



Incentive strategies for retired power battery closed-loop supply chain considering corporate social responsibility

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Abstract

Global environmental concerns and resource scarcity are driving the growth in sales of electric vehicles (EVs). Reusing and recycling retired batteries from EVs has significant economic value and reduces the environmental burden. Rising raw material prices have intensified competition among recyclers; in particular, recyclers without corporate social responsibility (CSR) have been added. These observations lead to a game-theoretical model consisting of three players: a battery manufacturer, a recycler with CSR and a recycler without CSR (non-CSR). The non-CSR recycler enjoys a cost advantage over the CSR recycler, but may not be considered by the consumers with high environmental awareness (CEA). We explore the incentive strategies for CSR recyclers outperform, and how the equilibrium is affected by the recyclers' Stackelberg game. Results show that (1) the deposit-refund is the most profitable strategy for all members and the whole supply chain if raw material price rises high enough; otherwise, a contract strategy should be adopted. (2) Improving CEA and echelon utilization ratio is more conducive to the implementation of revenue-sharing contract. In addition, increasing CEA contributed to CSR recycler collects more retired batteries instead of non-CSR recycler. (3) Stackelberg game between recyclers may hurt supply chain. However, CSR recycler may benefit from the non-CSR recycler-led Stackelberg game. Our work provides the basis of incentive strategies for different participants in the closed-loop supply chain of retired batteries, in particular, to encourage retired batteries flow to CSR recyclers.

Keywords Retired power battery recycling · Corporate social responsibility · Closed-loop supply chain · Incentive strategies · Stackelberg game

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1 Introduction

Global environmental concerns and resource scarcity are driving the transport sector toward new energy vehicles. The growth of electric vehicles (EVs) has been particularly impressive over the past three years, with sales of 2.2 million electric vehicles in 2019 but tripling to 6.6 million by 2021, accounting for nearly 9% of the global vehicle market. Lithium-ion batteries (LIBs) have become the battery system of choice for EVs, particularly plug-in hybrid electric vehicles (HEVs) and battery electric vehicles (BEVs). This is due to their low weight, higher energy density, long cycle life and the ability to provide deep discharge. By 2025, LIBs battery sales in the HEVs and BEVs markets are expected to reach more than \$15 billion, while up to 21 million cumulative end-of-life LIBs packs will be generated between 2015 and 2040. Studies have shown that reusing and recycling retired LIBs derive significant economic value from the exploitation and reuse of these scarce resources (Gu et al., 2017) and reduce the environmental burden of land and water pollution (Babar et al., 2021; Zeng et al., 2015).

However, LIBs face an increasing challenge on supply chain. The supply of most materials included in LIBs, such as manganese, nickel and natural graphite, is likely to meet near-term demand, while the supply of cobalt is at risk of potential supply disruption (Olivetti et al., 2017; Sun et al., 2019). Over the past few years, shortages of raw materials have led to significant cost fluctuations. Specifically, during the COVID-19 epidemic, supply disruptions caused a significant increase in raw material prices. For example, the price of cobalt has tripled since the beginning of 2017 (from \$30/kg to \$93/kg in March 2018), falling back to just under \$26/kg in July 2019 according to Trading Economics. And battery-grade lithium carbonate has soared from \$17,000/t in 2021 to \$75,000/t in 2022, a growth rate of 341%.

The rise in raw material price has also attracted an influx of recyclers, making competition intensify. Corporate social responsibility (CSR) activities, especially environmental responsibility activities, can bring positive externalities to enterprises and make up for the increased opportunity costs of environmental protection and innovation. Recyclers benefit from recycled materials in retired batteries, which increases as raw material prices rise. This leads to the existence of CSR recyclers and non-CSR recyclers in the market. Recyclers with CSR obtain retired batteries from formal sources and the disassemble and dispose at a cost to meet environmental requirements. Unregulated recycling treatment by non-CSR recyclers is harmful to the environment, safety and resources (De Rousseau et al., 2017; Tian et al., 2020). The COVID-19 pandemic has changed the way consumers travel (Al Halbusi et al., 2022; Mamirkulova et al., 2022; Yu et al., 2022), prompting a continued focus on CSR among business managers (Aman et al., 2019; Raza, 2017). We are concerned about how to increase the flow of retired LIBs to CSR recyclers and increase their profits, given that they do not have a recycling price advantage over non-CSR competitors.

Our work is related to the literature on recycling channel management of closed-loop supply chains (CLSCs), as comprehensively reviewed by Hong et al. (2013), M. Huang et al. (2013), and Savaskan et al. (2004). A strand of papers analyzed profit maximization models to investigate optimal pricing, return rates and production decisions. These essentially answer the question of whether customers should return products to retailers, third parties or directly to OEMs? (De Giovanni & Zaccour, 2014; Gu et al., 2017; Q. He et al., 2019; Y. Huang & Wang, 2018; Johari & Hosseini-Motlagh, 2019). The aforementioned works built several models to analyze and compare the optimal decisions across different recycling channels, few of which involve peer competition in the CLSC. Savaskan et al. (2006) extended the model by introducing competitive retailing in the forward channel. David et al.

(2015) advocated the supply chain with symmetric retailers. De Giovanni (2018) provided a joint incentive mechanism with competitive retailers in the CLSC. In fact, there is a large literature on competitive recycling of Waste Electrical and Electronic Equipment (WEEE) (Liu et al., 2016; Y. Liu et al., 2021; Toyasaki et al., 2011), and given its similarities, recycling of LIBs can build significantly on past experience with general e-waste management and extended producer responsibility (Zeng et al., 2015). However, unlike WEEE, the recycling of LIBs includes cascade utilization, recycling and disposal. Abbasi et al. (2021) analyzed the relationship between electricity consumption, electricity prices and real GDP in commercial and industrial sectors and concluded that waste leads to the rise in electricity prices. And reasonable prices, formal and proper assurance of power demand, can enhance the confidence of the local industry and attract foreign investors (Raza Abbasi et al., 2021). Therefore, our model will take into account the benefits that recyclers derive from cascading and recycling.

In addition, there is also unequal status in the competition between recyclers, such as both parties making decisions at the same time or one of them taking priority. For channel power structures, research has focused on the inequality between upstream suppliers and downstream firms. Choi et al. (2013) studied the performance of CLSCs under different channel leaders and found that the most effective model was one led by the retailer rather than the collector. Saha et al. (2016) demonstrated that each channel member has an incentive to play the channel leader role. Zhao et al. (2022) studied the optimal pricing in three Chinese recycling channels. These studies concluded that in CLSCs, channel leadership belongs to the manufacturer, retailer or collector. Few researchers have focused on changes in leadership among members at the same level. Therefore, our work focuses on the optimal decisions under different types of competition.

Another related stream of the literature focuses on the CSR of members in CLSCs. A set of papers in the literature examines the optimal CSR effort, CSR investment or CSR performance and profit levels (Abbas et al., 2019; Fu et al., 2022; Hosseini-Motlagh et al., 2019; Modak & Kelle, 2021; Ni et al., 2010; Panda et al., 2017). Ni et al. (2010) elaborated on the optimal allocation of social responsibility in a two-echelon supply chain. Modak et al. (2021) integrate CSR in CLSCs with social work donations and recycling investments. Hosseini-Motlagh et al. (2019) explored the optimal level of CSR investment in reverse supply chains. These efforts use philanthropy as the vision of the firm rather than profitability. Bian et al. (2021) advocated a game-theoretical model from the perspective of strategic competition rather than philanthropy and investigate the adoption of operational incentives that are consistent with CSR. Yue et al. (2022) analyzed the importance of CSR for CLSCs in LIBs and found that total profits under CSR would increase. However, there is still a lack of the literature examining competition between CSR members and non-CSR members in LIBs recycling CLSCs.

Generally, our research extends the work of Bian et al. (2021) and Yue et al. (2022) by considering the effect of competition between CSR recycler and non-CSR recycler. Specifically, our work contributes to the literature on CLSCs in the following ways:

1. From an economic, environmental and resource perspective, members' CSR plays a key role in CLSC's profitability. Previous works have focused on finding the optimal level of CSR effort or investment decisions, while our study concentrates on exploring incentive strategies for CSR members to win in competition with non-CSRs.
2. For the LIBs recycling CLSC, we explore the competitive activities between peer recyclers and the impact of competing parties' Stackelberg game on the equilibrium solution, which is different from recycling channel selection in existing studies.

3. Distinct from WEEE recycling, LIBs have a variety of disposal options after collection. Our model incorporates the cascade utilization of retired batteries as well as recycling and discusses the role of consumer environmental awareness (CEA) and the influence of raw material price.

Six different game theory models of retired LIBs CLSCs, respectively, are used to examine the effect of incentive strategies to increase return quantity and profits of CSR recycler. We use these models to answer the following questions:

1. 1 What are the optimal prices, return quantities and profits under different game models?
2. 2 Under different conditions, which incentive strategy is the best, in terms of promoting the return quantity of CSR recycler and the whole CLSC profit?
3. 3 What is the effect of CEA and raw material price on optimal decisions and profit?
4. 4 How does the competitive structure of recyclers affect the optimal performance of the supply chain?

The remainder of the paper is organized as follows. Section 2 describes the model assumptions and notation. Section 3 details the model building and equilibrium solutions. Section 4 contains the equilibrium analysis and sensitivity analysis of the models. Section 4.1 discusses two extensions of the model by exploring the impact of the recycler's Stackelberg game on the equilibrium solution. Finally, we conclude with a summary of our findings in Sect. 4.2.

2 Model Assumptions and Notions

This study focuses on a recycling CLSC for retired LIBs consisting of a battery manufacturer, an CSR recycler (usually retailers), a non-CSR recycler and consumers. According to De Rousseau et al. (2017), retired LIBs can be divided into three categories after collection and testing. Some of them can be used for echelon utilization, such as peak shaving and energy arbitrage, as EV batteries often hold up to 80% of their capacity for their remaining life. Some can be recycled, using smelter technology for material extraction. Note that LIBs can also be recycled after being echelon utilization. The rest are landfilled.

Consider a profit-maximizing CLSC with one battery manufacturer and two competing recyclers. The battery manufacturer, as the Stackelberg leader, charges a wholesale price for new batteries and sets a buy-back price for recycled materials to the recyclers. The CSR recycler (denoted as RF) benefits in both the forward and reverse supply chains, while the non-CSR recycler (denoted as RI) only performs in the reverse supply chain. Following the manufacturer's decisions, recycler RF chooses a retail price and the two recyclers determine their collection prices. Each recycler gains by providing retired LIBs that can be echelon utilization or by selling recycled material to the battery manufacturer.

For focusing on our analysis purposes, in line with the existing literature (Atasu et al., 2013; Q. He et al., 2019), we assume that the firms are perfectly rational and they maximize their respective expected profits to choose their decision variables. Table 1 shows the notations are used for developing the mathematical models.

Superscript $k \in \{D, DRS, DCS, DFS, SF, SI\}$ refers to the vertical Nash game, revenue-sharing contract, cost-sharing contract and deposit-refund scheme, recycler RF Stackelberg game, recycler RI Stackelberg game, respectively. Superscript $l \in \{M, RF, RI, SC\}$ refers to the battery manufacturer, the recycler RF, the recycler RI and the whole supply chain, respectively.

Table 1 Notations

Parameter	Definition
p^k	unit retail price of a new battery
w^k	unit wholesale price of a new battery
τ_l^k	coefficient of the collection price from recycler $l, 0 < \tau_l^k < 1$
p_l^k	unit collection price from recycler l
C_n	unit manufacturing cost of a new battery using raw materials
C_r^k	unit buy-back price of recycled materials
q_l^k	return quantity of recycler $l, q_l^k > 0$
θ	expect value of the retired LIBs in the non-CSR channel, $0 < \theta < 1$
v	cross-recycling value influence coefficient, $0 < v < 1$
I	CSR investment, $I > 0$
α	proportion of return quantity that can be echelon utilization, $0 < \alpha < 1$
A	unit benefit from echelon utilization battery, $A > 0$
Π_l	profit function for CLSC member l

The model is based on the following assumptions.

Assumption 1 Linear dependency between demand for new batteries and their retail prices is considered in this study. Similar demand functions have been used in many other literatures (Atasu et al., 2013; Choi et al., 2013; De Giovanni & Zaccour, 2014). Some scholars have incorporated CSR efforts into the consideration of demand growth (Bian et al., 2021). However, in our research, the impact of CSR efforts on the increased demand for new batteries is no longer considered, since non-CSR recycler is only involved in the reverse supply chain and has no effect on the forward supply chain market. Thus, the demand for new batteries is $D = \phi - p$, where ϕ refers to the market potential, and p is the unit retail price of new batteries.

Assumption 2 Consistent with empirical research and theoretical literature (Choi et al., 2013; Ullah et al., 2021), we assume that battery manufacturer can reduce costs by using recycled materials rather than raw materials to produce new batteries, so the unit manufacturing cost with raw materials C_n should satisfy the condition $C_n > C_r$.

Assumption 3 We consider that customers are heterogeneous in their valuations for recycling channel and denote this characteristic of customers by $v(0 < v < 1)$. The expectation for the RF recycling channel is $v\theta$, while the expectation for the RI recycling channel is θ , where θ is the consumer's valuation of retired LIBs. Following the literature (Timoumi et al., 2021), we consider θ to be uniformly distributed in the interval $[0, 1]$. Specifically, we use $U_{RF} = p_{RF} - v\theta$ to model the net utility of consumers returning retired LIBs to recycler RF at price p_{RF} , and $U_{RI} = p_{RI} - \theta$ to model the net utility of recycler RI. As v approaches 0, consumers perceive a large difference in expected value between the two channels, with the utility value of recycler RF being higher than that of recycler RI. Then, they will prefer the RF recycling channel, which means that such consumers have a higher CEA. And v close to 1 implies different recycling channels have little impact on consumers' willing to

return. Such consumers have a lower level of CEA and choose a recycling channel solely based on the recycling price. Consumers select recycler RF for retired LIBs recycling only when $U_{RF} \geq \max\{U_{RI}, 0\}$ and choose recycler RI when $U_{RI} \geq \max\{U_{RF}, 0\}$. Therefore, we obtain the recycling quantity of recycler RF as $q_{RF} = \frac{p_{RF} - v p_{RI}}{v(1-v)}$, and $q_{RI} = \frac{p_{RI} - p_{RF}}{1-v}$ for recycler RI. The collection price needs to satisfy $p_{RI} > p_{RF} > v p_{RI} > 0$ to ensure that both channels have a positive recycling volume.

Assumption 4 In practice, recyclers set the collection price of retired LIBs based on the proportion of cobalt and nickel extracted from the battery and the price coefficient of cobalt. As cobalt is also a raw material required to produce new batteries, our research focuses on the impact of raw material prices on LIBs collection price. Therefore, collection prices are expressed as $p_{RI} = \tau_{RI} c_n$, $p_{RF} = \tau_{RF} c_n$, where τ_{RI} and τ_{RF} refer to collection price coefficients set by recycler RI and recycler RF, respectively. c_n is the price per unit of raw material represented by cobalt.

Assumption 5 Recycled batteries, after testing, can be classified as echelon use batteries, renewable use batteries and non-hazardous disposal batteries. This study is concerned with the first two cases. The proportions of retired LIBs used for echelon utilization and renewable utilization are α and $1 - \alpha$, respectively. Under extended producer responsibility (EPR), the echelon enterprises are responsible for collecting and recycling the batteries after echelon utilization, and gaining revenue from retired echelon batteries. For example, the benefits of lithium iron phosphate (LFP) batteries direct recycling for recycled materials are low due to the low proportions of lithium, so recycling after echelon utilization will yield the greatest benefits. As echelon enterprises are not part of the CLSC for this study, this revenue is not considered.

Assumption 6 Recycler RF is required to incur CSR costs to meet the minimum environmental protection requirements set by the government, which is an advantage for non-CSR recycler. In addition, following the literature (Bian et al., 2021), we assume that the CSR cost borne by recycler RF to achieve CEA level v is Iv^2 , reflecting the diminishing impact of CEA.

3 Model formulation and solution

3.1 Vertical Nash game model (model D)

We first consider model D, in which there is a vertical Nash game between recyclers. First, the battery manufacturer determines the wholesale price of new batteries and the buy-back price of recycled materials. Then, recycler RF sets the retail price in forward supply chain, while independently fixes the collection price in the reverse supply chain at the same time as the recycler RI. The optimization problem for the CLSC of retired LIBs in model D is as follows.

$$\begin{aligned}
 & \max_{\pi_M} \pi_M(w, c_r | p, p_{RI}, p_{RF}) = (w - c_n)(\phi - p) + (c_n - c_r)(q_{RI} + q_{RF}) \\
 & \text{s.t. } \left\{ \begin{array}{l}
 (p_{RI}) \in \operatorname{argmax}_{\pi_{RI}} = A\alpha q_{RI} + (c_r - p_{RI})(1 - \alpha)q_{RI} \\
 (p, p_{RF}) \in \operatorname{argmax}_{\pi_{RF}} = (p - w)(\phi - p) + A\alpha q_{RF} + (c_r - p_{RF} - Iv^2)(1 - \alpha)q_{RF} \\
 v p_{RI} < p_{RF}
 \end{array} \right.
 \end{aligned} \tag{1}$$

Based on the above constraints, we can apply the Karush–Kuhn–Tucker (KKT) necessity conditions and backward induction to obtain the optimal solution, where the superscript “*” denotes the equilibrium state.

Proposition 1 (Proof in Appendix A)

When condition (2) is satisfied, we find a unique optimal solution for the optimization problem of model D, as shown in Eq. (3).

$$\frac{Iv^2(2 + 2v - v^2)}{(1 - v)(2 + v)} < c_n + \frac{A\alpha}{1 - \alpha} \tag{2}$$

$$\left\{ \begin{array}{l}
 p_{RF}^{D*} = \frac{(v + 2)[A\alpha + c_n(1 - \alpha)] - 2Iv^2(1 - \alpha)}{2(4 - v)(1 - \alpha)} \\
 p_{RI}^{D*} = \frac{3(2 + v)[A\alpha + c_n(1 - \alpha)] + 2Iv^2(1 - v)(1 - \alpha)}{2(2 + v)(4 - v)(1 - \alpha)} \\
 c_r^{D*} = \frac{1}{2} \left[\frac{2Iv^2}{2 + v} + \frac{A\alpha}{\alpha - 1} + 2c_n \right]
 \end{array} \right. \tag{3}$$

And the optimal return quantity by the recyclers is as in Eq. (4).

$$\left\{ \begin{array}{l}
 q_{RF}^{D*} = \frac{(v^2 + v - 2)[A\alpha - c_n(\alpha - 1)] + Iv^2(v^2 - 2v - 2)(\alpha - 1)}{(v - 4)(2 + v)(v - 1)(\alpha - 1)} \\
 q_{RI}^{D*} = \frac{(v^2 + v - 2)[A\alpha - c_n(\alpha - 1)] + 6Iv^2(\alpha - 1)}{2(v - 4)(2 + v)(v - 1)(\alpha - 1)}
 \end{array} \right. \tag{4}$$

3.2 Revenue sharing contract model (model DRS)

In this model, we investigate a battery manufacturer offering a revenue-sharing contract to the recycler RF. After observing the contract, recyclers RF and RI as a follower simultaneously determine the collection prices for retired batteries. The optimization problem for the CLSC of retired LIBs in model DRS is as follows.

$$\begin{aligned}
 & \max_{\pi_M} \pi_M(w, c_r | p, p_{RI}, p_{RF}) = (w - c_n)(\phi - p) + (c_n - c_r)(q_{RI} + q_{RF}) - \delta(c_n - c_r)q_{RF} \\
 & \text{s.t. } \left\{ \begin{array}{l}
 (p_{RI}) \in \operatorname{argmax}_{\pi_{RI}} = A\alpha q_{RI} + (c_r - p_{RI})(1 - \alpha)q_{RI} \\
 (p, p_{RF}) \in \operatorname{argmax}_{\pi_{RF}} = (p - w)(\phi - p) + A\alpha q_{RF} + \delta(c_n - c_r)q_{RF} + (c_r - p_{RF} - Iv^2)(1 - \alpha)q_{RF} \\
 v p_{RI} < p_{RF}
 \end{array} \right.
 \end{aligned} \tag{5}$$

Proposition 2 (Proof in Appendix A)

When condition (6) is satisfied, we find a unique optimal solution for the optimization problem of model DRS, as shown in Eq. (7).

$$\left\{ \begin{aligned} & \frac{2Iv^2(2-3v^2+v^3)(1-\alpha) - 2Iv^2\delta(2-v)(1-v)(2-\alpha) + Iv^2\delta^2(2-v)^2}{2(1-v)^2(2+v)(1-\alpha) - (1-v)(8+v^2-12v+4v\alpha-4\alpha)\delta - 2(1-v)(2-v)\delta^2} < c_n + \frac{A\alpha}{1-\alpha} \\ & v + \delta + \sqrt{12 - (4-\delta)\delta} < 4 \\ & 0 < \alpha < \frac{v + v^2 - 2(1-\delta)^2 - v\delta(4-\delta)}{(2+v-2\delta)(v-1)} \end{aligned} \right. \tag{6}$$

$$\left\{ \begin{aligned} p_{RF}^{DRS*} &= \frac{2Iv^2(\alpha-1) + A\alpha(2+v) + 2\delta c_n}{(v-4)(\alpha-1)} + \frac{[(2+v)(\alpha-1) + 2\delta][Iv^2(\alpha-1)(2-2v-2\delta+v\delta) - A\alpha(v-1)(2+v-2\delta) - c_n[(\alpha-1)(v^2+v-2) - 2\delta(v-1)(\alpha-3) - 2\delta^2(v-2)]]}{(v-4)(\alpha-1)[2(\alpha-1)(v^2+v-2) - 4\delta(v-1)(\alpha-2) - 2\delta^2(v-2)]} \\ p_{RI}^{DRS*} &= \frac{Iv^2(\alpha-1) + 3A\alpha + \delta c_n}{(v-4)(\alpha-1)} + \frac{[3(\alpha-1) + \delta]\{ -c_n[(\alpha-1)(v^2+v-2) - 2\delta(v-1)(\alpha-3) - 2\delta^2(v-2)] \}}{2(v-4)(\alpha-1)[(\alpha-1)(v^2+v-2) - 2\delta(v-1)(\alpha-2) - \delta^2(v-2)]} \\ c_r^{DRS*} &= \frac{A\alpha(v-1)(2+v-2\delta) - Iv^2(\alpha-1)[2+v(\delta-2) - 2\delta] + c_n[(\alpha-1)(v^2+v-2) - 2\delta(v-1)(\alpha-3) - 2\delta^2(v-2)]}{2(\alpha-1)(v^2+v-2) - 4\delta(v-1)(\alpha-2) - 2\delta^2(v-2)} \end{aligned} \right. \tag{7}$$

And the optimal return quantity by the recyclers is as in Eq. (8).

$$\left\{ \begin{aligned} q_{RF}^{DRS*} &= \frac{(v-1)[2(1-v)(2+v)(1-\alpha) - (8-12v+v^2-4\alpha+4v\alpha)\delta + 2(2-v)\delta^2][c_n(\alpha-1) - A\alpha] + Iv^2(\alpha-1)[(4-6v^2+2v^3)(\alpha-1) + 2(2-v)(1-v)(2-\alpha)\delta - (2-v)^2\delta^2]}{2v(4-v)(1-v)(\alpha-1)[(2-v-v^2)(1-\alpha) - 2(1-v)(2-\alpha)\delta + (2-v)\delta^2]} \\ q_{RI}^{DRS*} &= \frac{(v-1)[2(1-v)(2+v)(1-\alpha) - (5v-8+2\alpha-2v\alpha)\delta + 2(3-v)\delta^2][c_n(\alpha-1) - A\alpha] + Iv^2(\alpha-1)[6(v-1)(\alpha-1) + (v-1)(8-v-6\alpha+v\alpha)\delta + (2-v)\delta^2]}{2(4-v)(1-v)(\alpha-1)[(2-v-v^2)(1-\alpha) - 2(1-v)(2-\alpha)\delta + (2-v)\delta^2]} \end{aligned} \right. \tag{8}$$

3.3 Cost-sharing contract model (model DCS)

In this model, we investigate a CSR cost-sharing contract offered by the battery manufacturer to the recycler RF with a CSR cost-sharing ratio of λ . After observing the contract, the recyclers RF and RI act as followers to simultaneously determine the recycling price for retired batteries. The optimization problem for the CLSC of retired LIBs in model DCS is as follows.

$$s.t. \left\{ \begin{aligned} \max \pi_M(w, c_r | p, p_{RI}, p_{RF}) &= (w - c_n)(\phi - p) + (c_n - c_r)(q_{RI} + q_{RF}) - \lambda Iv^2(1-\alpha)q_{RF} \\ (p_{RI}) &\in \operatorname{argmax}_{p_{RI}} = A\alpha q_{RI} + (c_r - p_{RI})(1-\alpha)q_{RI} \\ (p, p_{RF}) &\in \operatorname{argmax}_{p_{RF}} = (p - w)(\phi - p) + A\alpha q_{RF} + [c_r - p_{RF} - (1-\lambda)Iv^2](1-\alpha)q_{RF} \\ & \quad v p_{RI} < p_{RF} \end{aligned} \right. \tag{9}$$

When condition (10) is satisfied, we find a unique optimal solution for the optimization problem of model DCS, as shown in Eq. (11).

$$\frac{Iv^2[v^2 - 2v - 2 + (4 - v)v\lambda + 2(1 - v)\alpha\lambda]}{2 - v - v^2} < c_n + \frac{A\alpha}{1 - \alpha} \tag{10}$$

$$\left\{ \begin{aligned} p_{RF}^{DCS*} &= \frac{(2 + v)[A\alpha - (\alpha - 1)c_n] - 2Iv^2(\alpha\lambda - 1)(\alpha - 1)}{2(v - 4)(\alpha - 1)} \\ p_{RI}^{DCS*} &= \frac{3(2 + v)[A\alpha - (\alpha - 1)c_n] - 2Iv^2(\alpha - 1)[1 - v + (3\alpha + v - 4)\lambda]}{2(v - 4)(2 + v)(\alpha - 1)} \\ c_r^{DCS*} &= \frac{1}{2} \left[\frac{2Iv^2(1 - 2\lambda + \alpha\lambda)}{2 + v} + \frac{A\alpha}{\alpha - 1} + c_n \right] \end{aligned} \right. \tag{11}$$

And the optimal return quantity by the recyclers is as in Eq. (12).

$$\left\{ \begin{aligned} q_{RF}^{DCS*} &= \frac{(2 - v - v^2)[A\alpha + (1 - \alpha)c_n] - Iv^2(1 - \alpha)[2 + 2v - v^2 - v\lambda(4 - v) - 2\alpha\lambda(1 - v)]}{v(4 - v)(1 - v)(2 + v)(1 - \alpha)} \\ q_{RI}^{DCS*} &= \frac{(2 - v - v^2)[A\alpha + (1 - \alpha)c_n] + 2Iv^2(1 - \alpha)[3 + \lambda(4 - v) + \alpha\lambda(1 - v)]}{2(4 - v)(1 - v)(2 + v)(1 - \alpha)} \end{aligned} \right. \tag{12}$$

3.4 Deposit-refund scheme model (model DFS)

Governments increase the recycling rate of used products through diverse policy tools, such as recovery investment subsidies, taxes and subsidies, government supervision, collection and disposal of funds and penalties for non-compliance, incentives or rewards and penalties, advanced recycling fees and government subsidy fees (Hong et al., 2014; Saha et al., 2016; Zhang et al., 2020). Environmentally oriented policies can effectively improve social welfare (Aman et al., 2022). China has implemented a unique deposit-refund scheme to promote effective recycling of EV batteries. Specifically, a recycling fee is levied on EV sales and a subsidy is provided to retailers who collect used EV batteries. In line with Calabrese et al. (2021), we describe this policy in terms of a deposit-refund scheme.

In this model, we discuss the impact of a deposit-refund scheme on competition between CSR recycler and non-CSR recycler. The government levies a recycling and disposal fund F on recycler RF depending on the sale of new batteries, and subsidize recycler RF with s when recycling is complete.

$$\begin{aligned} \max \pi_M(w, c_r | p, p_{RI}, p_{RF}) &= (w - c_n)(\phi - p) + (c_n - c_r)(q_{RI} + q_{RF}) \\ (p_{RI}) \in \operatorname{argmax} \pi_{RI} &= A\alpha q_{RI} + (c_r - p_{RI})(1 - \alpha)q_{RI} \\ \text{s.t. } \left\{ \begin{aligned} (p, p_{RF}) \in \operatorname{argmax} \pi_{RF} &= (p - w - F)(\phi - p) + A\alpha q_{RF} + (c_r - p_{RF} - Iv^2 + s)(1 - \alpha)q_{RF} \\ v p_{RI} &< p_{RF} \end{aligned} \right. \end{aligned} \tag{13}$$

When condition (14) is satisfied, we find a unique optimal solution for the optimization problem of model DFS, as shown in Eq. (15).

$$\frac{(s - Iv^2)(2 + 2v - v^2)}{2 - v - v^2} < c_n + \frac{A\alpha}{1 - \alpha} \tag{14}$$

$$\left\{ \begin{aligned} p^{DFS*} &= \frac{F + 3\phi + c_n}{4} \\ w^{DFS*} &= \frac{\phi + c_n - F}{2} \\ p_{RF}^{DFS*} &= \frac{2(Iv^2 - s)(\alpha - 1) + (2 + v)[A\alpha - (\alpha - 1)c_n]}{2(v - 4)(\alpha - 1)} \\ p_{RI}^{DFS*} &= \frac{2(v - 1)(\alpha - 1)(Iv^2 - s)(\alpha - 1) + 3(2 + v)[A\alpha - (\alpha - 1)c_n]}{2(v - 4)(2 + v)(\alpha - 1)} \\ c_r^{DFS*} &= \frac{1}{2} \left[\frac{2(Iv^2 - s)}{2 + v} + \frac{A\alpha}{\alpha - 1} + c_n \right] \end{aligned} \right. \tag{15}$$

And the optimal return quantity by the recyclers is as in Eq. (16).

$$\left\{ \begin{aligned} q_{RF}^{DFS*} &= \frac{(2 - v - v^2)[A\alpha + c_n(1 - \alpha)] + (s - Iv^2)(2 + 2v - v^2)(1 - \alpha)}{v(4 - v)(1 - v)(2 + v)(1 - \alpha)} \\ q_{RI}^{DFS*} &= \frac{(2 - v - v^2)[A\alpha + c_n(1 - \alpha)] + 6(s - Iv^2)(1 - \alpha)}{2(4 - v)(1 - v)(2 + v)(1 - \alpha)} \end{aligned} \right. \tag{16}$$

Note that $\pi_{SC}^{DFS} \geq \pi_{SC}^D$ must be satisfied for the model DFS to be meaningful, with condition as Eq. (17).

$$\left\{ \begin{aligned} s &< \frac{2(2 - v - v^2)G_2C_n}{4G_1} + \frac{(2 + v)\sqrt{(v - 1)C_n^2[G_3 + 3\alpha G_4 + 4\alpha^2(v - 1)(4 + v - 2v^2)^2] + 3v\phi(\phi - c_n)(4 - v)^2G_1}}{4G_1} \\ F &> \sqrt{(\phi - c_n)^2 + \frac{16s(1 - \alpha)G_1(s - 2Iv^2) - 16s(2 - v - v^2)G_2[A\alpha + (1 - \alpha)c_n]}{3v(1 - v)(4 - v)^2(2 + v)^2(1 - \alpha)}} \end{aligned} \right. \tag{17}$$

where $G_1 = -12 - 11v + 3v^2 + 3v^3 - v^4 + 4\alpha + 17v\alpha - 4v^3\alpha + v^4\alpha$, $G_2 = 12 + 3v - 3v^2 - 4\alpha - v\alpha + 2v^2\alpha$, $G_3 = 96v - 576 - 100v^2 - 64v^3 + 23v^4 + 25v^5 - 11v^6 + v^7$, $G_4 = 128 + 88v^2 - 68v^3 - 7v^4 + 32v^5 - 12v^6 + v^7$.

4 Equilibrium Analysis

The deposit-refund scheme is under the guidance and involvement of the government, but the subsidy funds come from the retailers and can be seen as a policy of EPR. Therefore, we compare the deposit-refund scheme with the contracts. By comparison model D (there is a vertical Nash game between recyclers) with model DRS (battery manufacturer shares revenue with recycler RF), model DCS (battery manufacturer shares CSR cost with recycler RF) and model DFS (government levies recycling fees and subsidies recycler RF), we have the following results. Note that we use the superscript DS which refers to coordinated CLSC.

Proposition 3 (Proof in Appendix B)

The recyclers' collection prices are given as follows:

$$\begin{aligned}
 &P_{RF}^{DFS*} > P_{RF}^{DRS*} > P_{RF}^{DCS*} > P_{RF}^{D*} \\
 &P_{RI}^{D*} > P_{RI}^{DCS*} > P_{RI}^{DFS*} > P_{RI}^{DRS*}
 \end{aligned}$$

Proposition 3 summarizes the results of comparing recyclers' optimal collection prices for the three incentive models with the original one. The collection price of recycler RF increases under all three incentive strategies (i.e., $P_{RF}^{D*} > P_{RF}^{DRS*}$), while the collection price of recycler RI decreases (i.e., $P_{RI}^{D*} > P_{RI}^{DRS*}$). Recall that non-CSR recycler relies on cost advantage to obtain retired LIBs at higher collection price. However, incentive strategies would improve this situation by increasing the collection price of CSR recycler. The deposit-refund option is the most effective in raising CSR recycler's collection price compared to the contract models. But the most effective in reducing prices for non-CSR recyclers is revenue sharing contract.

Proposition 4 (Proof in Appendix B)

The recyclers' recycling quantities are given as follows:

$$\begin{aligned}
 &(a) \quad q_{RF}^{DFS*} > q_{RF}^{DRS*} > q_{RF}^{DCS*} > q_{RF}^{D*} \\
 &(b) \quad q_{RI}^{D*} > q_{RI}^{DCS*} > q_{RI}^{DRS*} > q_{RI}^{DFS*} \quad \text{for} \quad \psi_0(v) < c_n + \frac{A\alpha}{1-\alpha} < \phi_1(v), \quad \text{but} \\
 &q_{RI}^{D*} > q_{RI}^{DCS*} > q_{RI}^{DFS*} > q_{RI}^{DRS*} \quad \text{for} \quad c_n + \frac{A\alpha}{1-\alpha} > \phi_1(v) \\
 &(c) \quad q_{RI+RF}^{DFS*} > q_{RI+RF}^{DCS*} > q_{RI+RF}^{DRS*} > q_{RI+RF}^{D*}
 \end{aligned}$$

Proposition 4 suggests that under all incentive scenarios, higher collection prices generate higher recycling quantities for CSR recycler. This implies that the incentive strategy enhances the recovery of recycler RF (i.e., $q_{RF}^{D*} > q_{RF}^{DRS*}$), and model DFS is the most efficient. This conclusion is consistent with that of the collection price (see Proposition 3 (a)). For recycler RI, lower collection prices have also led to lower recycling quantities. However, the comparison between scenarios DFS and DRS is not as straightforward. The same conclusion (i.e., $q_{RI}^{DFS*} > q_{RI}^{DRS*}$) holds only under certain condition (i.e., $c_n + \frac{A\alpha}{1-\alpha} > \phi_1(v)$). Compared to model D, total recoveries in all incentive strategy models have increased, although recoveries from recycler RI are decreasing (i.e., $q_{RI}^{D*} > q_{RI}^{DRS*}$). This indicates that CSR recycler's recycling is contributing more to the total recycling under the incentive strategy. The most significant improvement is in model DFS, followed by model DCS.

In conclusion, the deposit-refund scheme (model DFS) facilitates higher collection price and recycling quantity of CSR recycler, and even total quantity. Comparisons between contract models show that revenue sharing contract (model DRS) is conducive to higher collection price, while cost-sharing contract (model DCS) is conducive to higher recovery quantity.

Lemma 1 (Proof in Appendix B)

(a) The non-CSR recycler's collection price p_{RI}^* and recycling quantity q_{RI}^* decrease with CEA. However, the CSR recycler's collection price p_{RF}^* decreases with CEA, but quantity q_{RF}^* increases with the CEA. The total recycling quantity q_{RI+RF}^* increases with CEA as well.

(b) The profit of CSR recycler and the whole supply chain increase with CEA, but non-CSR recycler's profit decreases with CEA.

Lemma 1 presents how CEA affects decision variables and profits. Recall that v repre-

sents the difference in the expected value of recycling channels, with smaller values of v referring to more environmentally conscious consumers who prefer CSR recycler. It leads to an increase in recycler RF (i.e., $\frac{\partial q_{RF}^*}{\partial v} < 0$) and higher profits (i.e., $\frac{\partial \Pi_{RF}^*}{\partial v} < 0$). This result suggests that CEA favors lower collection price and boosts the quantity recycled by CSR recycler, even though non-CSR recycler has a higher price advantage (i.e., $p_{RI} > p_{RF}$). However, CEA has the opposite effect on the profitability of recycler RI, which increases strictly in v (i.e., $\frac{\partial \Pi_{RI}^*}{\partial v} > 0$). In short, a higher CEA is more beneficial to CSR recycler and even the entire CLSC, but hurts non-CSR recycler.

Lemma 2 (Proof in Appendix B)

(a) The recyclers' collection price and quantity increase with raw material price c_n which stands for both CSR recycler (i.e., p_{RF}^*, q_{RF}^*) and non-CSR recycler (i.e., p_{RI}^*, q_{RI}^*).

(b) The profits of recyclers and the whole supply chain increase with raw material price c_n .

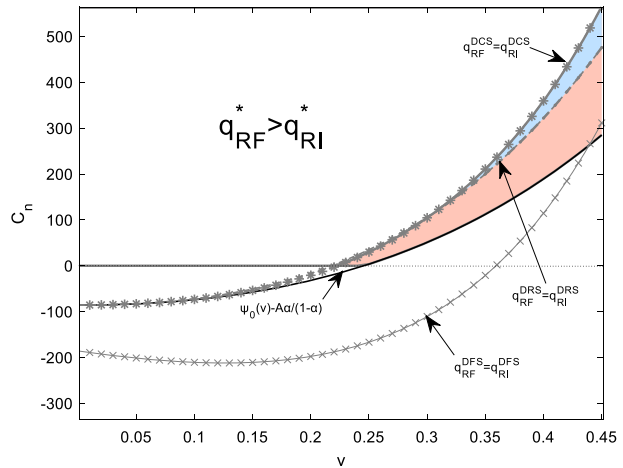
Lemma 2 describes how raw material prices affect decision variables and profits. As the rise in c_n puts more cost pressure on battery manufacturer, they tend to increase their buy-back prices with recyclers to obtain more renewable material for new battery production. Accordingly, recyclers seek more retired LIBs to meet market demand by increasing collection prices. The conclusion suggests that rising raw material prices are driving a boom in the recycling market for retired LIBs, with both collection prices and volumes growing (i.e., $\frac{\partial p^*}{\partial c_n} > 0$ and $\frac{\partial q^*}{\partial c_n} > 0$).

Lemma 2(b) shows that supply chain profits monotonically increase in c_n (i.e., $\frac{\partial \Pi_{SC}^*}{\partial c_n} > 0$), which is the same conclusion as for battery manufacturer and recyclers. This result differs from previous findings in the literature (M. Huang et al., 2013), which show that the profits of manufacturer and supply chain always fall as costs rise. The difference is due to that in our setting the collection price is positively correlated with the raw material price (i.e., $p = \tau c_n, 0 < \tau < 1$). Battery manufacturer benefits from cost savings in recycled materials, while recyclers profit from higher collection prices and quantities, despite rising raw material price. This explains the influx of recyclers into the retired LIBs recycling market during the period of rising raw material costs. It appears that high raw material price makes it more attractive for recyclers and battery manufacturer to participate in the recycling of retired batteries.

4.1 Numerical experiments

This section uses numerical examples to illustrate the performance of the model developed in the previous section and how it varies with parameters, including share ratios and echelon utilization ratio. The following parameters are used: $I = 1000$, $A = 200$, $\phi = 1000$, $\alpha = 0.3$, $\delta = 0.2$, $\lambda = 0.2$, and v is a continuous value from 0 to 0.45, where the value of α, δ, v is within the range calculated by Eq. 6. Note that to ensure the deposit-refund scheme is meaningful ($\pi_{SC}^{DFS} \geq \pi_{SC}^D$), we obtain an upper bound on the subsidy of 146.61 by setting the raw material price equal to 350, where the DFS strategy is optimal for CLSC (see Fig. 2a). Therefore, for simplicity, we assume a subsidy of 100 ($s = 100$) and a fund of 1100 ($F = 1100$) with a lower bound of 1070.220 (see Eq. (17)). The numerical analysis results will validate our findings and provide us with more meaningful insights.

Fig. 1 Recycling volume region for $q_{RF}^* > q_{RI}^*$ in models DRS, DCS and DFS



First, we investigate whether non-CSR recycler collects more retired batteries than CSR recycler under the condition that recycler RI always has a higher recycling price than recycler RF (i.e., $p_{RI} > p_{RF}$). The shaded region is within the bounds of the parameter c_n space (i.e., $c_n > \max\{0, \psi_0(v) - \frac{Az}{1-z}\}$), where $\psi_0(v)$ is obtained from the KKT condition of model DRS (see Eq. (6)). Interestingly, we found that this finding only holds under certain conditions, as shown in Fig. 1. In all incentive strategy models, high raw material price and high CEA are more conducive to promoting recycling quantity by CSR recycler. Moreover, under the model DFS, recycler RF always collected more retired batteries than recycler RI (i.e., $q_{RF}^{DFS*} > q_{RI}^{DFS*}$), as the threshold value (i.e., $q_{RF}^{DFS*} = q_{RI}^{DFS*}$) is outside the boundary space. Compared to model DCS, there is a larger area where $q_{RF}^* > q_{RI}^*$ can be achieved in the DRS model, since revenue sharing contract is more effective in boosting the quantity of recycler RF recovered (i.e., $q_{RF}^{DRS*} > q_{RF}^{DCS*}$) and reducing the amount of recycler RI recovered (i.e., $q_{RI}^{DCS*} > q_{RI}^{DRS*}$) than cost-sharing contract, as demonstrated in Proposition 4(b).

Next, we examine the performance of supply chain members in different situations as shown in Fig. 2. Similarly, shaded region is within the boundary of the parameter c_n space for the same KKT condition (i.e., $c_n > \max\{0, \psi_0(v) - \frac{Az}{1-z}\}$). The equilibrium results show that the deposit-refund scheme is the most advantageous option for all members, if raw material price c_n is sufficiently high. And if raw material price c_n is low, the most effective strategy is contract (see Fig. 2a–d). In addition, we find the range support for model DRS gets larger than that of model DCS as v becomes smaller. Therefore, battery manufacturer and recycler RF are more likely to adopt a revenue-sharing contract strategy if there is a high CEA. Otherwise, the battery manufacturer is more inclined to share CSR cost with the recycler RF (see Fig. 2b, c). These findings are consistent with Proposition 4(c), where a deposit-refund scheme proves to be the most efficient strategy for increasing recycler recovery, followed by a cost-sharing contract strategy (i.e., $q_{RI+RF}^{DFS*} > q_{RI+RF}^{DCS*} > q_{RI+RF}^{DRS*}$).

In general, if raw material price is sufficiently high, a deposit-refund scheme is a better option for all members, even the entire supply chain. Otherwise, revenue-sharing contract is

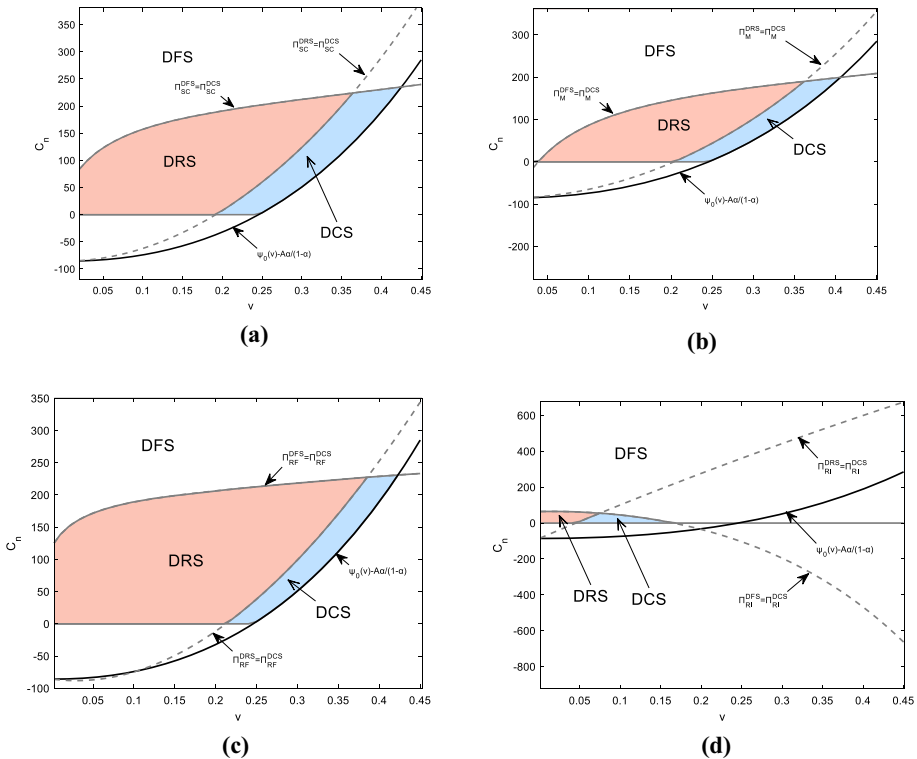


Fig. 2 Characterization of equilibrium region in models DRS, DCS and DFS; (a) CLSC; (b) battery manufacturer; (c) CSR recycler (RF); and (d) non-CSR recycler (RI)

more favorable to CLSC when CEA is high, while cost-sharing contract is more advantageous when CEA is low.

4.2 Sensitivity analysis

In this subsection, we investigate how parameters affect the equilibrium decisions in different models. Specifically, it includes revenue sharing rate (δ), cost sharing rate (λ), echelon utilization rate (α), recycling disposal fund (F) and recycling subsidy (s), respectively. Following the literature (Ge et al., 2022), the optimal decision choice of supply chain members is represented by the equilibrium region, which is divided by two lines at the parameter space boundary (i.e., $C_e > \max\{0, \psi_0(v) - \frac{A\alpha}{1-\alpha}\}$). One line represents the comparison between the model DFS and the model DCS, obtained by the equation $\Pi^{DFS} = \Pi^{DCS}$; the other line represents the comparison between the model DRS and the model DCS, obtained by $\Pi^{DRS} = \Pi^{DCS}$.

4.2.1 Effects of revenue sharing rate δ

First, we examine the impact of the revenue sharing rate δ on supply chain performance. Since deposit-refund scheme and cost-sharing contract are not affected by δ , we use gray

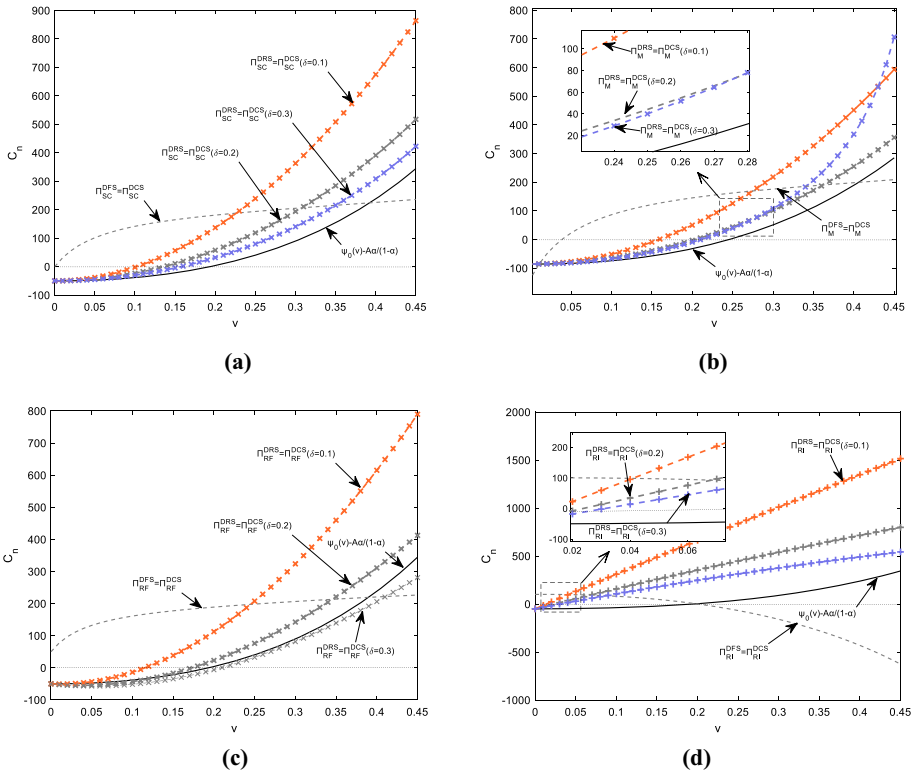


Fig. 3 The impact of δ on the profits of CLSC and members; **(a)** CLSC; **(b)** battery manufacturer; **(c)** CSR recycler (RF); and **(d)** non-CSR recycler (RI)

lines to indicate that the threshold $\Pi^{DFS} = \Pi^{DCS}$ does not vary with δ . As revenue-sharing contract will hurt the battery manufacturer's profit, we set an upper limit ($\delta < 0.7769$) through the equations $\pi_M^{DRS} \geq \pi_M^D$ and $\pi_{RF}^{DRS} \geq \pi_{RF}^D$ to make the contract acceptable to both parties. Figure 3 shows the change in the equilibrium region for revenue sharing ratios of $\delta = 0.1$, $\delta = 0.2$, $\delta = 0.3$, respectively. Recall that in the contract model, the revenue sharing strategy is optimal for both the battery manufacturer and the recycler RF (see Fig. 2b, c). There is no doubt that as δ increases, the equilibrium area of model DRS becomes progressively larger and model DCS decreases accordingly (see Fig. 3a–d). This means that revenue sharing has a wider applicability condition. It is worth noting that at $\delta = 0.3$, battery manufacturer only opts for revenue-sharing contract when the CEA is high (see Fig. 3b). In contrast, the recycler RF will not choose a cost-sharing contract under any condition (see Fig. 3c), due to $\delta=0.3$ being outside the space boundary (i.e., $c_n > \max\{0, \psi_0(v) - \frac{A\alpha}{1-\alpha}\}$).

4.2.2 Effects of cost-sharing rate λ

Similarly, we simulate the effects of λ on manufacturer, recyclers and CLSC performance. The upper limit of the cost sharing rate ($\lambda < 0.6956$) is obtained through the equations $\pi_M^{DCS} \geq \pi_M^D$ and $\pi_{RF}^{DCS} \geq \pi_{RF}^D$ to ensure acceptance of the contract by both parties.

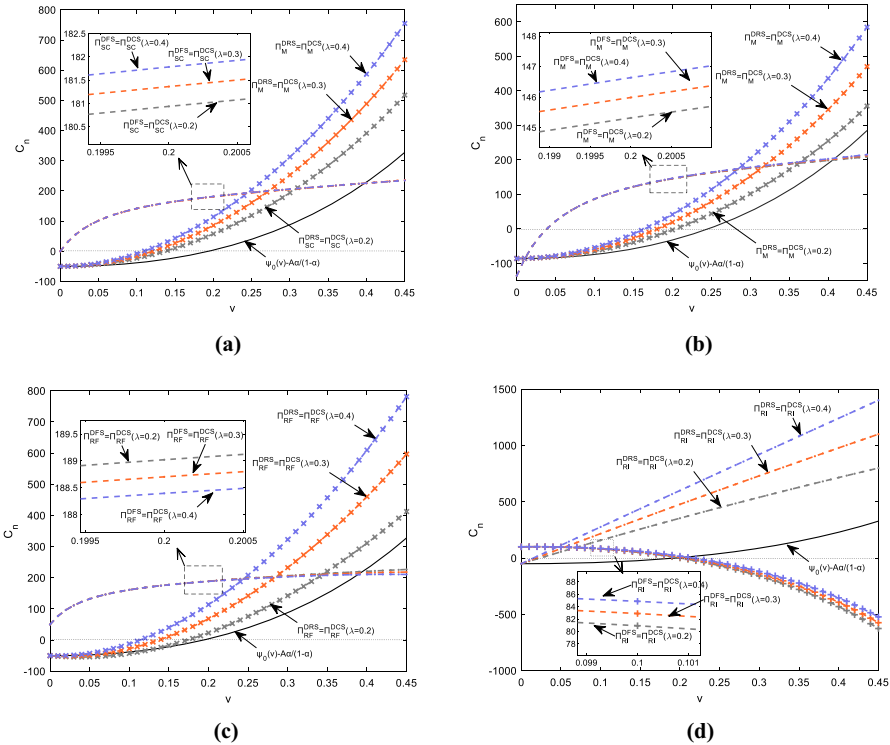


Fig. 4 The impact of λ on the profits of CLSC and members; **(a)** CLSC; **(b)** battery manufacturer; **(c)** CSR recycler (RF); and **(d)** non-CSR recycler (RI)

Changes in cost sharing ratio have an impact on both dividing lines, and Fig. 4 illustrates the equilibrium region for cost sharing ratios of $\lambda = 0.2$, $\lambda = 0.3$ and $\lambda = 0.4$, respectively. Compared to model DRS, as λ increases, the equilibrium region of model DCS is expanding and CLSC prefers cost-sharing contract instead of revenue-sharing contract (see Fig. 4a–d). The same conclusion holds for model DFS except recycler RF (see Fig. 4a, b, d). However, we find recycler RF has the largest equilibrium region at the lowest cost sharing ratio (i.e., $\lambda = 0.2$). In fact, a variation in λ is more significant for the threshold $\Pi^{DRS} = \Pi^{DCS}$ than that for the threshold $\Pi^{DFS} = \Pi^{DCS}$. This suggests an increase in the cost sharing ratio (λ) has insignificant effect on CSR recycler's optimal strategy, but can expand the conditions under which cost-sharing contract applies compared to revenue sharing contract.

4.2.3 Effects of echelon utilization rate α

Renewable energy can effectively restrain carbon emission (Abbasi, Adedoyin, et al., 2021), and echelon utilization is an important way to regenerate retired batteries. We are interested in the impact of echelon utilization rate (α) on the CLSC and member profits. The range of α value is $[0, 0.84]$, which is obtained from the KKT condition of the model DRS (see Eq. (6)). We therefore chose $\alpha = 0.3, 0.4, 0.5$ to simulate the three cases, and the effect is shown in Fig. 5. We first examine the effects of α on the threshold $\Pi^{DRS} = \Pi^{DCS}$ and find that an increase in α moves the contract decision closer to a revenue sharing contract. This

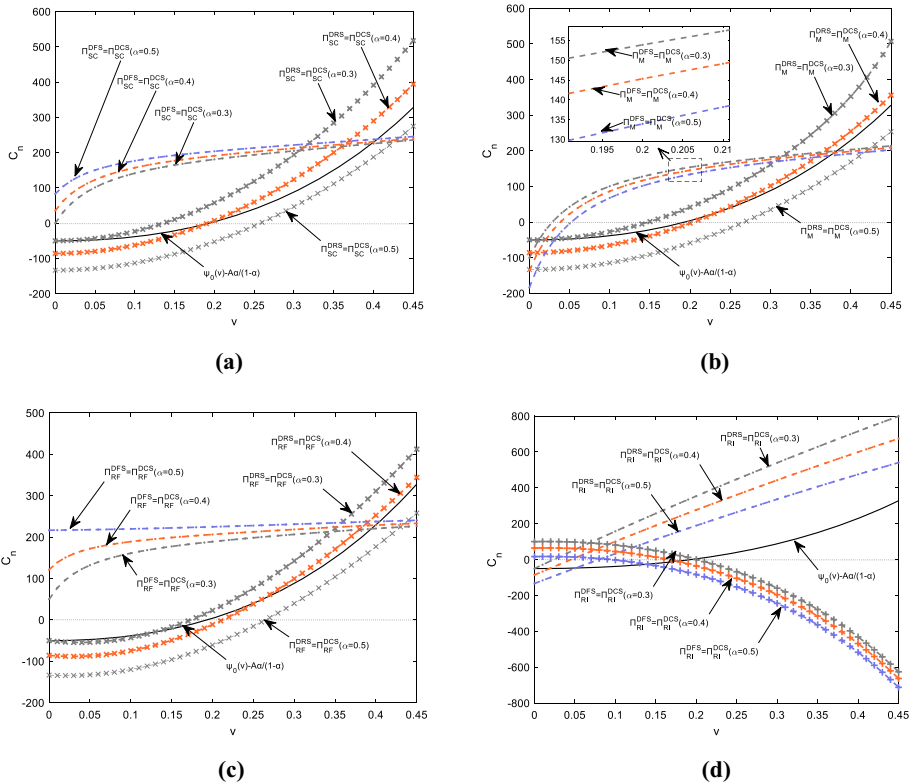


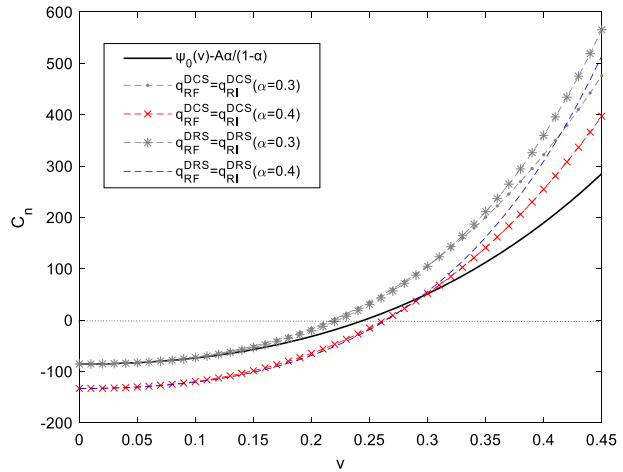
Fig. 5 The impact of α on the profits of CLSC and members; (a) CLSC; (b) battery manufacturer; (c) CSR recycler (RF); and (d) non-CSR recycler (RI)

observation holds for CLSC and all members (see Fig. 5a–d). Moreover, when α reaches 0.5, there is no opportunity to choose a cost-sharing contract, except for recycler RI (see Fig. 5a–c), as the equilibrium region of the model DCS is beyond the space boundary (i.e., $c_n > \max\{0, \psi_0(v) - \frac{A\alpha}{1-\alpha}\}$). The effect of α on the threshold $\Pi^{DFS} = \Pi^{DCS}$ shows an increase in the echelon utilization rate is beneficial for the CLSC (see Fig. 5a) and the recycler RF (see Fig. 5c) to choose a cost-sharing contract. Interestingly, we observe that this finding is the exact opposite for battery manufacturer and recycler RI. With increasing α , they prefer the deposit-refund option as the line $(\Pi^{DFS} = \Pi^{DCS})$ shifts downward (see Fig. 5b, d).

Overall, when comparing the decisions between model DRS and model DCS, both battery manufacturer and CSR recycler would prefer revenue-sharing contract over cost-sharing contract, as α increases. This finding is consistent with the CLSC and non-CSR recycler. However, a comparison of model DFS and model DCS shows that battery manufacturer prefers the deposit-refund option, while CSR recycler opts for cost-sharing contract.

Recall that non-CSR recycler does not collect more retired batteries than CSR recycler under the condition that recycler RI always has a higher collection price (i.e., $p_{RI} > p_{RF}$). Revenue-sharing contract has been proved to be more effective in promoting the recycling quantity of CSR recycler (i.e., $q_{RF}^{DRS*} > q_{RF}^{DCS*}$) and reducing the recycling quantity of

Fig. 6 The impact of α on recyclers' recycling quantity



non-CSR recycler (i.e., $q_{RI}^{DCS*} > q_{RI}^{DRS*}$) than cost-sharing contract, as demonstrated in Proposition 4 and shown in Fig. 1. Figure 6 illustrates the impact of echelon utilization rate on the recyclers' recycling quantity when α is increased from 0.3 to 0.4. The result shows that under both contract incentives, an increase in echelon utilization rate is more beneficial to CSR recycler's recycling volumes, and that cost-sharing contract is more effective.

4.2.4 Effects of deposit fund F and subsidy s

Dynamic incentives and penalties have been shown to be effective in motivating manufacturers to participate in battery recycling (He & Sun, 2022). In this subsection, we examine the impact of the recycling disposal fund F and subsidy s on supply chain performance. Setting the raw material price equal to 350 yields an upper bound of 146.61 for s and a lower bound of 1070.220 for F (see Eq. (17)), to ensure that the deposit-refund policy is meaningful ($\pi_{SC}^{DFS} \geq \pi_{SC}^D$). Following the literature on deposit refunds (Calabrese et al., 2021), we argue that recycler RF can receive up to 50% of the disposal fund (i.e., $F \geq 2s$) and that increasing subsidy within a range can promote the recycling of retired LIBs. Using the same analysis, we can obtain a threshold value of F for 992.181 when s is equal to 120 and 882.702 when s is equal to 140 (see Eq. (17)). Therefore, we assume a 10% reduction in the disposal fund and a 20% increase in the subsidy for each option, i.e., Scenario I ($F = 1100, s = 100$), Scenario II ($F = 992, s = 120$) and Scenario III ($F = 891, s = 140$) as shown in Fig. 7. Consistent with Fig. 3, we use the gray lines to refer to the fact that the threshold $\Pi^{DRS} = \Pi^{DCS}$ does not vary with F and s . Scenario III intuitively outperforms Scenario I for recycler RF, which expands the equilibrium region of model DFS as the line $\Pi^{DFS} = \Pi^{DCS}$ shifts downward (see Fig. 7c), while recycler RI moves closer to the contract strategy under Scenario III than that under Scenario I, as the line $\Pi^{DFS} = \Pi^{DCS}$ move upward (see Fig. 7d). However, the comparison is less straightforward for battery manufacturer and CLSC. Compared to Scenario I, the supply chain under Scenario III expands the equilibrium region of model DFS when both c_n and v are low, while it enlarges the equilibrium region of model DCS when both c_n and v are high (see Fig. 7a). The same conclusion holds for battery manufacturer as shown in Fig. 7b.

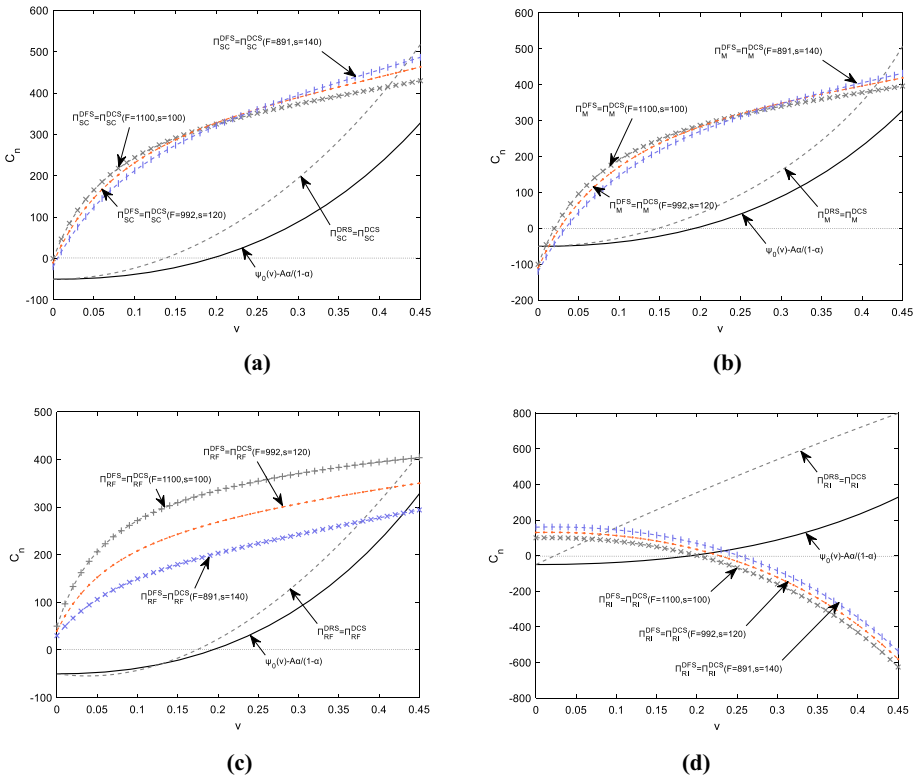


Fig. 7 The impact of F and s on the profits of CLSC and members; (a) CLSC; (b) battery manufacturer; (c) CSR recycler (RF); and (d) non-CSR recycler (RI)

Overall, the simultaneous reduction of disposal fund and increase in subsidy make the choice of model DFS more widely applicable for CSR recycler, but the opposite conclusion is reached for non-CSR recycler. For battery manufacturer and CLSC, on the other hand, the threshold line only moves in favor of model DFS if raw material price is low and CEA is high.

We use Table 2 to show the changes of equilibrium regions of different participants and supply chains with the increase in parameters. Note the equilibrium region variations of

Table 2 Equilibrium region varies as the parameters increase

	Battery manufacturer			CSR recycler			Non-CSR recycler			Closed-loop supply chain		
	DFS	DRS	DCS	DFS	DRS	DCS	DFS	DRS	DCS	DFS	DRS	DCS
δ	-	↑	↓	-	↑	↓	-	↑	↓	-	↑	↓
λ	↓	↓	↑	↑	↓	↑	↓	↓	↑	↓	↓	↑
α	↑	↑	↓	↓	↑	↓	↑	↑	↓	↓	↑	↓
F	↑/↓	-	-	↓	-	↑	↓	-	↑	↑/↓	-	-

battery manufacturer and supply chain as deposit fund F is nonmonotonic. The conclusion depends on raw material prices and CEA.

5 Model extensions: Stackelberg game model

5.1 CSR recycler Stackelberg game model (model SF)

Corporate business strategy, size and status have obvious influence on the firm’s performance (Mubeen et al., 2022; X. Zhang et al., 2022). In this model, recycler RF acts as a leader, setting the retail price and collection price in preference to the battery manufacturer who gives the wholesale price and the buy-back price for recycled material. Recycler RI acts as a follower in setting the collection price.

With condition (18) is satisfied, we find a unique optimal solution for the optimization problem of model SF, as shown in Eq. (19).

$$\frac{Iv^2(2 - v)(1 + v)}{2(1 - v)} < c_n + \frac{A\alpha}{1 - \alpha} \tag{18}$$

$$\left\{ \begin{aligned} c_r^{SF*} &= \frac{1}{4} \left[Iv^2(2 - v) + \frac{2A\alpha}{\alpha - 1} + 2c_n \right] \\ p_{RF}^{SF*} &= \frac{2[c_n(\alpha - 1) - A\alpha] + Iv^2(v - 2)(\alpha - 1)}{4(2 - v)(\alpha - 1)} \\ p_{RI}^{SF*} &= \frac{2(3 - v)[c_n(\alpha - 1) - A\alpha] + Iv^2(v - 2)(v - 1)(\alpha - 1)}{8(2 - v)(\alpha - 1)} \end{aligned} \right. \tag{19}$$

And the optimal return quantity by the recyclers is as in Eq. (20).

$$\left\{ \begin{aligned} q_{RF}^{SF*} &= \frac{2(v - 1)(v - 4)[c_n(\alpha - 1) - A\alpha] + Iv^2(2 + v - v^2)(\alpha - 1)}{8v(v - 1)(\alpha - 1)} \\ q_{RI}^{SF*} &= \frac{1}{8} \left[\frac{Iv^2(3 - v)}{(1 - v)} + \frac{2A\alpha}{(1 - \alpha)(2 - v)} + \frac{2c_n}{2 - v} \right] \end{aligned} \right. \tag{20}$$

5.2 Non-CSR recycler Stackelberg game model (model SI)

We now consider model SI, in which recycler RI determines the collection price after the battery manufacturer gives the wholesale price and the buy-back price of recycled material. Recycler RF acts as a follower and sets the collection price after the recycler RI.

With condition (21) is satisfied, we find a unique optimal solution for the optimization problem of model SI, as shown in Eq. (22).

$$\frac{Iv^2(16 + 8v - 23v^2 + 7v^3)}{(4 - v)(1 - v)(4 + v - v^2)} < c_n + \frac{A\alpha}{1 - \alpha} \tag{21}$$

$$\left\{ \begin{aligned} c_r^{SI*} &= \frac{1}{2} \left[\frac{Iv^2(v-4)}{v^2-v-4} + \frac{A\alpha}{\alpha-1} + c_n \right] \\ p_{RF}^{SI*} &= \frac{(v^2-v-4)[c_n(\alpha-1) - A\alpha] - Iv^2(v-4)(\alpha-1)}{8(v-2)(\alpha-1)c_n} \\ p_{RI}^{SI*} &= \frac{(v^2-v-4)(v-3)[c_n(\alpha-1) - A\alpha] + Iv^2(3v^2-9v+8)(\alpha-1)}{4(v-2)(\alpha-1)(v^2-v-4)c_n} \end{aligned} \right. \quad (22)$$

And the optimal return quantities by the recyclers is as in Eq. (23).

$$\left\{ \begin{aligned} q_{RF}^{SI*} &= \frac{(v^2-v-4)(v-1)(v-4)[c_n(\alpha-1) - A\alpha] + Iv^2(16+8v-23v^2+7v^3)(\alpha-1)}{8v(v-2)(v-1)(v^2-v-4)(\alpha-1)} \\ q_{RI}^{SI*} &= \frac{1}{8} \left[\frac{Iv^2(v^2+3v-12)}{(v^2-v-4)(1-v)} + \frac{A\alpha}{1-\alpha} + c_n \right] \end{aligned} \right. \quad (23)$$

5.3 Equilibrium Analysis

By comparing model D (there is a vertical Nash game between recyclers) with model SF (recycler RF is the leader of Stackelberg game) and model SI (recycler RI is the leader of Stackelberg game), we obtain the following results. Note that, for simplicity, we use the superscript S which refers to Stackelberg game.

Proposition 5 (Proof in Appendix B)

The impacts of Stackelberg games on optimal collection prices are:

- (a) $p_{RF}^{D*} > p_{RF}^{SI*} > p_{RF}^{SF*} > 0$
- (b) $p_{RI}^{D*} > p_{RI}^{SF*} > p_{RI}^{SI*} > 0$.

Proposition 5 illustrates the collection price decisions when different recyclers act as leaders of the Stackelberg game. In the vertical Nash game, competing recyclers both give higher collection prices (i.e., $p_{RF}^{D*} > p_{RF}^{S*}$ and $p_{RI}^{D*} > p_{RI}^{S*}$) to obtain a competitive advantage. In contrast, recyclers set the collection price based on the competitor's price as a follower in the Stackelberg game. It usually leads to a higher price in the competitor's Stackelberg game. This conclusion holds true for both CSR recycler and non-CSR recycler (i.e., $p_{RF}^{SI*} > p_{RF}^{SF*}$ and $p_{RI}^{SF*} > p_{RI}^{SI*}$).

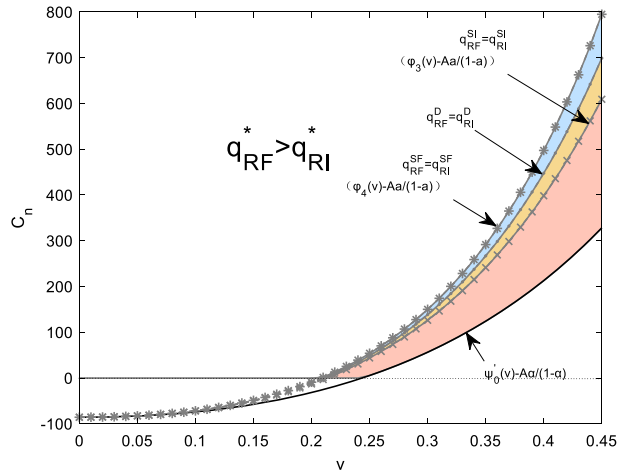
Proposition 6 (Proof in Appendix B)

The impacts of Stackelberg games on optimal recycling quantities are:

- (a) $q_{RF}^{SI*} > q_{RF}^{D*} > q_{RF}^{SF*}$, $q_{RI}^{SF*} > q_{RI}^{D*} > q_{RI}^{SI*}$ for $c_n + \frac{A\alpha}{1-\alpha} > \varphi_2(v)$, but $q_{RI}^{D*} > q_{RI}^{SF*} > q_{RI}^{SI*} > 0$ for $\psi_0'(v) < c_n + \frac{A\alpha}{1-\alpha} < \varphi_2(v)$
- (b) $q_{RI}^* > q_{RF}^*$ for $\psi_0'(v) < c_n + \frac{A\alpha}{1-\alpha} < \varphi_3(v)$, but $q_{RF}^* > q_{RI}^*$ for $\varphi_4(v) < c_n + \frac{A\alpha}{1-\alpha}$
- (c) $q_{RI+RF}^{D*} > q_{RI+RF}^{SI*} > q_{RI+RF}^{SF*}$

We compare the collection quantity of retired LIBs under the Stackelberg games, summarized in Proposition 6. Higher collection price results in higher recycling quantities in the Stackelberg game as well, which is consistent with the conclusion of Proposition 4. Recyclers outperform in competitor-led Stackelberg games (i.e., $q_{RF}^{SI*} > q_{RF}^{SF*}$ and $q_{RI}^{SF*} > q_{RI}^{SI*}$). However, this conclusion does not always hold under the vertical Nash game. Our results show that CSR recycler collected more retired LIBs in model SI than in

Fig. 8 Recycling volume region for $q_{RF}^* > q_{RI}^*$ in models D, SF and SI



model D (i.e., $q_{RF}^{SI*} > q_{RF}^{D*}$), while non-CSR recyclers hold the same conclusion only under conditions (i.e., $c_n + \frac{A\alpha}{1-\alpha} > \varphi_2(v)$), which are closely related to raw material price and CEA (see Proposition 6(a)).

Similarly, non-CSR recycler does not always collect more retired batteries than CSR recycler, even though the recycler RI has a higher collection price consistently (i.e., $p_{RI} > p_{RF}$). To present this conclusion visually (Proposition 6(b)), a numerical example is carried out using the following parameters: $I = 1000, A = 200, \alpha = 0.3$, and v is a continuous value from 0 to 0.45 as illustrated in Fig. 8. The space boundary for the parameter c_n (i.e., $c_n > \max\{0, \psi_0'(v) - \frac{A\alpha}{1-\alpha}\}$) is obtained from the KKT condition of the model SF (see Eq. (18)). High raw material price and high CEA have been shown to be more conducive to boosting recycler RF's recycling quantity (see Fig. 1). Compared to model D, model SI expands the range of conditions under which equation $q_{RF}^* > q_{RI}^*$ holds, while model SF narrows it. This is aligned with the finding that recyclers perform well in competitor-led games (see Proposition 6(a)). Furthermore, the higher the CEA, the more retired LIBs CSR recycler is able to collect for the same raw material price, reminding us of the significance of raising the CEA to improve CSR recycler's recycling volumes.

For total recoveries, the Stackelberg game scenario is not higher than the vertical Nash game (i.e., $q_{RI+RF}^{D*} > q_{RI+RF}^{S*}$). And the recycler RI leads Stackelberg game outstanding performance. Recall that in model SI, recycler RF enjoys the highest recycling quantity, while recycler RI has the lowest (see Proposition 6(a)), which implies a greater contribution from CSR recycler.

Proposition 7 (Proof in Appendix B)

The profits of CLSC and its members are shown below.

- (a) $\Pi_{SC}^{D*} > \Pi_{SC}^{SF*} > \Pi_{SC}^{SI*}$ for $\psi_1(v) < c_n + \frac{A\alpha}{1-\alpha}$ but $\Pi_{SC}^{D*} > \Pi_{SC}^{SI*} > \Pi_{SC}^{SF*}$ for $\psi_0'(v) < c_n + \frac{A\alpha}{1-\alpha} < \psi_1(v)$
- (b) $\Pi_M^{D*} > \Pi_M^{SI*} > \Pi_M^{SF*}$ for $\psi_0'(v) < c_n + \frac{A\alpha}{1-\alpha}$
- (c) $\Pi_{RF}^{SI*} > \Pi_{RF}^{SF*} > \Pi_{RF}^{D*}$ for $\psi_2(v) < c_n + \frac{A\alpha}{1-\alpha}$ but $\Pi_{RF}^{SI*} > \Pi_{RF}^{D*} > \Pi_{RF}^{SF*}$ for $\psi_0'(v) < c_n + \frac{A\alpha}{1-\alpha} < \psi_2(v)$
- (d) $\Pi_{RI}^{SF*} > \Pi_{RI}^{SI*} > \Pi_{RI}^{D*}$ for $\psi_3(v) < c_n + \frac{A\alpha}{1-\alpha}$ but $\Pi_{RI}^{SI*} > \Pi_{RI}^{SF*} > \Pi_{RI}^{D*}$ for $\psi_0'(v) < c_n + \frac{A\alpha}{1-\alpha} < \psi_3(v)$

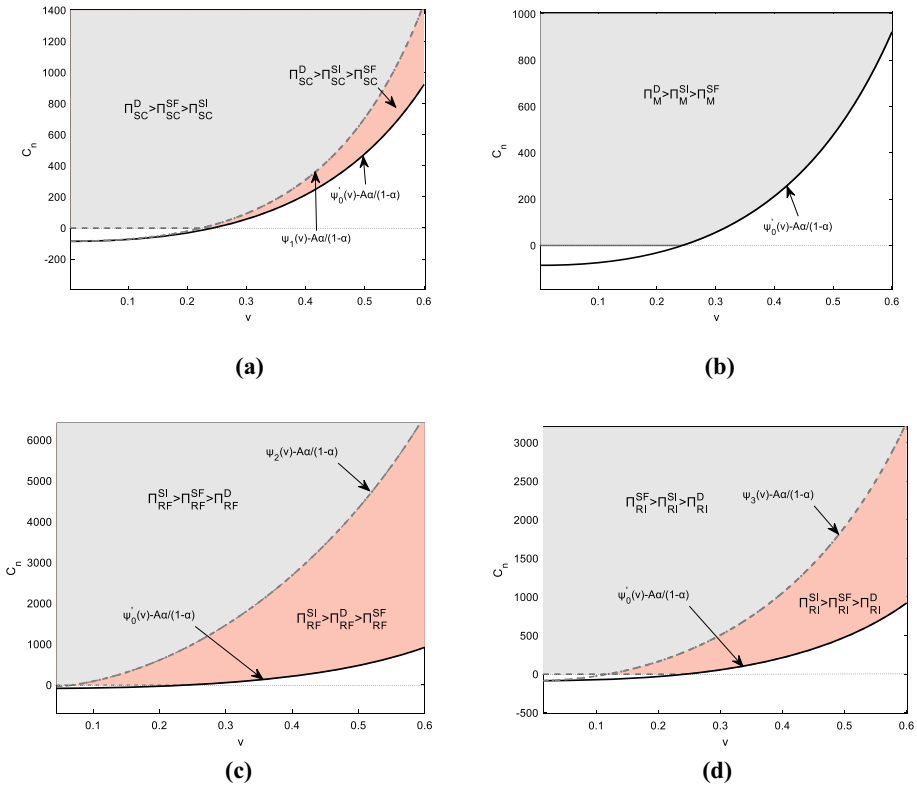


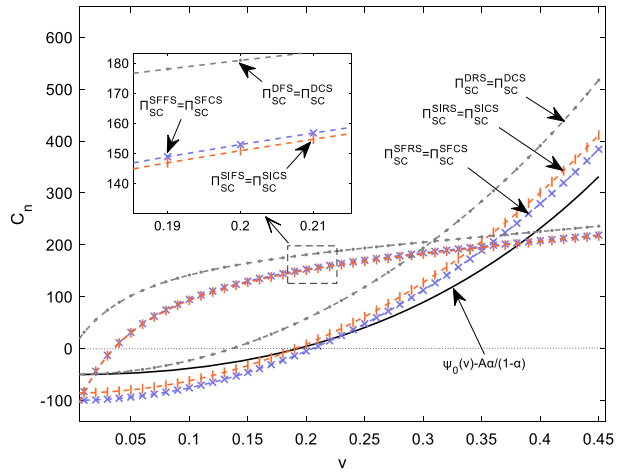
Fig. 9 Characterization of equilibrium region in models D, SF and SI; (a) CLSC; (b) battery manufacturer; (c) CSR recycler (RF); and (d) non-CSR recycler (RI)

Proposition 7 discusses how the Stackelberg game between recyclers affects the profits of CLSC and its members, which are closely related to raw material price and CEA. Again, numerical simulations are carried out using the parameters: $I = 1000, A = 200, \alpha = 0.3$, and v is a continuous value from 0 to 0.6. All the cases in Proposition 7(a)–(d) are depicted by the different regions in Fig. 9a–d.

According to Proposition 7(a) and Fig. 9a, the profit under the vertical Nash game is higher than that under Stackelberg game for CLSC (i.e., $\Pi_{SC}^{D*} > \Pi_{SC}^{S*}$), indicating that the recyclers’ Stackelberg game will hurt supply chain profit. Moreover, the profit loss under model SF is relatively less than under model SI, if raw material price and CEA are high. As shown in Fig. 9b, the vertical Nash game has an absolute advantage for the battery manufacturer over the Stackelberg game. Since total recycling quantity is highest in model D and lowest in model SF (see Proposition 6(c)), the battery manufacturer benefits from cost savings in recycled material and accordingly enjoys the highest profits in model D and lowest profits in model SF (see Proposition 7(b)). It implies that the Stackelberg game is equally detrimental to battery manufacturer’s profit.

Contrary to the findings of the battery manufacturer and CLSC, recycler RF has the best performance in the model SI (i.e., $\Pi_{RF}^{SI*} > \Pi_{RF}^{SF*}$ and $\Pi_{RF}^{SI*} > \Pi_{RF}^{D*}$), as shown in Fig. 9c. The intuition behind this result is that given the competition from recycler RI in model SI, recycler RF obtains more retired batteries at a higher recycling price (i.e.,

Fig. 10 The impact of recyclers' Stackelberg game on the CLSC



$q_{RF}^{SI*} > q_{RF}^{D*} > q_{RF}^{SF*}$ in Proposition 6(a)). As to whether the Stackelberg game is always better than the Nash game, it depends on the raw material price and CEA. Specifically, the Stackelberg game has an advantage when c_n and CEA are high, and conversely, profits are higher under the Nash game. We can find that the most unprofitable situation for recycler RI is the Nash game, just as the most profitable situation for recycler RF is model SI. Recycler RI is always more lucrative in the Stackelberg game than in the vertical Nash game (i.e., $\Pi_{RI}^{SF*} > \Pi_{RI}^{D*}$ and $\Pi_{RI}^{SI*} > \Pi_{RI}^{D*}$), as shown in Fig. 9d. The conclusion that recycler RI performs better in the competitor-led Stackelberg game when c_n and CEA are high holds again. Recycler RI has the highest recycling quantity in model SF (see Proposition 6(a)) for the same reason.

We have discussed the advantages and conditions for the application of incentive strategies under the vertical Nash game (see Fig. 2). The Stackelberg game among recyclers is also shown to have an impact on the optimal collection price, recycling volume and CLSC profit (see Propositions 5, 6 and 7). Therefore, we examine how the equilibrium regions of different incentive models shift under the Stackelberg game of recyclers. The comparison results are shown in Fig. 10. We obtain the thresholds $\Pi^{SFFS} = \Pi^{SFCS}$ and $\Pi^{SFRS} = \Pi^{SFCS}$ by calculating the optimal decisions for the revenue sharing contract model (SFRS), the cost-sharing contract model (SFCS) and the deposit-refund scheme model (SFFS) under the recycler RF Stackelberg game. The same approach can be used to obtain the optimal decision under the recycler RI Stackelberg game, denoted by the superscript SI instead of SF. The results show that the recyclers' Stackelberg game causes both lines to move downward and, accordingly, the equilibrium region for the deposit-refund scheme and the revenue sharing contract expands. In addition, the CSR recycler Stackelberg game expands the equilibrium region of the revenue sharing contract as shown by the line $\Pi^{SFRS} = \Pi^{SFCS}$ moving downward, while the non-CSR recycler Stackelberg game expands the equilibrium region of the deposit-refund scheme as shown by the straight line $\Pi^{SIFS} = \Pi^{SICCS}$ moving downward.

In general, the deposit-refund scheme is more conducive to promoting CLSC profit when CSR recycler leads the Stackelberg game, while the revenue-sharing contract is more effective than cost-sharing contract when non-CSR recycler leads the Stackelberg game.

6 Conclusions

6.1 Main Conclusions

In this article, we seek insights into incentive strategies in which CSR recycler can outperform better than non-CSR recycler, and how the equilibrium is affected by the recyclers' Stackelberg games. Inspired by some examples found in practice, we involve a three parties in the game model: a battery manufacturer that produces new batteries using raw or recycled materials, a CSR recycler that recycles at a CSR cost and a non-CSR recycler that enjoys a cost-saving advantage. Both recyclers profit from the sale of echelon utilized batteries and recycled materials. We explore the decisions of retired LIBs CLSC in four scenarios: a vertical Nash game model (model D), a revenue-sharing contract model (model DRS), a cost-sharing contract model (model DCS) and a deposit-refund scheme model (model DFS). In addition, we extend the model to the context of the Stackelberg game for recyclers.

Our research has the following conclusions:

- (1) Compared with contracts, the deposit-refund scheme (model DFS) not only increases the collection price of CSR recycler, but also promotes the recovery quantity. However, the contrast between contract models indicates that revenue-sharing contract (model DRS) favors higher collection price, while cost-sharing contract (model DCS) favors higher recycling quantity.
- (2) If raw material price is sufficiently high, the deposit-refund scheme is the most profitable strategy for all members, even for the whole supply chain. Otherwise, revenue-sharing contract is optimal for the performance of supply chain members when consumer environmental awareness (CEA) is high, while cost-sharing contract is more advantageous for the low CEA.
- (3) The results of extended model comparison show that recyclers outperform in the competitor-led Stackelberg games. CSR recycler has a higher collection price, recycling quantity and even profits in non-CSR recycler Stackelberg game, under the condition of high raw material price and CEA.
- (4) For the supply chain's performance, the deposit-refund scheme is the optimal strategy when the CSR recycler leads Stackelberg game, while the ideal solution is revenue-sharing contract when the non-CSR recycler leads Stackelberg game.

6.2 Limitations

The major limitations of the present study are the raw materials price and less consideration of battery quality. Although we creatively correlate raw material price with the collection price of retired batteries, due to the limitations of model building, only the major raw material price can be considered. In fact, the recycling of metals such as lithium, cobalt and nickel is also of concern. Secondly, battery quality also affects the recovery and disposal of retired batteries. In spite of batteries decay over time, our model is based on static games, and the results are still valid.

6.3 Recommendations

We provide some management advice for retired LIBs CLSC and members. Our findings suggest that (1) if raw material price rises sufficiently high, the deposit-refund

scheme (model DFS) is the optimal choice for all members and supply chain. Otherwise, a contract strategy should be adopted. (2) Improving consumer environmental awareness (CEA) and echelon utilization ratio is more conducive to the implementation of revenue-sharing contract (model DRS). (3) In addition, increasing CEA contributed to CSR recycler collects more retired batteries instead of non-CSR recycler. (4) For CLSC, avoiding the Stackelberg game between recyclers can increase total recycling quantities and thus contribute to total profits. (5) As a follower recycler, bidding after observing competitors' pricing in Stackelberg game may lead to higher recycling quantity, which is beneficial to both recyclers.

The research could be extended in the following ways: (1) The same competition observed in practice within the group of CSR recyclers and non-CSR recyclers could be considered in future studies. (2) Considering the quality of retired batteries (e.g., the health of the batteries) can be an insight for seeking more diverse management advice in the future.

6.4 Implications

Our research provides suggestions for the selection of incentive strategies for different participants in the closed-loop supply chain of retired batteries. In general, the deposit-refund scheme (model DFS) is the most profitable choice for all members and the supply chain, followed by contracts, in particular, to encourage retired batteries flow to CSR recyclers. Moreover, this study verifies the role of consumer environmental awareness (CEA) and raw material price in promoting the recycling price and quantity of CSR recycler.

Appendix A

Proof of Proposition 1

Based on the backward deduction rule, set $\frac{\partial \pi_{RI}}{\partial p_{RI}} = 0$, $\frac{\partial \pi_{RF}}{\partial p_{RF}} = 0$, then, $p_{RF} = \frac{(2+v)[c_r(1-\alpha)+A\alpha]-2Iv^2(1-\alpha)}{(4-v)(1-\alpha)}$, $p_{RI} = \frac{3[c_r(1-\alpha)+A\alpha]-Iv^2(1-\alpha)}{(4-v)(1-\alpha)}$

Substituting p_{RI} and p_{RF} in the profit function of the battery manufacturer, we gain

$$\begin{aligned} \max \pi_M(w, c_r | p, p_{RI}, p_{RF}) &= \frac{[(c_r - c_n)][(Iv^2 - 2c_r)(1 - \alpha) - 2A\alpha] + (1 - \alpha)(\phi - w)(w - c_n)}{2(1 - \alpha)} \\ \text{s.t. } &\frac{3v[c_r(1 - \alpha) + A\alpha] - Iv^2(1 - \alpha)}{(4 - v)(1 - \alpha)} - \frac{(2 + v)[c_r(1 - \alpha) + A\alpha] - 2Iv^2(1 - \alpha)}{(4 - v)(1 - \alpha)} < 0 \end{aligned}$$

Set $\frac{[(c_r - c_n)][(Iv^2 - 2c_r)(1 - \alpha) - 2A\alpha] + (1 - \alpha)(\phi - w)(w - c_n)}{2(1 - \alpha)} = f(x)$, $\frac{3v[c_r(1 - \alpha) + A\alpha] - Iv^2(1 - \alpha)}{(4 - v)(1 - \alpha)} - \frac{(2 + v)[c_r(1 - \alpha) + A\alpha] - 2Iv^2(1 - \alpha)}{(4 - v)(1 - \alpha)} = g(x)$

The Karush–Kuhn–Tucker (KKT) conditions of the above-constrained optimization problem are shown as follows

$$\begin{cases} *f(x) + *\gamma g(x) = 0 \\ \gamma g(x) = 0, \gamma \geq 0 \end{cases}$$

(1) When $\gamma > 0$, since $g(x) = 0$

$$p_{RI} = \frac{(1-\alpha)(2c_n - Iv^2) + 2A\alpha}{4(1-\alpha)}, p_{RF} = \frac{(1-\alpha)(2c_n - Iv^2)v + 2A\alpha v}{4(1-\alpha)}, q_{RI} = \frac{1}{4}(2c_n + \frac{2A\alpha}{1-\alpha} - Iv^2), q_{RF} = 0$$

Under this optimal condition, the recycler RF will not get any batteries, and we do not consider this situation of this study.

(2) When $\gamma = 0$,

$$p_{RF} = \frac{(v+2)[A\alpha + c_n(1-\alpha)] - 2Iv^2(1-\alpha)}{2(4-v)(1-\alpha)}, p_{RI} = \frac{3(2+v)[A\alpha + c_n(1-\alpha)] + 2Iv^2(1-v)(1-\alpha)}{2(2+v)(4-v)(1-\alpha)}$$

Since $g(x) < 0$

$$\frac{Iv^2(2 + 2v - v^2)}{(1 - v)(2 + v)} < c_n + \frac{A\alpha}{1 - \alpha} \tag{A1}$$

is the condition that should be met for above p_{RF} and p_{RI} .

We can use the same method to obtain the KKT conditions of model SF as:

$$\frac{Iv^2(2 - v)(1 + v)}{2(1 - v)} < c_n + \frac{A\alpha}{1 - \alpha} \tag{A2}$$

And the KKT condition of model SI is:

$$\frac{Iv^2(16 + 8v - 23v^2 + 7v^3)}{(4 - v)(1 - v)(4 + v - v^2)} < c_n + \frac{A\alpha}{1 - \alpha} \tag{A3}$$

Proof of Proposition 2

Based on the backward deduction rule, set $\frac{\partial \pi_{RI}}{\partial p_{RI}} = 0, \frac{\partial \pi_{RF}}{\partial p_{RF}} = 0$ then,

$$p_{RF} = \frac{v(1-\alpha)(c_r - 2Iv) + A\alpha(2+v) + (2-2\alpha-2\delta)c_r}{(4-v)(1-\alpha)}, p_{RI} = \frac{3A\alpha + \delta c_n + (3-3\alpha-\delta)c_r}{(4-v)(1-\alpha)}$$

Substituting p_{RI} and p_{RF} in the profit function of the battery manufacturer, we gain

$$\begin{aligned} & [Iv^2(1-\alpha)(c_r + c_n) - \delta c_n^2](2-2v+v\delta-2\delta) + 2A\alpha(1-v)(2+v-2\delta)(c_r - c_n) \\ & - 2c_n c_r [(2-v-v^2)(1-\alpha) - 2\delta(1-v)(3-\alpha) + 2\delta^2(2-v)] \\ & + 2c_r^2 [(2-v-v^2)(1-\alpha) - 2\delta(1-v)(2-\alpha) - \delta^2(2-v)] \\ \max \pi_M(w, c_r | p, p_{RI}, p_{RF}) = & \frac{\hspace{15em}}{2v(1-\alpha)(4-v)(v-1)} \\ - \frac{(c_n - w)(w - \phi)}{2} \text{ s.t. } & \frac{v[3A\alpha + \delta c_n + (3 - 3\alpha - \delta)c_r]}{(4 - v)(1 - \alpha)} - \frac{v(1 - \alpha)(c_r - 2Iv) + A\alpha(2 + v) + (2 - 2\alpha - 2\delta)c_r}{(4 - v)(1 - \alpha)} < 0 \end{aligned}$$

$$\begin{aligned} & [Iv^2(1-\alpha)(c_r + c_n) - \delta c_n^2](2-2v+v\delta-2\delta) + 2A\alpha(1-v)(2+v-2\delta)(c_r - c_n) \\ & - 2c_n c_r [(2-v-v^2)(1-\alpha) - 2\delta(1-v)(3-\alpha) + 2\delta^2(2-v)] \\ & + 2c_r^2 [(2-v-v^2)(1-\alpha) - 2\delta(1-v)(2-\alpha) - \delta^2(2-v)] \\ \text{Set } & \frac{\hspace{15em}}{2v(1-\alpha)(4-v)(v-1)} \\ \frac{(c_n - w)(w - \phi)}{2} = & k(x), \end{aligned}$$

$$\begin{aligned} & \frac{v[3A\alpha + \delta c_n + (3 - 3\alpha - \delta)c_r]}{(4 - v)(1 - \alpha)} - \frac{v(1 - \alpha)(c_r - 2Iv) + A\alpha(2 + v) + (2 - 2\alpha - 2\delta)c_r}{(4 - v)(1 - \alpha)} \\ & = l(x). \end{aligned}$$

The Karush–Kuhn–Tucker (KKT) conditions of the above-constrained optimization problem are shown as follows

$$\begin{cases} \nabla k(x) + \gamma \nabla l(x) = 0 \\ \gamma l(x) = 0, \gamma \geq 0 \end{cases}$$

(1) When $\gamma > 0$, since $l(x) = 0$

$$p_{RI} = \frac{(1-\alpha)(2c_n - Iv^2) + 2A\alpha}{4(1-\alpha)}, p_{RF} = \frac{(1-\alpha)(2c_n - Iv^2)v + 2A\alpha v}{4(1-\alpha)}, q_{RI} = \frac{1}{4} (2c_n + \frac{2A\alpha}{1-\alpha} - Iv^2),$$

$$q_{RF} = 0$$

Under this optimal condition, the recycler RF will not get any batteries, and we do not consider this situation of this study.

(2) When $\gamma = 0$,

$$p_{RF}^{DRS*} = \frac{2Iv^2(\alpha - 1) + A\alpha(2 + v) + 2\delta c_n}{(v - 4)(\alpha - 1)}$$

$$+ \frac{[(2 + v)(\alpha - 1) + 2\delta][Iv^2(\alpha - 1)(2 - 2v - 2\delta + v\delta) - A\alpha(v - 1)(2 + v - 2\delta) - c_n[(\alpha - 1)(v^2 + v - 2) - 2\delta(v - 1)(\alpha - 3) - 2\delta^2(v - 2)]]}{(v - 4)(\alpha - 1)[2(\alpha - 1)(v^2 + v - 2) - 4\delta(v - 1)(\alpha - 2) - 2\delta^2(v - 2)]}$$

$$p_{RI}^{DRS*} = \frac{Iv^2(\alpha - 1) + 3A\alpha + \delta c_n}{(v - 4)(\alpha - 1)}$$

$$+ \frac{[3(\alpha - 1) + \delta] \{ -c_n[(\alpha - 1)(v^2 + v - 2) - 2\delta(v - 1)(\alpha - 3) - 2\delta^2(v - 2)] \}}{2(v - 4)(\alpha - 1)[(\alpha - 1)(v^2 + v - 2) - 2\delta(v - 1)(\alpha - 2) - \delta^2(v - 2)]}$$

Since $g(x) < 0$

$$\left\{ \begin{aligned} & \frac{2Iv^2(2 - 3v^2 + v^3)(1 - \alpha) - 2Iv^2\delta(2 - v)(1 - v)(2 - \alpha) + Iv^2\delta^2(2 - v)^2}{2(1 - v)^2(2 + v)(1 - \alpha) - (1 - v)(8 + v^2 - 12v + 4v\alpha - 4\alpha)\delta - 2(1 - v)(2 - v)\delta^2} < c_n + \frac{A\alpha}{1 - \alpha} \\ & v + \delta + \sqrt{12 - (4 - \delta)\delta} < 4 \\ & 0 < \alpha < \frac{v + v^2 - 2(1 - \delta)^2 - v\delta(4 - \delta)}{(2 + v - 2\delta)(v - 1)} \end{aligned} \right.$$

(A4)

is the condition should be met for above p_{RF} and p_{RI} .

We can use the same method to obtain the KKT conditions of model DCS as:

$$\frac{Iv^2[v^2 - 2v - 2 + (4 - v)v\lambda + 2(1 - v)\alpha\lambda]}{2 - v - v^2} < c_n + \frac{A\alpha}{1 - \alpha}$$

(A5)

And the KKT condition of model DFS is:

$$\frac{(s - Iv^2)(2 + 2v - v^2)}{2 - v - v^2} < c_n + \frac{A\alpha}{1 - \alpha}$$

(A6)

Appendix B

Proof of Proposition 3

(a) Comparing the optimal prices of recycler RF in model D, model DRS, model DCS and model DFS, we obtain:

$$\begin{aligned}
 p_{RF}^{DFS*} - p_{RF}^{DRS*} &= \frac{s}{4-v} + \frac{[A\alpha + c_n(1-\alpha)] - Iv^3\delta^3(1-\alpha)^2}{2(1-\alpha)[2\delta(1-v)(2-\alpha) - (2-v-v^2)(1-\alpha) - \delta^2(2-v)]} > 0, \\
 p_{RF}^{DRS*} - p_{RF}^{DCS*} &= \frac{Iv^2\alpha\lambda}{4-v} + \frac{[A\alpha + c_n(1-\alpha)] - Iv^3\delta^3(1-\alpha)^2}{2(1-\alpha)[2\delta(1-v)(2-\alpha) - (2-v-v^2)(1-\alpha) - \delta^2(2-v)]} > 0, \\
 p_{RF}^{DCS*} - p_{RF}^{D*} &= \frac{Iv^2\alpha\lambda}{4-v} > 0.
 \end{aligned}$$

It can be easily checked that $p_{RF}^{DFS*} > p_{RF}^{DRS*} > p_{RF}^{DCS*} > p_{RF}^{D*}$ always holds when Eqs.(A4)-(A6) are satisfied.

(b) Comparing the optimal prices of recycler RI in model D, model DRS, model DCS and model DFS, we obtain:

$$p_{RI}^{D*} - p_{RI}^{DCS*} = \frac{Iv^2\lambda(4-v-3\alpha)}{(4-v)(2+v)} > 0, \quad p_{RI}^{DCS*} - p_{RI}^{DFS*} = \frac{s(1-v) - Iv^2\lambda(4-v-3\alpha)}{(4-v)(2+v)} > 0,$$

$$\begin{aligned}
 p_{RI}^{DFS*} - p_{RI}^{DRS*} &= \frac{(s-Iv^2)(1-v)}{(4-v)(2+v)} + \frac{2Iv^2(1-\alpha) + 2\delta c_n + 3[A\alpha + c_n(1-\alpha)]}{2(4-v)(1-\alpha)} + \\
 &\frac{(3-3\alpha-\delta)\{A(1-v)\alpha(2+v-2\delta) + Iv^2(1-\alpha)(2+v(2-\delta)) + 2\delta\}}{2(1-\alpha)[2\delta(1-v)(2-\alpha) - (2-v-v^2)(1-\alpha) - \delta^2(2-v)]} > 0.
 \end{aligned}$$

It can be easily checked that $p_{RI}^{D*} > p_{RI}^{DCS*} > p_{RI}^{DFS*} > p_{RI}^{DRS*}$ always holds when Eqs. (A4)-(A6) are satisfied.

Proof of Proposition 4

(a) Comparing the optimal quantity of recycler RF in model D, model DRS, model DCS and model DFS, we obtain:

$$\begin{aligned}
 q_{RF}^{DFS*} - q_{RF}^{DRS*} &= \frac{2s + (2-v)sv}{v(4-v)(2-v-v^2)} + \frac{(2-v-v^2)[A\alpha + c_n(1-\alpha)] - Iv^2(1-\alpha)[(2-v-v^2)\delta + (2-v)\delta^2]}{2(1-\alpha)(2-v-v^2)[2\delta(1-v)(2-\alpha) - (2-v-v^2)(1-\alpha) - \delta^2(2-v)]} > 0, \\
 q_{RF}^{DRS*} - q_{RF}^{DCS*} &= \frac{Iv^2\lambda[(4-v) + 2\alpha(1-v)]}{v(4-v)(2-v-v^2)} + \frac{[A\alpha + c_n(1-\alpha)] - Iv^2(4-v)[2\delta(1-v)(2-\alpha) + (2-v)\delta^2]}{2(1-\alpha)(2-v-v^2)(4-v)[2\delta(1-v)(2-\alpha) - (2-v-v^2)(1-\alpha) - \delta^2(2-v)]} > 0, \\
 q_{RF}^{DCS*} - q_{RF}^{D*} &= \frac{Iv^2\lambda[(4-v) + 2\alpha(1-v)]}{(4-v)(2-v-v^2)} > 0.
 \end{aligned}$$

It can be easily checked that $q_{RF}^{DFS*} > q_{RF}^{DRS*} > q_{RF}^{DCS*} > q_{RF}^{D*}$ always holds when Eqs.(A4)-(A6) are satisfied.

(b) Comparing the optimal quantity of recycler RI in model D, model DRS, model DCS and model DFS, we obtain:

$$q_{RI}^{D*} - q_{RI}^{DCS*} = \frac{lv^2\lambda[(4-v) + \alpha(1-v)]}{(4-v)(2-v-v^2)} > 0,$$

$$q_{RI}^{DCS*} - q_{RI}^{DRS*} = \frac{lv^2\lambda[(4-v) + \alpha(1-v)]}{(4-v)(2-v-v^2)} + \frac{\delta(1-\delta)[A\alpha + c_n(1-\alpha)] + 2lv^2(1-\delta) + lv^3[(1-v)\alpha + v + \delta - 3]}{2(1-\alpha)(2-v-v^2)[2\delta(1-v)(2-\alpha) - (2-v-v^2)(1-\alpha) - \delta^2(2-v)]} > 0,$$

$$q_{RI}^{DCS*} - q_{RI}^{DFS*} = \frac{3s + lv^2\lambda(4-v-\alpha + v\alpha)}{(4-v)(2-v-v^2)} > 0.$$

It can be easily checked that $q_{RI}^{D*} > q_{RI}^{DCS*} > q_{RI}^{DRS*}$ and $q_{RI}^{D*} > q_{RI}^{DCS*} > q_{RI}^{DFS*}$ always holds when Eqs.(A4)-(A6) are satisfied.

$$q_{RI}^{DRS*} - q_{RI}^{DFS*} = \frac{3s + 3lv^2 + [A\alpha + c_n(1-\alpha)]}{(4-v)(2-v-v^2)} + \frac{(1-v)[A\alpha + c_n(1-\alpha)][(2-v-v^2)(1-\alpha) - (8-5v-2\alpha + 2v\alpha)\delta + 2(3-v)\delta^2] + lv^2(1-\alpha)[6(1-v)(1-\alpha) + (1-v)(8-v + v\alpha - 6\alpha)\delta - (2-v)\delta^2]}{2(1-\alpha)(2-v-v^2)[2\delta(1-v)(2-\alpha) - (2-v-v^2)(1-\alpha) - \delta^2(2-v)]}.$$

$q_{RI}^{DRS*} - q_{RI}^{DFS*} > 0$ For $\psi_0(v) < c_n + \frac{A\alpha}{1-\alpha} < \varphi_1(v)$, but $q_{RI}^{DRS*} - q_{RI}^{DFS*} < 0$ for $c_n + \frac{A\alpha}{1-\alpha} > \varphi_1(v)$, where $\psi_0(v) = \frac{2lv^2(2-3v^2+v^3)(1-\alpha) - 2lv^2\delta(2-v)(1-v)(2-\alpha) + lv^2\delta^2(2-v)^2}{2(1-v)^2(2+v)(1-\alpha) - (1-v)(8+v^2 - 12v + 4v\alpha - 4\alpha)\delta - 2(1-v)(2-v)\delta^2}$
 $\varphi_1(v) = \frac{6s[(1-v)(2+v)(1-\alpha) - 2\delta(1-v)(2-\alpha) + \delta^2(2-v)] + lv^2[(2-v)\delta - (1-v)(2-v + v\alpha)]}{(4-v)(1-v)(2+v)(1-\delta)\delta}$.

(c) Comparing the optimal quantity of recycler RF and RI in model D, model DRS, model DCS and model DFS, we obtain:

$$q_{RI+RF}^{DFS*} - q_{RI+RF}^{DCS*} = \frac{s - lv^2\alpha\lambda}{(4-v)v} > 0,$$

$$q_{RI+RF}^{DCS*} - q_{RI+RF}^{DRS*} = \frac{lv\alpha\lambda}{4-v} + \frac{lv^2\delta(1-\alpha)^2 + \delta^2[A\alpha + c_n(1-\alpha)]}{2(1-\alpha)(2-v-v^2)[2\delta(1-v)(2-\alpha) - (2-v-v^2)(1-\alpha) - \delta^2(2-v)]} > 0,$$

$$q_{RI+RF}^{DRS*} - q_{RI+RF}^{D*} = \frac{lv^2\delta(1-\alpha)^2 + \delta^2[A\alpha + c_n(1-\alpha)]}{2(1-\alpha)(2-v-v^2)[2\delta(1-v)(2-\alpha) - (2-v-v^2)(1-\alpha) - \delta^2(2-v)]} > 0.$$

The conclusion $q_{RI+RF}^{DFS*} > q_{RI+RF}^{DCS*} > q_{RI+RF}^{DRS*} > q_{RI+RF}^{D*}$ always holds when Eqs.(A4)-(A6) are satisfied.

Proof of Lemma 1

Comparing the derivatives of optimal decision variables and profits with respect to v in model D, we obtain:

$$\frac{\partial p_{RF}^{D^*}}{\partial v} = \frac{3[A\alpha + c_n(1-\alpha)] - Iv^2(8-v)(1-\alpha)}{(4-v)^2(1-\alpha)} > 0,$$

$$\frac{\partial p_{RI}^{D^*}}{\partial v} = \frac{3[A\alpha + c_n(1-\alpha)] - 2Iv(1-\alpha)(22v - 16 + 4v^2 - v^3)}{2(2+v)^2(4-v)^2(1-\alpha)} > 0,$$

$$\frac{\partial q_{RF}^{D^*}}{\partial v} = \frac{2(2-v)(2-v-v^2)^2[A\alpha + c_n(1-\alpha)] - Iv^2(1-\alpha)(16 + 32v - 30v^2 + 8v^3 + v^4)}{v^2(2-v-v^2)^2(4-v)^2(1-\alpha)} < 0,$$

$$\frac{\partial q_{RI}^{D^*}}{\partial v} = \frac{(2-v-v^2)^2[A\alpha + c_n(1-\alpha)] - 6Iv(1-\alpha)(16 - 6v - v^3)}{2(2-v-v^2)^2(4-v)^2(1-\alpha)} > 0,$$

$$\frac{\partial \Pi_{RF}^{D^*}}{\partial v} = \frac{+2A\alpha c_n(16 + 4v + 5v^3 + 2v^4) - (2+v)^2(4-3v+2v^2)(1-\alpha)c_n^2 + I^2v^2(2-2v+v^2)(48+52v-106v^2+24v^3+11v^4-2v^5)(1-\alpha)}{v^2(2+v)^2(4-v)^3} + \frac{I^2v^2(2-2v+v^2)(48+52v-106v^2+24v^3+11v^4-2v^5)(1-\alpha)}{(-1+v)^2(2+v)^3(4-v)^3} > 0,$$

$$+ \frac{A^2\alpha^2(4-3v+2v^2)}{v^2(1-\alpha)} < 0,$$

$$\frac{\partial \Pi_{RI}^{D^*}}{\partial v} = \frac{\left\{ 6Iv(32 - 20v - 2v^2 + v^3)(1-\alpha) + (1-v)(2+v)^3[A\alpha + c_n(1-\alpha)] \right\}}{4(4-v)^3(1-v)^2(2+v)^3(1-\alpha)} > 0,$$

$$\frac{\partial \Pi_{SC}^{D^*}}{\partial v} = \frac{\left[4B_1Iv^2(1-v)^2(2+v)(1-\alpha) + AB_2(2+v)^2 \right] [A\alpha + c_n(1-\alpha)] - 4I^2v^4(1-\alpha)^2[184v + 164v^2 + 56v^3 + v(6-v)(13+v-v^2)] + 96(-3+\alpha) + 488v - 336v^2 - 234v^3 + 167v^4 - 6v^5 - 15v^6 + 2v^7}{4(4-v)^3(1-v)^2v^2(2+v)^3(1-\alpha)^2} < 0,$$

where $B_1 = (96 - 72v)(3 - \alpha) + v^2(36 + 15v - 36\alpha - 11v\alpha)$, $B_2 = 2v(18 - 5v - v^2) + 16\alpha - 48 - v\alpha(12 - 10v - v^2)$.

We can use the same method to obtain derivatives of optimal decision variables and profits with respect to v in model DRS, model DCS and model DFS.

Proof of Lemma 2

Comparing the derivatives of optimal decision variables and profits with respect to c_n in model D, we obtain:

$$\frac{\partial p_{RF}^{D^*}}{\partial c_n} = \frac{2+v}{2(4-v)} > 0, \quad \frac{\partial p_{RI}^{D^*}}{\partial c_n} = \frac{3}{2(4-v)} > 0, \quad \frac{\partial q_{RF}^{D^*}}{\partial c_n} = \frac{1}{v(4-v)} > 0, \quad \frac{\partial q_{RI}^{D^*}}{\partial c_n} = \frac{1}{4(4-v)} > 0,$$

$$\frac{\partial \Pi_{RF}^{D^*}}{\partial c_n} = \frac{16Iv^2(2-v-v^2)[A\alpha + c_n(1-\alpha)] + (4-v)^2v(2+v)\phi - (2+v)[16 - 8v^2 + v^3 + 16(-1+v)\alpha]c_n}{8v(4+v)^2(2+v)} > 0,$$

$$\frac{\partial \Pi_{RI}^{D^*}}{\partial c_n} = \frac{6Iv^2(1-\alpha) + (2-v-v^2)[A\alpha + c_n(1-\alpha)]}{2(4-v)^2(2+v)} > 0,$$

$$\frac{\partial \Pi_{SC}^{D^*}}{\partial c_n} = \frac{8Iv^2(1-\alpha)(12-4\alpha) + v(3-3v-\alpha+2v\alpha) + (2+v)[4A\alpha(-12+v+2v^2-(1-v)(4+v)\alpha) - 3(4-v)^2v(1-\alpha)\phi] + (2+v)(1-\alpha)[48+44v-32v^2+3v^3+4(1-v)(4+v)\alpha]c_n}{8v(4+v)^2(2+v)(1-\alpha)} > 0.$$

We can use the same method to obtain derivatives of optimal decision variables and profits with respect to c_n in model DRS, model DCS and model DFS.

Proof of Proposition 5

(a) Comparing the optimal price of recycler RF in model D, model SF and model SI, we obtain:

$$p_{RF}^{D*} - p_{RF}^{SI*} = \frac{lv^4(1-\alpha) + v^2(1-v)[A\alpha + c_n(1-\alpha)]}{8(4-v)(2-v)(1-\alpha)} > 0,$$

$$p_{RF}^{SI*} - p_{RF}^{SF*} = \frac{lv^3(1-\alpha) + v^2(1-v)[A\alpha + c_n(1-\alpha)]}{8(2-v)(1-\alpha)} > 0.$$

It can be easily checked that $p_{RF}^{D*} > p_{RF}^{SI*} > p_{RF}^{SF*} > 0$ always holds when Eqs.(A1)-(A3) are satisfied.

(b) Comparing the optimal price of recycler RI in model D, model SF and model SI, we obtain:

$$p_{RI}^{D*} - p_{RI}^{SI*} = \frac{lv^4(\alpha-1) - v^2(v-1)[A\alpha + c_n(1-\alpha)]}{8(4-v)(2-v)(\alpha-1)} > 0,$$

$$p_{RI}^{SI*} - p_{RI}^{SF*} = \frac{lv^3(\alpha-1) + v(v-1)[A\alpha + c_n(1-\alpha)]}{8(2-v)(1-\alpha)} > 0.$$

It can be easily checked that $p_{RI}^{D*} > p_{RI}^{SI*} > p_{RI}^{SF*} > 0$ always holds when Eqs.(A1)-(A3) are satisfied.

Proof of Proposition 6

(a) Comparing the optimal quantity of recycler RF in model D, model SF and model SI, we obtain:

$$q_{RF}^{SI*} - q_{RF}^{D*} = \frac{lv^3(40 - 18v + 3v^2 - v^3) + v(8 - 2v - 7v^2 + v^4)[A\alpha + c_n(1-\alpha)]}{8(4-v)(2-v)(1-\alpha)(8 - 2v - 7v^2 + v^4)} > 0,$$

$$q_{RF}^{D*} - q_{RF}^{SF*} = \frac{lv^2[4 + (3-v)v^2](1-\alpha) + 2(2-v-v^2)[A\alpha + c_n(1-\alpha)]}{8(-4+v)(-1+v)(2+v)(-1+\alpha)} > 0.$$

It can be easily checked that $q_{RF}^{SI*} > q_{RF}^{D*} > q_{RF}^{SF*}$ always holds when Eqs.(A1)-(A3) are satisfied.

We can use the same method to compare the optimal quantity of recycler RI in model D, model SF and model SI, and we obtain:

$$q_{RI}^{SF*} - q_{RI}^{SI*} = \frac{lv^3(2-v)^2(1-\alpha) + v[A\alpha + c_n(1-\alpha)]}{8(2-v)(4+v-v^2)} > 0,$$

$$q_{RI}^{D*} - q_{RI}^{SI*} = \frac{lv^3(24 + 2v - v^2 - v^3)(1-\alpha) + [8 + v(-2 - 7v + v^3)][A\alpha + c_n(1-\alpha)]}{8(4-v)(1-v)(2+v)(4+v-v^2)(1-\alpha)} > 0.$$

It can be easily checked that $q_{RI}^{SF*} > q_{RI}^{SI*}$ and $q_{RI}^{D*} > q_{RI}^{SI*}$ always holds when Eqs. (A1)-(A3) are satisfied.

$$q_{RI}^{SF*} - q_{RI}^{D*} = \frac{lv^3(4+8v-7v^3+v^4)(1-\alpha) + (2-v-v^2)[A\alpha + c_n(1-\alpha)]}{8(4-v)(2-v)(2+v)(1-v)(1-\alpha)}.$$

$q_{RI}^{SF*} - q_{RI}^{SI*} > 0$ For $c_n + \frac{A\alpha}{1-\alpha} > \varphi_2(v)$, but $q_{RI}^{SF*} - q_{RI}^{SI*} < 0$ for $\psi_0'(v) < c_n + \frac{A\alpha}{1-\alpha} < \varphi_2(v)$, where $\psi_0'(v) = \frac{lv^2(2-v)(1+v)}{2(1-v)}$, $\varphi_2(v) = \frac{lv^2(4+8v-7v^2+v^3)}{2(2-v-v^2)}$.

(b) Comparing the optimal quantity of recycler RF and RI in model D, model SF and model SI, we obtain:

$$q_{RF}^{SF*} - q_{RI}^{SF*} = \frac{lv^2(2+3v-4v^2+v^3)(1-\alpha) - 2(1-v)^2[A\alpha + c_n(1-\alpha)]}{4v(2-v)(1-v)(1-\alpha)},$$

$q_{RF}^{SF*} - q_{RI}^{SF*} > 0$ For $c_n + \frac{A\alpha}{1-\alpha} > \varphi_3(v)$, but $q_{RF}^{SF*} - q_{RI}^{SF*} < 0$ for $\psi_0'(v) < c_n + \frac{A\alpha}{1-\alpha} < \varphi_3(v)$, where $\varphi_3(v) = \frac{lv^2[16+v(1-v)(32-9v-v^2)]}{(1-v)(4-3v+v^2)(4+v-v^2)}$.

$$q_{RF}^{SI*} - q_{RI}^{SI*} = \frac{lv^2[16+v(1-v)(32-9v+v^2)] + (1-v)(4-3v+v^2)(4+v-v^2)[A\alpha + c_n(1-\alpha)]}{8v(2-v)(1-v)(4+v-v^2)(1-\alpha)},$$

$q_{RF}^{SI*} - q_{RI}^{SI*} > 0$ For $c_n + \frac{A\alpha}{1-\alpha} > \varphi_4(v)$, but $q_{RF}^{SI*} - q_{RI}^{SI*} < 0$ for $\psi_0'(v) < c_n + \frac{A\alpha}{1-\alpha} < \varphi_4(v)$, where $\varphi_4(v) = \frac{lv^2[2+v(3-v)(1-v)]}{2(1-v)^2}$.

(c) Comparing the optimal quantity of recycler RF and RI in model D, model SF and model SI, we obtain:

$$q_{RI+RF}^{D*} - q_{RI+RF}^{SI*} = \frac{lv^3(1-\alpha) + v(1-v)[A\alpha + c_n(1-\alpha)]}{8(4-v)(2-v)(1-\alpha)} > 0,$$

$$q_{RI+RF}^{SI*} - q_{RI+RF}^{SF*} = \frac{lv^2(1-\alpha) + (1-v)[A\alpha + c_n(1-\alpha)]}{8(2-v)(1-\alpha)} > 0.$$

The conclusion $q_{RI+RF}^{D*} > q_{RI+RF}^{SI*} > q_{RI+RF}^{SF*}$ always holds when Eqs.(A1)-(A3) are satisfied.

Proof of Proposition 7

(a) Comparing the optimal profits of CLSC in model D, model SF and model SI, we obtain:

$$\Pi_{SC}^{D*} - \Pi_{SC}^{SF*} = \frac{4(2-v-v^2)[A\alpha + c_n(1-\alpha)] \{ B_3[A\alpha + c_n(1-\alpha)] + B_4lv^2(2-v)(1-\alpha) \} + l^2v^4(2-v)^2(1-\alpha)^2B_5}{64(1-v)(2+v)^2(8-6v+v^2)^2(1-\alpha)^2},$$

Where $B_3 = (2-v-v^2)(32-36v+9v^2+12v\alpha-5v^2\alpha)$, $B_4 = 40v-64-24v\alpha+v^2[v-6-v^2(1-\alpha)+22\alpha-5v\alpha]$, $B_5 = 128-16v+48v\alpha+20v^2-186v^2\alpha+72v^3-80v^3\alpha-23v^4+51v^4\alpha-2v^5+v^6-(2+v)v^5\alpha$.

$$\Pi_{SC}^{D*} - \Pi_{SC}^{SF*} = \frac{B_6 v(1-v)[Ax+c_n(1-x)]^2}{64(8-6v+v^2)(1-x)^2} + \frac{I^2 v^5(1-x)^2 B_8 + 2Iv^3(1-x)B_7(8-2v-7v^2+v^4)[Ax+c_n(1-x)]}{64(4-v)^2(2-v)^2(1-v)(8+6v-v^2-v^3)^2}$$

Where $B_6 = v^2(-5 + \alpha) - 32\alpha + 12v(1 + \alpha)$, $B_7 = -256 + 544v - 368v^2 + 10v^3 + 59v^4 - 13v^5 + 512\alpha - 544v\alpha + 224v^2\alpha + 6v^3\alpha - 39v^4\alpha + 9v^5\alpha$, $B_8 = -4096 - 5376v + 8256v^2 - 496v^3 - 1364v^4 + 264v^5 - 169v^6 + 122v^7 - 21v^8 + 10240\alpha - 2304v\alpha - 10432v^2\alpha + 5456v^3\alpha + 644v^4\alpha - 1024v^5\alpha + 405v^6\alpha - 122v^7\alpha + 17v^8\alpha$.

The conclusions $\Pi_{SC}^{D*} > \Pi_{SC}^{SF*}$ and $\Pi_{SC}^{D*} > \Pi_{SC}^{SI*}$ always hold when Eqs.(A1)-(A3) are satisfied.

$$\Pi_{SC}^{SF*} - \Pi_{SC}^{SI*} = \frac{(1-v)[v(5-x)-8][Ax+c_n(1-x)]^2}{64(2-v)^2(1-x)^2} + \frac{2Iv^2 B_9[Ax+c_n(1-x)]}{64(2-v)^2(4+v-v^2)(1-x)} + \frac{I^2 v^4 B_{10}}{64(2-v)^2(4+v-v^2)^2}$$

where $B_9 = 32 - 36v + 19v^2 - 9v^3 + 2v^4 + 28v\alpha - 31v^2\alpha + 13v^3\alpha - 2v^4\alpha$, $B_{10} = -128 + 80v + 96v^2 - 139v^3 + 74v^4 - 13v^5 - 3v^6 + v^7 - 208v\alpha + 152v^2\alpha + 111v^3\alpha - 146v^4\alpha + 45v^5\alpha - v^6\alpha - v^7\alpha$.

$\Pi_{SC}^{SF*} - \Pi_{SC}^{SI*} > 0$ for $c_n + \frac{Ax}{1-x} > \psi_1(v)$, but $\Pi_{SC}^{SF*} - \Pi_{SC}^{SI*} < 0$ for $\psi_0(v) < c_n + \frac{Ax}{1-x} < \psi_1(v)$, where $\psi_0(v) = \frac{Iv^2(2-v)(1+v)}{2(1-v)}$,

$$\psi_1(v) = \frac{Iv^2[(32 - 36v - 3v\alpha + 19v^2 - 9v^3 + 2v^4 - 2v^4\alpha + 13v^3\alpha)(4016v^2 - 3904v - 2247v^3 + 672v^4 - 54v^5 - 24v^6 + 5v^7) + \alpha^2(576 + 640v - 368v^2 - 3991v^3 + 4818v^4 - 1942v^5 + 332v^6 - v^7 + 6v^8 - 6v^9)]}{(1-v)(4+v-v^2)(8-5v+v\alpha)}$$

(b) Comparing the optimal profits of battery manufacture in model D, model SF and model SI, we obtain:

$$\Pi_M^{D*} - \Pi_M^{SF*} = \frac{I^2 v^5(v^2 + 6v - 24)(1-x)^2 + v(v^3 + v^2 - 6v - 8)[Ax+c_n(1-x)][2Iv^2(1-x) + Ax+c_n(1-x)]}{16(4-v)(2-v)(2+v)(4+v-v^2)(1-x)^2}$$

$$\Pi_M^{SI*} - \Pi_M^{SF*} = \frac{I^2 v^4(4 + 5v - 5v^2 + v^3)}{16(2-v)(4+v-v^2)} + \frac{2Iv^2(1-x)[Ax+c_n(1-x)] + (1-v)[Ax+c_n(1-x)]^2}{16(2-v)(1-x)^2}$$

The conclusion $\Pi_M^{D*} > \Pi_M^{SI*} > \Pi_M^{SF*}$ always holds when Eqs.(A1)-(A3) are satisfied.

(c) Comparing the optimal profits of recycler RF in model D, model SF and model SI, we obtain:

$$\Pi_{RF}^{SI*} - \Pi_{RF}^{SF*} = \frac{2Iv^4 B_{11}[Ax+c_n(1-x)]}{64v(2-v)^2(v^2-v-4)} + \frac{I^2 v^6(1-x)^2 B_{12} + v^2(1-v)^2(4+v-v^2)^2[Ax+c_n(1-x)]^2}{64v(2-v)^2(1-v)(4+v-v^2)^2(1-x)}$$

where

$$B_{11} = -36 + 47v - 23v^2 + 4v^3,$$

$$B_{12} = -304 + 136v + 389v^2 - 416v^3 + 137v^4 + 4v^5 - 12v^6 + 2v^7.$$

$$\Pi_{RF}^{SF*} - \Pi_{RF}^{D*} = \frac{Av\alpha[8+v(-2-7v+v^3)][Ax+B_{13}(v-1)-v^2B_{14}(x-1)] + Iv^3(x-1)(18v-40+v^2)[Ax+B_{13}(v-1)-Iv^2B_{14}(x-1)]}{64(-64+36v^2-4v^3-5v^4+v^5)(1-v)(1-x)} + \frac{(v^2+v^3-8+6v)(2v^3B_{15}(x-1)c_n+B_{13}c_n(v-1)[v(x-1)c_n-2Ax])}{64(-64+36v^2-4v^3-5v^4+v^5)}$$

where

$$B_{13} = -256 - 64v + 120v^2 + 10v^3 - 15v^4 + v^5,$$

$$B_{14} = -256 - 192v + 328v^2 + 14v^3 - 77v^4 + 15v^5,$$

$$B_{15} = 512 - 704v + 376v^2 - 42v^3 - 29v^4 + 7v^5.$$

The conclusions $\Pi_{RF}^{SI*} - \Pi_{RF}^{SF*} > 0$ and $\Pi_{RF}^{SF*} - \Pi_{RF}^{D*} > 0$ always hold when Eqs. (A1)-(A3) are satisfied.

$$\Pi_{RF}^{D*} - \Pi_{RF}^{SF*} = \frac{I^2 v^5 B_{16}(v-2)(1-x)^2 + 4AI(-2+v)(-1+v)v^3(20-3v^2+v^3)(x-1)\alpha + 4A^2 v^2(2-v-v^2)^2}{32(4-v)^2(2+v)^2} + \frac{Iv^3 c_n(2-v)(10-5v+v^2)(x-1) - 4vc_n(v+v^2-2)[2Ax+(1-x)c_n]}{32(4-v)^2(v^2-4)}$$

where $B_{16} = -72 - 20v + 74v^2 - 15v^3 - 4v^4 + v^5$.

$\Pi_{RF}^{D*} - \Pi_{RF}^{SF*} > 0$ for $\psi_0(v) < c_n + \frac{Az}{1-\alpha} < \psi_2(v)$, but $\Pi_{RF}^{D*} - \Pi_{RF}^{SF*} < 0$ for $c_n + \frac{Az}{1-\alpha} > \psi_2(v)$, where $\psi_2(v) = \frac{lv^3[(2-v)(10-5v+v^2)+2\sqrt{4-2v}(4-v)(1-v)]}{2v(1-v)}$.

(d) Comparing the optimal profits of recycler RI in model D, model SF and model SI, we obtain:

$$\Pi_{RI}^{SI*} - \Pi_{RI}^{D*} = \frac{[4Az + lv^2(v^2 + 3v - 12)(x-1) - Azv(3-v)(1+v) + (1-v)(4+v-v^2)(x-1)c_n]^2}{32(1-v)(1-x)(2-v)(4+v-v^2)^2} + \frac{8(6lv^2(x-1) + (v+v^2-2)(Az + (1-x)c_n))^2}{32(1-v)(1-x)(4-v)^2(2+v)^2}$$

$$\Pi_{RI}^{SF*} - \Pi_{RI}^{D*} = \frac{[lv^2(3-v)(2-v)(1-x) + 2(v-1)(Az + (1-x)c_n)]^2}{64(1-v)(1-x)(2-v)^2} - \frac{16(6lv^2(x-1) + (v+v^2-2)(Az + (1-x)c_n))^2}{64(1-v)(1-x)(4-v)^2(2+v)^2}$$

The conclusions $\Pi_{RI}^{SI*} - \Pi_{RI}^{D*} > 0$ and $\Pi_{RI}^{SF*} - \Pi_{RI}^{D*} > 0$ always hold when Eqs. (A1)-(A3) are satisfied.

$$\Pi_{RI}^{SI*} - \Pi_{RI}^{SF*} = \frac{2(2-v)[4Az + lv^2(v^2 + 3v - 12)(x-1) + (4-3v-2v^2+v^3)(Az + (1-x)c_n)]^2}{64(1-v)(1-x)(2-v)^2(4+v-v^2)^2} - \frac{[lv^2(3-v)(2-v)(1-x) + 2(v-1)(Az + (1-x)c_n)]^2}{64(1-v)(1-x)(2-v)^2}$$

$\Pi_{RI}^{SI*} - \Pi_{RI}^{SF*} > 0$ For $\psi_0(v) < c_n + \frac{Az}{1-\alpha} < \psi_3(v)$, but $\Pi_{RI}^{SI*} - \Pi_{RI}^{SF*} < 0$ for $c_n + \frac{Az}{1-\alpha} > \psi_3(v)$, where $\psi_3(v) = \frac{lv^3[2(2-3v+v^2)^2 + \sqrt{4-2v}(1-v)(8+5v-6v^2+v^3)]}{v(1-v)(4+v-v^2)}$.

Data Availability All data generated or analyzed during this study are included in this published article.

Declarations

Conflict of interest The authors declare no conflict of interest. There is no professional or other personal interest of any nature or kind in any product, service and/or company that could be construed as influencing the position presented in, or the review of, the manuscript entitled.

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