}^t p_2^i$ by solving the first order condition $\partial \pi_{M2} / \partial p_2 = 0$ in terms of p_2 . ${}^t p_2^i$ in model i is obtained as

$$\begin{aligned} {}^t p_2^i &= \frac{1}{4\beta} (p_2 I + p_2 II) \\ p_2 I &= 2a + 2Q_{PG} + 2c_{envir}\beta + 2c_{manu}\beta + 2c_{ntr}\beta - a\beta_1\theta + Q_{PG}\beta_1\theta \\ p_2 II &= c_{manu}\beta\beta_1\theta + c_{ntr}\beta\beta_1\theta - a\beta_2\gamma\theta + Q_{PG}\beta_2\gamma\theta + c_{manu}\beta\beta_2\gamma\theta + c_{ntr}\beta\beta_2\gamma\theta \end{aligned}$$

- 2 Substituting ${}^t p_2^i$ into the profit of the third party as the Stackelberg leader in model i , π_{T2}^i , the tentative profit of the third party is calculated as ${}^t \pi_{T2}^i$. The third party optimally determines γ in model i to maximize the own profit ${}^t \pi_{T2}^i$ in model i . ${}^t \pi_{T2}^i$ in model i is concave for γ if the following same condition in models I, II and III derived by using software Mathematica is satisfied:

$$\begin{aligned} \frac{\partial^2 \pi_T^i}{\partial \gamma^2} &= -\frac{1}{8\beta} dc(\alpha_h - \alpha_l)(-a + Q_{PG} + (c_{manu} + c_{ntr})\beta) \\ &\quad \times (a + Q_{PG} + (c_{manu} + c_{ntr})\beta)\beta_2^2(\alpha_h(-4 + 4\beta_1 + 3\beta_2\gamma) - \alpha_l(4\beta_1 + 3\beta_2\gamma))\theta \quad (16) \\ &< 0, \end{aligned}$$

Note that equation (16) is the condition where ${}^t \pi_{T2}^i$ in model i is concave for γ , and this paper assumes this condition.

Using software Mathematica, the third party determines the optimal value γ^i in model i by solving the first order condition $\partial \pi_{T2}^i / \partial \gamma = 0$ in terms of γ satisfying equation (15).

γ^i in model I is obtained as

$$\begin{aligned}
\gamma^I &= \frac{1}{3(\alpha_h - \alpha_l)^2 \beta_2^2} \cdot 2 \left(\gamma^I I - \gamma^I II \cdot \sqrt{\gamma^I III \cdot \beta_2^2 \cdot (\gamma^I IV + \gamma^I V \cdot \gamma^I VI + \gamma^I VII)} \right) \\
\gamma^I I &= -2(\alpha_h - \alpha_l)(\alpha_h(-1 + \beta_1) - \alpha_l \beta_1) \beta_2 \\
\gamma^I II &= \frac{1}{dc(a + Q_{PG} + (c_{manu} + c_{ntr}) \beta)} \\
\gamma^I III &= dc(\alpha_h - \alpha_l)^2 (a + Q_{PG} + (c_{manu} + c_{ntr}) \beta) \\
\gamma^I IV &= a \cdot dc(\alpha_l - \alpha_h \beta_1 + \alpha_l \beta_1)^2 \\
\gamma^I V &= dc(Q_{PG} + (c_{manu} + c_{ntr}) \beta) \\
\gamma^I VI &= (\alpha_h - \alpha_h \beta_1 + \alpha_l \beta_1)^2 \\
\gamma^I IV &= 6\beta c_{ntr} \lambda.
\end{aligned} \tag{16}$$

γ^{II} in model II is obtained as

$$\begin{aligned}
\gamma^{II} &= \frac{1}{3(\alpha_h - \alpha_l)^2 \beta_2^2} \cdot 2 \left(\gamma^{II} I - \gamma^{II} II \cdot \sqrt{\gamma^{II} III \cdot \beta_2^2 \cdot (\gamma^{II} IV + \gamma^{II} V \cdot \gamma^{II} VI - \gamma^{II} VII)} \right) \\
\gamma^{II} I &= \gamma^I I = -2(\alpha_h - \alpha_l)(\alpha_h(-1 + \beta_1) - \alpha_l \beta_1) \beta_2 \\
\gamma^{II} II &= \gamma^I II = \frac{1}{dc(a + Q_{PG} + (c_{manu} + c_{ntr}) \beta)} \\
\gamma^{II} III &= \gamma^I III = \gamma^I III = dc(\alpha_h - \alpha_l)^2 (a + Q_{PG} + (c_{manu} + c_{ntr}) \beta) \\
\gamma^{II} IV &= \gamma^I IV = a \cdot dc(\alpha_l - \alpha_h \beta_1 + \alpha_l \beta_1)^2 \\
\gamma^{II} V &= \gamma^I V = dc(Q_{PG} + (c_{manu} + c_{ntr}) \beta) \\
\gamma^{II} VI &= \gamma^I VI = (\alpha_h - \alpha_h \beta_1 + \alpha_l \beta_1)^2 \\
\gamma^{II} IV &= 6\beta(\eta_{th} - c_{ntr} \lambda).
\end{aligned} \tag{17}$$

γ^{III} in model III is obtained as

$$\begin{aligned}
\gamma^{III} &= \gamma^{II} = \frac{1}{3(\alpha_h - \alpha_l)^2 \beta_2^2} \cdot 2 \left(\gamma^{III} I - \gamma^{III} II \cdot \sqrt{\gamma^{III} III \cdot \beta_2^2 \cdot (\gamma^{III} IV + \gamma^{III} V \cdot \gamma^{III} VI - \gamma^{III} VII)} \right) \\
\gamma^{III} I &= \gamma^{II} I = \gamma^I I = -2(\alpha_h - \alpha_l)(\alpha_h(-1 + \beta_1) - \alpha_l \beta_1) \beta_2 \\
\gamma^{III} II &= \gamma^{II} II = \gamma^I II = \frac{1}{dc(a + Q_{PG} + (c_{manu} + c_{ntr}) \beta)} \\
\gamma^{III} III &= \gamma^{II} III = \gamma^I III = \gamma^I III = dc(\alpha_h - \alpha_l)^2 (a + Q_{PG} + (c_{manu} + c_{ntr}) \beta) \\
\gamma^{III} IV &= \gamma^{II} IV = \gamma^I IV = a \cdot dc(\alpha_l - \alpha_h \beta_1 + \alpha_l \beta_1)^2 \\
\gamma^{III} V &= \gamma^{II} V = \gamma^I V = dc(Q_{PG} + (c_{manu} + c_{ntr}) \beta) \\
\gamma^{III} VI &= \gamma^{II} VI = \gamma^I VI = (\alpha_h - \alpha_h \beta_1 + \alpha_l \beta_1)^2 \\
\gamma^{III} IV &= \gamma^{II} IV = 6\beta(\eta_{th} - c_{ntr} \lambda).
\end{aligned} \tag{18}$$

- 3 Substituting the optimal value γ^k of the third party, who is the decision leader, into the battery manufacturer's provisional value ${}^t p_2^i$, the battery manufacturer as the decision follower can finally determine the optimal value p_2^i .

6 Numerical analysis

Numerical analysis first compares the optimal operations, profit and SW in models I, II and III, giving numerical examples. The optimal operations in each model are the battery price p_1 in the first period, the battery price p_2 and the secondary use rate of medium-quality batteries in the second period.

The following numerical examples are used as $c_{ntr} = 0.9$, $c_{manu} = 0.5$, $\alpha = 40$, $\beta = 4$, $Q_{pg} = 20$, $n_{evp} = 2$, $R_{engy} = 15$, $\eta_{th} = 0.15$, $\delta_c = 0.4$, $\delta_d = 5$, $\eta = 0.15$, $p_{collect2} = 0.5$, $k = 100$, $\theta = 0.5$, $c_d = 0.2$, $\beta_1 = 0.2$, $\beta_2 = 0.4$, $\beta_3 = 0.4$, $dc = 0.2$, $c_{envir} = 3$, $\alpha_h = 0.8$, $\alpha_l = 0.3$, $\lambda = 0.8$, $N_d = 0.2$, $e_n = 0.4$, $e_{ue} = 0.4$, $e_r = 0.2$. The values of numerical examples were chosen based on the assumptions of conditions regarding the optimal decisions for decision variables, p_1 , p_2 and γ in model i ($i \in \{I, II, III\}$) in this paper, the reasonable relationship between the parameters and previous similar research works.

Table 2 Optimal operations of CLSC in first and second periods in each model

Model (i)	p_1^i	p_2^i	γ^i	π_{M1}^i	π_{P1}^i	π_{N1}^i	π_{T2}^i	π_{M2}^i	π_{P2}^i	π_{N2}^i
I	8.2	9.58	0.19	136.0	185.0	59.0	1.5	161.5	930.9	6.9
II	8.2	9.51	0.54	136.0	185.0	59.0	24.7	157.6	936.6	6.8
III	8.2	9.51	0.54	136.0	185.0	59.0	24.7	157.6	936.7	6.8

Table 3 The profits, CS, EI and SW in the second period of each model

Model (i)	π_{S2}^i	CS_2^i	EI_2^i	π_{sw2}^i
I	1,100.7	183.4	-12.9	1,271.1
II	1,125.7	181.0	-12.8	1,293.9
III	1,125.8	181.0	-12.8	1,294.0

Next, the following parameters:

- 1 collection rate of used EV batteries θ
- 2 percentage of quality classification of used batteries ($\beta_1, \beta_2, \beta_3$)
- 3 recycling rate of low-quality batteries λ
- 4 percentage of government subsidy to a third party for secondary use batteries sales η_{th}
- 5 percentage of government subsidy of used battery collection cost δ_c
- 6 percentage of government subsidy for used battery dismantling δ_d
- 7 percentage of government subsidy for the purchase of secondary use batteries η .

Affect the optimal operation of the two-period CLSC, profits of each member and CLSC, CS, EI and SW.

6.1 Comparison of optimal operation and SW in each model

Table 2 shows the comparison of the optimal operation and the profit of each member in model i ($i \in \{I, II, III\}$). Table 3 shows the comparison the profit of CLSC CS, EI and the SW in model i . The results are summarized below.

The optimal value of the battery price p_2 in the second period in model II, p_2^{II} , is equal to p_2^{III} in model III. p_2^{II} and p_2^{III} are lower p_2^I in model I. The optimal value of the secondary use rate γ of the medium-quality used batteries in model II, γ^{II} , is equal to γ^{III} in model III. γ^{II} and γ^{III} are higher than γ^I in model I.

Note that the profit of a power grid company in the second period in model I, $\pi_{p_2}^I$, is different from $\pi_{p_2}^{III}$ in model II because the optimal values p_2^I and γ^I are different from p_2^{III} and γ^{III} , although $\pi_{p_2}^I$ and $\pi_{p_2}^{III}$ are same profit function before p_2 and γ are optimized. The profit of CLSC in the second period in model III, $\pi_{s_2}^{III}$, is highest among other models. The CS in the second period in model II, CS_2^{II} , is equal to CS_2^{III} in model III. CS_2^{II} and CS_2^{III} are lower than CS_2^I in model I. The EI in the second period in model II, EI_2^{II} , is equal to EI_2^{III} in model III. EI_2^{II} and EI_2^{III} are lower than EI_2^I in model I. As a result, the SW in the second period in model II, π_{sw2}^{II} , is equal to π_{sw2}^{III} in model III. π_{sw2}^{II} and π_{sw2}^{III} are higher than π_{sw2}^I in model I.

6.2 Percentage of quality classification of used batteries ($\beta_1, \beta_2, \beta_3$)

When β_1 increases and β_2 decreases in models I, II and III, Tables 4a1-I, 4a1-II and 4a1-III show the effect on optimal decision values and profit of each member in the second period, and Table 4b1-I, 4b1-II and 4b1-III show the effect on the profit of CLSC, CS and EI and SW in the second period.

When β_1 increases and β_3 decreases in models I, II and III, Tables 4a2-I, 4a2-II and 4a2-III show the effect on optimal decision values and profit of each member in the second period and Tables 4b2-I, 4b2-II and 4b2-III show the effect on the profit of CLSC, CS and EI and SW in the second period.

The standard values of the combination of ($\beta_1, \beta_2, \beta_3$) in each table were chosen as ($\beta_1, \beta_2, \beta_3$) = (0.2, 0.4, 0.4) and the values of each combination of β_1, β_2 and β_3 were varied in increments of 0.04, based on the assumptions of conditions regarding the optimal decisions for decision variables, p_2 and γ , in model i ($i \in \{I, II, III\}$) in this paper.

Each combination of ($\beta_1, \beta_2, \beta_3$) shows the answer of RQ1. The optimal value of γ for each model as to the combination of ($\beta_1, \beta_2, \beta_3$) shows the answer of RQ2. The profits of each member, and CLSC for each model as to the combination of ($\beta_1, \beta_2, \beta_3$) shows the answer of RQ3.

From Tables 4a1-I, 4a1-II and 4a1-III, 4a2-I, 4a2-II and 4a2-III, it can be seen that the optimal value of p_2^I in model i does not almost change for the changes of the values of $\beta_1, \beta_2, \beta_3$. That is, p_2^I is almost robust for changes of the values of $\beta_1, \beta_2, \beta_3$.

From Tables 4a1-I, 4a1-II and 4a1-III, 4a2-I, 4a2-II and 4a2-III, it can be seen below. The optimal value of γ^i in model i tends to decrease when β_1 increases and β_2 decreases in models i and when β_1 increases and β_3 decreases in model i . This is because for both pattern changes, the quantity of batteries $q_{m/2}$ purchased by a power grid company in the medium quality batteries decreased, but the optimal value of γ^i in model i was changed by a third party to be exactly the same value. As a result, the profits of a third party, a battery manufacturer and a power grid company in model i decrease under the situation, while the profit of a vehicle manufacturer increases.

Table 4a1-I The effect on optimal decision values and profit of each member in the second period when β_1 increases and β_2 decreases in model I

β_1	β_2	β_3	p_2^I	γ^I	π_{T2}^I	π_{M2}^I	π_{P2}^I	π_{N2}^I
0.00	0.60	0.40	9.58	0.45	2.1	161.6	936.9	0.0
0.04	0.56	0.40	9.58	0.41	2.0	161.6	935.8	1.4
0.08	0.52	0.40	9.58	0.37	1.8	161.5	934.6	2.8
0.12	0.48	0.40	9.58	0.32	1.7	161.5	933.3	4.1
0.16	0.44	0.40	9.58	0.26	1.6	161.5	932.1	5.5
0.20	0.40	0.40	9.58	0.19	1.5	161.5	930.9	6.9
0.24	0.36	0.40	9.58	0.10	1.4	161.4	929.6	8.3

Table 4a1-II The effect on optimal decision values and profit of each member in the second period when β_1 increases and β_2 decreases in model II

β_1	β_2	β_3	p_2^{II}	γ^{II}	π_{T2}^{II}	π_{M2}^{II}	π_{P2}^{II}	π_{N2}^{II}
0.00	0.60	0.40	9.52	0.67	25.3	157.9	942.3	0.0
0.04	0.56	0.40	9.52	0.65	25.2	157.9	941.2	1.4
0.08	0.52	0.40	9.52	0.63	25.0	157.8	940.1	2.7
0.12	0.48	0.40	9.51	0.61	24.9	157.7	938.9	4.1
0.16	0.44	0.40	9.51	0.58	24.8	157.7	937.8	5.5
0.20	0.40	0.40	9.51	0.54	24.7	157.6	936.6	6.8
0.24	0.36	0.40	9.51	0.49	24.5	157.6	935.4	8.2

Table 4a1-III The effect on optimal decision values and profit of each member in the second period when β_1 increases and β_2 decreases in model III

β_1	β_2	β_3	p_2^{III}	γ^{III}	π_{T2}^{III}	π_{M2}^{III}	π_{P2}^{III}	π_{N2}^{III}
0.00	0.60	0.40	9.52	0.67	25.3	157.9	942.5	0.0
0.04	0.56	0.40	9.52	0.65	25.2	157.9	941.4	1.4
0.08	0.52	0.40	9.52	0.63	25.0	157.8	940.2	2.7
0.12	0.48	0.40	9.51	0.61	24.9	157.7	939.1	4.1
0.16	0.44	0.40	9.51	0.58	24.8	157.7	937.9	5.5
0.20	0.40	0.40	9.51	0.54	24.7	157.6	936.7	6.8
0.24	0.36	0.40	9.51	0.49	24.5	157.6	935.5	8.2

Table 4a2-I The effect on optimal decision values and profit of each member in the second period when β_1 increases and β_3 decreases in Model I

β_1	β_2	β_3	p_2^I	γ^I	π_{T2}^I	π_{M2}^I	π_{P2}^I	π_{N2}^I
0.00	0.40	0.60	9.58	0.67	2.1	161.6	936.9	0.0
0.04	0.40	0.56	9.58	0.57	2.0	161.6	935.8	1.4
0.08	0.40	0.52	9.58	0.48	1.8	161.5	934.6	2.8
0.12	0.40	0.48	9.58	0.38	1.7	161.5	933.3	4.1
0.16	0.40	0.44	9.58	0.28	1.6	161.5	932.1	5.5
0.20	0.40	0.40	9.58	0.19	1.5	161.5	930.9	6.9
0.24	0.40	0.36	9.58	0.09	1.4	161.4	929.6	8.3

Table 4a2-II The effect on optimal decision values and profit of each member in the second period when β_1 increases and β_3 decreases in model II

β_1	β_2	β_3	p_2^{II}	γ^{II}	π_{T2}^{II}	π_{M2}^{II}	π_{P2}^{II}	π_{N2}^{II}
0.00	0.40	0.60	9.52	1.00	25.3	157.9	942.3	0.0
0.04	0.40	0.56	9.52	0.92	25.2	157.9	941.2	1.4
0.08	0.40	0.52	9.52	0.82	25.0	157.8	940.1	2.7
0.12	0.40	0.48	9.51	0.73	24.9	157.7	938.9	4.1
0.16	0.40	0.44	9.51	0.64	24.8	157.7	937.8	5.5
0.20	0.40	0.40	9.51	0.54	24.7	157.6	936.6	6.8
0.24	0.40	0.36	9.51	0.44	24.5	157.6	935.4	8.2

Table 4a2-III The effect on optimal decision values and profit of each member in the second period when β_1 increases and β_3 decreases in model III

β_1	β_2	β_3	p_2^{III}	γ^{III}	π_{T2}^{III}	π_{M2}^{III}	π_{P2}^{III}	π_{N2}^{III}
0.00	0.40	0.60	9.52	1.01	25.3	157.9	942.5	0.0
0.04	0.40	0.56	9.52	0.92	25.2	157.9	941.4	1.4
0.08	0.40	0.52	9.52	0.82	25.0	157.8	940.2	2.7
0.12	0.40	0.48	9.51	0.73	24.9	157.7	939.1	4.1
0.16	0.40	0.44	9.51	0.64	24.8	157.7	937.9	5.5
0.20	0.40	0.40	9.51	0.54	24.7	157.6	936.7	6.8
0.24	0.40	0.36	9.51	0.44	24.5	157.6	935.5	8.2

Table 4b1-I The effect on the profit of CLSC, CS and EI and SW in the second period when β_1 increases and β_2 decreases in model I

β_1	β_2	β_3	π_{S2}^I	CS_2^I	EI_2^I	π_{sw2}^I
0.00	0.60	0.40	1,100.7	183.5	-13.0	1,271.3
0.04	0.56	0.40	1,100.7	183.5	-13.0	1,271.2
0.08	0.52	0.40	1,100.7	183.5	-12.9	1,271.2
0.12	0.48	0.40	1,100.7	183.5	-12.9	1,271.2
0.16	0.44	0.40	1,100.7	183.4	-12.9	1,271.2
0.20	0.40	0.40	1,100.7	183.4	-12.9	1,271.1
0.24	0.36	0.40	1,100.7	183.4	-12.9	1,271.1

Table 4b1-II The effect on the profit of CLSC, CS and EI and SW in the second period when β_1 increases and β_2 decreases in model II

β_1	β_2	β_3	π_{S2}^{II}	CS_2^{II}	EI_2^{II}	π_{sw2}^{II}
0.00	0.60	0.40	1,125.6	181.2	-12.8	1,293.9
0.04	0.56	0.40	1,125.6	181.1	-12.8	1,293.9
0.08	0.52	0.40	1,125.6	181.1	-12.8	1,293.9
0.12	0.48	0.40	1,125.7	181.1	-12.8	1,293.9
0.16	0.44	0.40	1,125.7	181.0	-12.8	1,293.9
0.20	0.40	0.40	1,125.7	181.0	-12.8	1,293.9
0.24	0.36	0.40	1,125.7	181.0	-12.8	1,293.9

Table 4b1-III The effect on the profit of CLSC, CS and EI and SW in the second period when β_1 increases and β_2 decreases in model III

β_1	β_2	β_3	π_{S2}^{III}	CS_2^{III}	EI_2^{III}	π_{sw2}^{III}
0.00	0.60	0.40	1,125.7	181.2	-12.8	1,294.1
0.04	0.56	0.40	1,125.7	181.1	-12.8	1,294.1
0.08	0.52	0.40	1,125.8	181.1	-12.8	1,294.0
0.12	0.48	0.40	1,125.8	181.1	-12.8	1,294.0
0.16	0.44	0.40	1,125.8	181.0	-12.8	1,294.0
0.20	0.40	0.40	1,125.8	181.0	-12.8	1,294.0
0.24	0.36	0.40	1,125.8	181.0	-12.8	1,293.9

Table 4b2-I The effect on the profit of CLSC, CS and EI and SW in the second period when β_1 increases and β_3 decreases in model I

β_1	β_2	β_3	π_{S2}^I	CS_2^I	EI_2^I	π_{sw2}^I
0.00	0.40	0.60	1,100.7	183.5	-13.0	1,271.3
0.04	0.40	0.56	1,100.7	183.5	-13.0	1,271.2
0.08	0.40	0.52	1,100.7	183.5	-12.9	1,271.2
0.12	0.40	0.48	1,100.7	183.5	-12.9	1,271.2
0.16	0.40	0.44	1,100.7	183.4	-12.9	1,271.2
0.20	0.40	0.40	1,100.7	183.4	-12.9	1,271.1
0.24	0.40	0.36	1,100.7	183.4	-12.9	1,271.1

Table 4b2-II The effect on the profit of CLSC, CS and EI and SW in the second period when β_1 increases and β_3 decreases in model II

β_1	β_2	β_3	π_{S2}^{II}	CS_2^{II}	EI_2^{II}	π_{sw2}^{II}
0.00	0.40	0.60	1,125.6	181.2	-12.8	1,293.9
0.04	0.40	0.56	1,125.6	181.1	-12.8	1,293.9
0.08	0.40	0.52	1,125.6	181.1	-12.8	1,293.9
0.12	0.40	0.48	1,125.7	181.1	-12.8	1,293.9
0.16	0.40	0.44	1,125.7	181.0	-12.8	1,293.9
0.20	0.40	0.40	1,125.7	181.0	-12.8	1,293.9
0.24	0.40	0.36	1,125.7	181.0	-12.8	1,293.9

Table 4b2-III The effect on the profit of CLSC, CS and EI and SW in the second period when β_1 increases and β_3 decreases in model III

β_1	β_2	β_3	π_{S2}^{III}	CS_2^{III}	EI_2^{III}	π_{sw2}^{III}
0.00	0.40	0.60	1,125.7	181.2	-12.8	1,294.1
0.04	0.40	0.56	1,125.7	181.1	-12.8	1,294.1
0.08	0.40	0.52	1,125.8	181.1	-12.8	1,294.0
0.12	0.40	0.48	1,125.8	181.1	-12.8	1,294.0
0.16	0.40	0.44	1,125.8	181.0	-12.8	1,294.0
0.20	0.40	0.40	1,125.8	181.0	-12.8	1,294.0
0.24	0.40	0.36	1,125.8	181.0	-12.8	1,293.9

Table 5a Effect of collection rate θ on the optimal operation and SW in model I

θ	p_2^I	γ^I	π_{T2}^I	π_{M2}^I	π_{P2}^I	π_{N2}^I	π_{S2}^I	CS_2^I	EI_2^I	π_{sw2}^I
0.30	9.63	0.19	9.6	161.0	928.9	4.2	1,103.7	185.3	-13.3	1,275.8
0.35	9.61	0.19	8.0	161.1	929.4	4.8	1,103.3	184.8	-13.2	1,275.0
0.40	9.60	0.19	6.1	161.2	929.9	5.5	1,102.7	184.4	-13.1	1,274.0
0.45	9.59	0.19	3.9	161.3	930.4	6.2	1,101.8	183.9	-13.0	1,272.7
0.50	9.58	0.19	1.5	161.5	930.9	6.9	1,100.7	183.4	-12.9	1,271.1

Table 5b Effect of collection rate θ on the optimal operation and SW in model II

θ	p_2^{II}	γ^{II}	π_{T2}^{II}	π_{M2}^{II}	π_{P2}^{II}	π_{N2}^{II}	π_{S2}^{II}	CS_2^{II}	EI_2^{II}	π_{sw2}^{II}
0.30	9.59	0.54	22.4	158.7	932.4	4.1	1,117.6	183.8	-13.2	1,288.2
0.35	9.57	0.54	23.2	158.4	933.5	4.8	1,119.8	183.1	-13.1	1,289.9
0.40	9.55	0.54	23.8	158.1	934.5	5.5	1,121.9	182.4	-13.0	1,291.4
0.45	9.53	0.54	24.3	157.9	935.6	6.2	1,123.9	181.7	-12.9	1,292.7
0.50	9.51	0.54	24.7	157.6	936.6	6.8	1,125.7	181.0	-12.8	1,293.9

Table 5c Effect of collection rate θ on the optimal operation and SW in model III

θ	p_2^{III}	γ^{III}	π_{T2}^{III}	π_{M2}^{III}	π_{P2}^{III}	π_{N2}^{III}	π_{S2}^{III}	CS_2^{III}	EI_2^{III}	π_{sw2}^{III}
0.30	9.59	0.54	22.4	158.7	932.4	4.1	1,117.6	183.8	-13.2	1,288.3
0.35	9.57	0.54	23.2	158.4	933.5	4.8	1,119.9	183.1	-13.1	1,289.9
0.40	9.55	0.54	23.8	158.1	934.6	5.5	1,122.0	182.4	-13.0	1,291.4
0.45	9.53	0.54	24.3	157.9	935.6	6.2	1,124.0	181.7	-12.9	1,292.8
0.50	9.51	0.54	24.7	157.6	936.7	6.8	1,125.8	181.0	-12.8	1,294.0

From Tables 4b1-I, 4b1-II and 4b1-III; 4b2-I, 4b2-II and 4b2-III; and 4b3-I, 4b3-II and 4b3-III, it can be seen below. The SW π_{sw2}^i in model $i \in \{I, II, III\}$ in CLSC in the second period is unaffected by changes in the percentage of quality classification of used batteries ($\beta_1, \beta_2, \beta_3$). That is, p_2^i is almost robust for changes of the values of $\beta_1, \beta_2, \beta_3$. This is because the profit of CLSC which the sum of the profits of all members in CLSC, the CS and EIs were almost unaffected by all pattern changes of β_1, β_2 and β_3 .

6.3 Effect of collection rate θ on optimal operation and SW in each model

Tables 5a, 5b and 5c shows the effect of the collection rate θ on the optimal operation, the profits, CS and EI and SW in the second period in models I, II and III. Based on the assumptions of conditions regarding the optimal decisions for decision variables, p_2 and γ , in model i ($\in \{I, II, III\}$) in this paper, the standard value of θ in each table was chosen as 0.5 and the value of θ was varied in increments of 0.05, based on the assumptions of conditions regarding the optimal decisions for decision variables, p_2 and γ , in model i ($\in \{I, II, III\}$) in this paper. The results from Tables 5a, 5b and 5c are summarized below.

As θ increases, the optimal value of the battery price p_2^i in the second period in model i decreases. The optimal value of the battery price p_2 in the second period in model II, p_2^{II} , and p_2^{III} in model III are lower than p_2^I in model I. This is because the collection rate θ increases, resulting in the increase in the quantity of high-quality batteries q_{h2} and medium-quality batteries q_{m2} and the decrease in the quantity of new batteries q_2 . The optimal value of the secondary use rate γ^i in model i is not affected even if the collection rate θ changes. In model I, as θ increases, the profit of the third party in the second period only decreases, while the profits of other members increase under this situation. As a result, the profit of CLSC in the second period, π_{S2}^I , the CS_2^I and the EI_2^I in model I decrease as θ increases, and then the SW in the second period in model I, π_{sw2}^I , decreases as θ increases.

Table 6a Effect of recycling rate λ on the optimal operation and SW in model I

λ	p_2^I	γ^I	π_{T2}^I	π_{M2}^I	π_{P2}^I	π_{N2}^I	π_{S2}^I	CS_2^I	EI_2^I	π_{sw2}^I
0.76	9.56	0.27	0.7	157.9	932.2	6.9	1,097.6	182.9	-13.1	1,267.4
0.80	9.58	0.19	1.5	161.5	930.9	6.9	1,100.7	183.4	-12.9	1,271.1
0.84	9.59	0.10	2.3	165.1	929.5	6.9	1,103.8	184.0	-12.8	1,275.0
0.88	9.61	0.03	3.1	168.7	928.2	6.9	1,106.9	184.5	-12.6	1,278.8

Table 6b Effect of recycling rate λ on the optimal operation and SW in model II

λ	p_2^{II}	γ^{II}	π_{T2}^{II}	π_{M2}^{II}	π_{P2}^{II}	π_{N2}^{II}	π_{S2}^{II}	CS_2^{II}	EI_2^{II}	π_{sw2}^{II}
0.76	9.50	0.63	23.9	154.0	938.1	6.8	1,122.8	180.4	-13.0	1,290.2
0.80	9.51	0.54	24.7	157.6	936.6	6.8	1,125.7	181.0	-12.8	1,293.9
0.84	9.53	0.45	25.4	161.2	935.2	6.9	1,128.7	181.6	-12.7	1,297.6
0.88	9.54	0.37	26.3	164.9	933.8	6.9	1,131.8	182.2	-12.5	1,301.4

Table 6c Effect of recycling rate λ on the optimal operation and SW in model III

λ	p_2^{III}	γ^{III}	π_{T2}^{III}	π_{M2}^{III}	π_{P2}^{III}	π_{N2}^{III}	π_{S2}^{III}	CS_2^{III}	EI_2^{III}	π_{sw2}^{III}
0.76	9.50	0.63	23.9	154.0	938.2	6.8	1,122.9	180.4	-13.0	1,290.3
0.80	9.51	0.54	24.7	157.6	936.6	6.8	1,125.8	181.0	-12.8	1,294.0
0.84	9.53	0.45	25.4	161.2	935.2	6.9	1,128.8	181.6	-12.7	1,297.7
0.88	9.54	0.37	26.3	164.9	933.8	6.9	1,131.8	182.2	-12.5	1,301.5

In models II and III, as θ increases, the profits of a third party and a battery manufacturer in the second period decrease, while the profits of a power grid company and a vehicle

manufacturer increase under this situation. As a result, the profit of CLSC in the second period in models II and III, π_{S2}^{II} and π_{S2}^{III} , increases, the CS_2^{II} and CS_2^{III} in models II and III decrease and the EI_2^{II} and EI_2^{III} in models II and III are improved, as θ increases, and then the SW in the second period in models II and III, π_{sw2}^{II} and π_{sw2}^{III} , increase as θ increases.

6.4 Effect of recycling rate λ on optimal operation and SW in each model

Tables 6a, 6b and 6c show the effect of the recycling rate λ on the optimal operation, the profits, CS and EI and SW in the second period in models I, II and III. Based on the assumptions of conditions regarding the optimal decisions for decision variables, p_2 and γ , in model i ($i \in \{I, II, III\}$) in this paper, the standard value of λ in each table was chosen as 0.8 and the value of λ was varied in increments of 0.04, based on the assumptions of conditions regarding the optimal decisions for decision variables, p_2 and γ , in model i ($i \in \{I, II, III\}$) in this paper. The results from Tables 6a, 6b and 6c are summarized below.

Table 7a The effect of percentage of government subsidy to a third party for secondary use batteries sales η_{th} on the optimal operation and SW in model II

η_{th}	p_2^{II}	γ^{II}	π_{T2}^{II}	π_{M2}^{II}	π_{P2}^{II}	π_{N2}^{II}	π_{S2}^{II}	CS_2^{II}	EI_2^{II}	π_{sw2}^{II}
0.07	9.55	0.35	24.5	159.7	933.5	6.9	1,124.6	182.3	-12.9	1,294.0
0.11	9.53	0.44	24.6	158.7	935.0	6.9	1,125.1	181.7	-12.9	1,293.9
0.15	9.51	0.54	24.7	157.6	936.6	6.8	1,125.7	181.0	-12.8	1,293.9
0.19	9.49	0.64	24.7	156.5	938.2	6.8	1,126.3	180.3	-12.8	1,293.8
0.23	9.48	0.74	24.8	155.4	939.9	6.8	1,126.9	179.6	-12.8	1,293.8

Table 7b The effect of percentage of government subsidy to a third party for secondary use batteries sales η_{th} on the optimal operation and SW in model III

η_{th}	p_2^{III}	γ^{III}	π_{T2}^{III}	π_{M2}^{III}	π_{P2}^{III}	π_{N2}^{III}	π_{S2}^{III}	CS_2^{III}	EI_2^{III}	π_{sw2}^{III}
0.07	9.55	0.35	24.5	159.7	933.5	6.9	1,124.6	182.3	-12.9	1,294.0
0.11	9.53	0.44	24.6	158.7	935.1	6.9	1,125.2	181.7	-12.9	1,294.0
0.15	9.51	0.54	24.7	157.6	936.7	6.8	1,125.8	181.0	-12.8	1,294.0
0.19	9.49	0.64	24.7	156.5	938.3	6.8	1,126.4	180.3	-12.8	1,293.9
0.23	9.48	0.74	24.8	155.4	940.0	6.8	1,127.0	179.6	-12.8	1,293.9

As λ increases, the optimal value of the battery price p_2^i in the second period in model i increases. The optimal value of the battery price p_2 in the second period, p_2^i , increases in model II, p_2^{II} , and p_2^{III} in model III are lower than p_2^I in model I. This is due to the increase in the recycling rate λ for low-quality batteries increases the quantity of recycled material q_{old2} and decreases the quantity of new batteries q_{n2} . As λ increases, the optimal value of the secondary use rate γ^i in model i is decreases. This is due to the increase in the recycling rate λ of low-quality batteries improves the profit of a third party by recycling the batteries into materials rather than secondary use of medium-quality batteries. As λ increases, only the profit of a power grid company in the second period only in model i , π_{P2}^i , decreases, but the profits of other members in model i , π_{M2}^i , π_{T2}^i , π_{P2}^i , increase. As

a result, the profit of CLSC in the second period, π_{S2}^i , and the CS_2^i increases, and the EI_2^i in model i is improved as λ increases, and then the SW in the second period in model i , π_{sw2}^i , increases as θ increases.

These results showed that the increase in the recycling rate λ of used batteries enables a favourable decision making in CLSC from the viewpoint of social evaluation.

6.5 Effect of percentage of government subsidy to a third party for secondary use batteries sales η_{th} on optimal operation and SW

Tables 7a and 7b show the effect of the percentage of government subsidy to a third party for secondary use batteries sales η_{th} on the optimal operation, the profits, CS and EI and SW in the second period in models II and III. Based on the assumptions of conditions regarding the optimal decisions for decision variables, p_2 and γ , in model i ($i \in \{I, II, III\}$) in this paper, the standard value of η_{th} in each table was chosen as 0.15 and the value of η_{th} was varied in increments of 0.04, based on the assumptions of conditions regarding the optimal decisions for decision variables, p_2 and γ , in model i ($i \in \{I, II, III\}$) in this paper. The results are summarized below.

The optimal value of the battery price p_2 in the second period in model II, p_2^{II} , and p_2^{III} in model III are same for the change of η_{th} . As η_{th} increases, p_2^{II} and p_2^{III} decrease.

Table 8a The effect of percentage of subsidy of used battery collection cost δ_c on the optimal operation and SW in model II

δ_c	p_2^{II}	γ^{II}	π_{T2}^{II}	π_{M2}^{II}	π_{P2}^{II}	π_{N2}^{II}	π_{S2}^{II}	CS_2^{II}	EI_2^{II}	π_{sw2}^{II}
0.2	9.51	0.54	22.2	157.6	936.6	6.8	1,123.2	181.0	-12.8	1,291.4
0.4	9.51	0.54	24.7	157.6	936.6	6.8	1,125.7	181.0	-12.8	1,293.9
0.6	9.51	0.54	27.2	157.6	936.6	6.8	1,128.2	181.0	-12.8	1,296.4
0.8	9.51	0.54	29.7	157.6	936.6	6.8	1,130.7	181.0	-12.8	1,298.9

Table 8b The effect of percentage of subsidy of used battery collection cost δ_c on the optimal operation and SW in model III

δ_c	p_2^{III}	γ^{III}	π_{T2}^{III}	π_{M2}^{III}	π_{P2}^{III}	π_{N2}^{III}	π_{S2}^{III}	CS_2^{III}	EI_2^{III}	π_{sw2}^{III}
0.2	9.51	0.54	22.2	157.6	936.7	6.8	1,123.3	181.0	-12.8	1,291.5
0.4	9.51	0.54	24.7	157.6	936.7	6.8	1,125.8	181.0	-12.8	1,294.0
0.6	9.51	0.54	27.2	157.6	936.7	6.8	1,128.3	181.0	-12.8	1,296.5
0.8	9.51	0.54	29.7	157.6	936.7	6.8	1,130.8	181.0	-12.8	1,299.0

The optimal value of the secondary use rate in model II, γ^{II} , and γ^{III} in model III are same for the change of η_{th} . As η_{th} increases, γ^{II} and γ^{III} increase. As η_{th} increases, the profits of a third party and a power grid company increase, while the profits of a battery manufacturer and a vehicle manufacture decrease. As a result, the profit of CLSC increases, as η_{th} increases. This is because the increment of the profits of a third party and a power grid company is higher than reduction of the profits of a battery manufacturer and a vehicle manufacture. As η_{th} increases, in models II and III, the profit of CLSC, π_{S2}^{II} , and π_{S2}^{III} , increases and the EI, EI_2^{II} and EI_2^{III} , is improved, while the CS, CS_2^{II} and CS_2^{III} decreases. As a result, the SW in model II, π_{sw2}^{II} , and π_{sw2}^{III} in model III decreases, as η_{th}

increases. This is because the reduction of the CS, CS_2^{II} and CS_2^{III} is higher than the improvements of the profit of CLSC, π_{S2}^{III} , and π_{S2}^{III} , and the EI, EI_2^{II} and EI_2^{III} , as η_{th} increases. The above results are the first answer of RQ4.

6.6 Effect of percentage of government subsidy of used battery collection cost δ_c on optimal operation and SW in each model

Tables 8a and 8b show the effect of the percentage of government subsidy of used battery collection cost δ_c on the optimal operation, the profits, CS and EI and SW in the second period in models II and III. Based on the assumptions of conditions regarding the optimal decisions for decision variables, p_2 and γ , in model i ($i \in \{I, II, III\}$) in this paper, the standard value of δ_c in each table was chosen as 0.4 and the value of η_{th} was varied in increments of 0.2, based on the assumptions of conditions regarding the optimal decisions for decision variables, p_2 and γ , in model i ($i \in \{I, II, III\}$) in this paper. The results are summarized below.

The optimal value of the battery price p_2 in the second period in model II, p_2^{II} , and p_2^{III} in model III are unchanged even if the effect of δ_c increases. The optimal value of the secondary use rate in model II, γ^{II} , and γ^{III} in model III are unchanged even if the effect of δ_c increases. As δ_c increases, the profit of a third party only increases, while the profits of a battery manufacturer, a power grid company and a vehicle manufacture are unchanged. As δ_c increases, in models II and III, the profit of CLSC, π_{S2}^{II} , and π_{S2}^{III} , only increases, while the EI, EI_2^{II} and EI_2^{III} , and the CS, CS_2^{II} and CS_2^{III} are unchanged. As a result, the SW in model II, π_{sw2}^{II} , and π_{sw2}^{III} in model III increases, as δ_c increases.

Table 9a The effect of percentage of subsidy for used battery dismantling cost δ_d on the optimal operation and SW in model II

δ_d	p_2^{II}	γ^{II}	π_{T2}^{II}	π_{M2}^{II}	π_{P2}^{II}	π_{N2}^{II}	π_{S2}^{II}	CS_2^{II}	EI_2^{II}	π_{sw2}^{II}
1	9.51	0.54	10.3	157.6	936.6	6.8	1,111.3	181.0	-12.8	1,279.5
3	9.51	0.54	17.5	157.6	936.6	6.8	1,118.5	181.0	-12.8	1,286.7
5	9.51	0.54	24.7	157.6	936.6	6.8	1,125.7	181.0	-12.8	1,293.9
7	9.51	0.54	31.9	157.6	936.6	6.8	1,132.9	181.0	-12.8	1,301.1

Table 9b The effect of percentage of subsidy for used battery dismantling cost δ_d on the optimal operation and SW in model III

δ_d	p_2^{III}	γ^{III}	π_{T2}^{III}	π_{M2}^{III}	π_{P2}^{III}	π_{N2}^{III}	π_{S2}^{III}	CS_2^{III}	EI_2^{III}	π_{sw2}^{III}
1	9.51	0.54	10.3	157.6	936.7	6.8	1,111.4	181.0	-12.8	1,279.6
3	9.51	0.54	17.5	157.6	936.7	6.8	1,118.6	181.0	-12.8	1,286.8
5	9.51	0.54	24.7	157.6	936.7	6.8	1,125.8	181.0	-12.8	1,294.0
7	9.51	0.54	31.9	157.6	936.7	6.8	1,133.0	181.0	-12.8	1,301.2

These results showed that the increase in the percentage of subsidy of used battery collection cost δ_c to a third party enables a favourable decision making in the collection activity of used batteries in CLSC from the viewpoint of social evaluation. The above results are the second answer of RQ4.

6.7 Effect of percentage of government subsidy for used battery dismantling cost δ_d on optimal operation and SW in each model

Tables 9a and 9b show the effect of the percentage of government subsidy for used battery dismantling cost δ_d on the optimal operation, the profits, CS and EI and SW in the second period in models II and III. Based on the assumptions of conditions regarding the optimal decisions for decision variables, p_2 and γ , in model i ($i \in \{I, II, III\}$) in this paper, the standard value of δ_d in each table was chosen as 5 and the value of δ_d was varied in increments of 2, based on the assumptions of conditions regarding the optimal decisions for decision variables, p_2 and γ , in model i ($i \in \{I, II, III\}$) in this paper. The results are summarized below.

The optimal value of the battery price p_2 in the second period in model II, p_2^{II} , and p_2^{III} in model III are unchanged even if δ_d increases. The optimal value of the secondary use rate in model II, γ^{II} , and γ^{III} in model III are unchanged even if δ_d increases. As δ_d increases, the profit of a third party only increases, while the profits of a battery manufacturer, a power grid company and a vehicle manufacture are unchanged. As δ_d increases, in models II and III, the profit of CLSC, π_{S2}^{II} , and π_{S2}^{III} , only increases, while the EI, EI_2^{II} and EI_2^{III} , and the CS, CS_2^{II} and CS_2^{III} are unchanged. As a result, the SW in model II, π_{sw2}^{II} , and π_{sw2}^{III} in model III increases, as δ_d increases.

Table 10a The effect of percentage of subsidy for the purchase of secondary use batteries η on the optimal operation and SW in model I

η	p_2^I	γ^I	π_{T2}^I	π_{M2}^I	π_{P2}^I	π_{N2}^I	π_{S2}^I	CS_2^I	EI_2^I	π_{sw2}^I
0.00	9.58	0.19	1.5	161.5	930.8	6.9	1,100.6	183.4	-12.9	1,271.1
0.05	9.58	0.19	1.5	161.5	930.8	6.9	1,100.7	183.4	-12.9	1,271.1
0.10	9.58	0.19	1.5	161.5	930.8	6.9	1,100.7	183.4	-12.9	1,271.1
0.15	9.58	0.19	1.5	161.5	930.9	6.9	1,100.7	183.4	-12.9	1,271.1
0.20	9.58	0.19	1.5	161.5	930.9	6.9	1,100.7	183.4	-12.9	1,271.2
0.25	9.58	0.19	1.5	161.5	930.9	6.9	1,100.7	183.4	-12.9	1,271.2
0.30	9.58	0.19	1.5	161.5	930.9	6.9	1,100.7	183.4	-12.9	1,271.2

Table 10b The effect of percentage of subsidy for the purchase of secondary use batteries η on the optimal operation and SW in model III

η	p_2^{III}	γ^{III}	π_{T2}^{III}	π_{M2}^{III}	π_{P2}^{III}	π_{N2}^{III}	π_{S2}^{III}	CS_2^{III}	EI_2^{III}	π_{sw2}^{III}
0.00	9.51	0.54	24.7	157.6	936.6	6.8	1,125.7	181.0	-12.8	1,293.9
0.05	9.51	0.54	24.7	157.6	936.6	6.8	1,125.7	181.0	-12.8	1,293.9
0.10	9.51	0.54	24.7	157.6	936.7	6.8	1,125.8	181.0	-12.8	1,293.9
0.15	9.51	0.54	24.7	157.6	936.7	6.8	1,125.8	181.0	-12.8	1,294.0
0.20	9.51	0.54	24.7	157.6	936.7	6.8	1,125.8	181.0	-12.8	1,294.0
0.25	9.51	0.54	24.7	157.6	936.7	6.8	1,125.8	181.0	-12.8	1,294.0
0.30	9.51	0.54	24.7	157.6	936.8	6.8	1,125.9	181.0	-12.8	1,294.0

These results showed that the percentage of government subsidy for used battery dismantling δ_d to a third party enables a favourable decision making in dismantling

activity of used batteries in CLSC from the viewpoint of social evaluation. The above results are the third answer of RQ4.

6.8 Effect of percentage of government subsidy for the purchase of secondary use batteries η on optimal operation and SW in each model

Tables 10a and 10b show the effect of the percentage of government subsidy for the purchase of secondary use batteries η on the optimal operation, the profits, CS and EI and SW in the second period in models I and III. Based on the assumptions of conditions regarding the optimal decisions for decision variables, p_2 and γ , in model i ($i \in \{I, II, III\}$) in this paper, the standard value of η in each table was chosen as 0.15 and the value of η was varied in increments of 0.05, based on the assumptions of conditions regarding the optimal decisions for decision variables, p_2 and γ , in model i ($i \in \{I, II, III\}$) in this paper. The results are summarized below.

The optimal value of the battery price p_2 in the second period in model II, p_2^{II} , and p_2^{III} in model III are unchanged even if δ_d increases. The optimal value of the secondary use rate in model II, γ^{II} , and γ^{III} in model III are unchanged even if δ_d increases.

As η increases, the profit of a power grid company only increases, while the profits of a third party, a battery manufacturer and a vehicle manufacture are unchanged. As η increases, in models I and III, the profit of CLSC, π_{s2}^I , and π_{s2}^{III} , only increases, while the EI, EI_2^I and EI_2^{III} , and the CS, CS_2^I and CS_2^{III} are unchanged. As a result, the SW in model II, π_{sw2}^I , and π_{sw2}^{III} in model III increases, as η increases.

These results showed that the increase in the percentage of subsidy for secondary use batteries purchase batteries η to a power grid company enables a favourable decision making in purchase of secondary use batteries in CLSC from the viewpoint of social evaluation. The above results are the fourth answer of RQ4.

7 Conclusions

This paper proposed the optimal operation of a two-period CLSC considering quality of used batteries, their secondary use and recycling into materials, and government subsidy programs for the secondary use of batteries, and made SW evaluation for the optimal operation in CLSC. The CLSC consisted a battery manufacturer, a third party, a power grid company, and a vehicle manufacturer. This paper considered model I where the government gives a subsidy η only to a power grid company who purchases secondary use batteries, model II where the government gives subsidies (δ_c , δ_d , η_{th}) to a third party who collects, dismantles, and sells secondary use of used batteries and model III where the government gives a subsidy η to a power grid company who purchases secondary use batteries, and subsidies η , δ_c , δ_d , η_{th} to a third party who collects dismantles used batteries, and sells secondary use batteries.

Numerical analysis first compared the optimal operation, profit and SW of models I, II and III, giving numerical examples. Next, sensitivity analysis clarified how the collection rate θ , the quality classification and recycling rate of used batteries and government subsidies for collection, dismantling and secondary use affected the optimal

operation of the two-period CLSC and the SW. The results of the SW were summarized below.

The SW in second period was equal for models II and III and higher than for model I.

The SW in government subsidy model for collection, dismantling and secondary use in CLSC in the second period was unaffected by changes in the percentage of quality classifications: high quality, medium quality and low quality of used batteries.

As the collection rate of used EV batteries θ increased, the SW in CLSC in second period decreased in model I and increased in models II and III.

The SW in the second period in CLSC increased for all models as λ increased. These results showed that the increase in the recycling rate λ of used batteries enables a favourable decision making in CLSC from the viewpoint of social evaluation.

As the percentage of government subsidy to a third party for secondary use batteries sales η_{th} increased, the SW in second period in models II and III decreased.

As the percentage of subsidy of used battery collection cost δ_c increased, the SW in second period in models II and III increased. The increase in the percentage of subsidy of used battery collection cost δ_c to a third party enabled a favourable decision making in the collection activity of used batteries in CLSC from the viewpoint of social evaluation.

As the percentage of government subsidy for used battery dismantling δ_d increased, the values of SW in models II and III increased. The increase in the percentage of government subsidy for used battery dismantling δ_d to a third party enabled a favourable decision making in dismantling activity of used batteries in CLSC from the viewpoint of social evaluation.

As the percentage of subsidy for secondary use batteries purchase batteries η increased, the values of SW in models II and III increased. The increase in the percentage of subsidy for secondary use batteries purchase batteries η to a power grid company enabled a favourable decision making in purchase of secondary use batteries in CLSC from the viewpoint of social evaluation.

Without public subsidies from the government The two-period CLSC model in this study would be able to promote the secondary use and recycling of used EV batteries by sharing the revenues and costs generated by the secondary use and recycling of used EV batteries among all relevant companies involved in the CLSC in the second period.

The two-period CLSC model in this study mainly targets the automotive industry that handles EV batteries. However, it is possible to replace EV batteries with general products such as home appliances, PCs, and semiconductors. In this case, we believe that the modelling and optimal operation decision methods for secondary use and recycling of used products in the two-period CLSC model proposed in this study can be applied to used products handled by general manufacturing industries.

As future research, it is necessary to incorporate

- 1 the collection rate of used batteries
- 2 the warranty periods of new batteries, secondary use batteries and recycled materials
- 3 government subsidies for activities of collection, dismantling and secondary use into the optimal operation of two-period CLSC.

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References

- Ding, P., Zhao, Z. and Li, X. (2020) 'Government subsidies in the power battery recycling industry', *Industrial Management and Data Systems*, Vol. 120, No. 6, pp.1059–1083.
- Gong, B., Shi, C.V., Li, X. and Cheng, J. (2020) 'Do the subsidies help or hurt the remanufacturing closed-loop supply chain?', *Managerial and Decision Economics*, Vol. 42, No. 4, pp.961–973.
- Gu, X., Zhou, L., Huang, H., Shi, X. and Ieromonachou, P. (2021) 'Electric vehicle battery secondary use under government subsidy: a closed-loop supply chain perspective', *International Journal of Production Economics*, Vol. 234, No. 108035, 14pp.
- He, P., He, Y. and Xu, H. (2019) 'Channel structure and pricing in a dual-channel closed-loop supply chain with government subsidy', *International Journal of Production Economics*, Vol. 213, pp.108–123.
- Hong, Z. and Guo, X. (2019) 'Green product supply chain contracts considering environmental responsibilities', *Omega*, Vol. 83, pp.155–166.
- Krass, D., Nedorezov, T. and Ovchinnikov, A. (2013) 'Environmental taxes and the choice of green technology', *Production and Operations Management*, Vol. 22, No. 5, pp.1035–1055.
- Liu, Y. and Xiao, T. (2020) 'Pricing and collection rate decisions and reverse channel choice in a socially responsible supply chain with green consumers', *IEEE Transactions on Engineering Management*, Vol. 67, No. 2, pp.483–495.
- Nielsen, I.E., Majumder, S. and Saha, S. (2019) 'Game-theoretic analysis to examine how government subsidy policies affect a closed-loop supply chain decision', *Applied Sciences*, Vol. 10, No. 1, p.145, 23pp.
- Wang, W., Yang, S., Xu, L. and Yang, X. (2019) 'Carrot/stick mechanisms for collection responsibility sharing in multi-tier closed-loop supply chain management', *Transportation Research Part E*, Vol. 125, pp.366–387.
- Xiong, Y., Yang, J. and Li, Y. (2016) 'Price and carbon emission decisions under pressures of consumer, regulator and competition', *International Journal of Manufacturing Technology and Management*, Vol. 30, Nos. 1–2, pp.87–115.
- Xue, J., Gong, R., Zhao, L., Ji, X. and Xu, Y. (2019) 'A green supply-chain decision model for energy-saving products that accounts for government subsidies', *Sustainability*, Vol. 11, No. 8, Article ID 2209, pp.1–17.
- Yi, Y. and Li, J. (2018) 'The effect of governmental policies of carbon taxes and energy-saving subsidies on enterprise decisions in a two-echelon supply chain', *Journal of Cleaner Production*, Vol. 181, pp.675–691.