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Optimal Production Strategies in Closed-Loop Supply Chains under Carbon Policies and Diverse Recovery Modes

Wei Cui, Qiaolun Gu

School of Economics and Management, Tianjin University of Technology and Education,
Tianjin 300222, China

Abstract

Addressing manufacturers' persistently low efficiency in collecting and reusing post-consumer returns, this study develops a closed-loop supply chain (CLSC) model composed of one manufacturer and one recycler under a government-mandated deposit–refund scheme for new products. A take-back contract governing post-consumer returns recovery is explicitly embedded in the model, and numerical simulations are employed to examine how government policies and the manufacturer's production strategies jointly affect the supply chain. The results show that, by leveraging this take-back contract with consumers and expanding the production scale of remanufactured goods, the manufacturer can significantly raise the remanufacturing yield from post-consumer returns. When both the carbon price per ton and the government deposit are relatively high, this strategy accelerates the deposit-refund cycle and increases the manufacturer's total profit through enlarged scale effects.

Keywords

Deposit-refund System; Closed-loop Supply Chain; Production Strategy; Remanufactured Products.

1. Introduction

The problem of climate warming and over-exploitation and consumption of resources has gradually become the focus of global attention. Effective July 1, 2024, the European Union's New Battery Regulation entered into force, mandating that all traction batteries entering the European market must establish dual compliance thresholds by 2027: full life-cycle carbon footprint traceability and a minimum recycling quota. Concurrently, China's Ministry of Industry and Information Technology issued the Administrative Measures for the Recycling and Utilization of Power Batteries for New Energy Vehicles (Draft for Comment) on July 11, 2024. This draft, for the first time, proposes a tripartite government-mandated deposit–refund scheme involving government, manufacturers, and consumers, with pilot programs launched in Shanghai and Shenzhen. Under this scheme, a deposit of CNY 60 per kilowatt-hour (kWh) of new battery sold is levied; manufacturers receive a full refund only if over 90 % of materials from end-of-life batteries achieve closed-loop remanufacturing. This simultaneous tightening of international and domestic regulations underscores the government-mandated deposit–refund scheme as a critical factor in green supply chain design.

A government-mandated deposit–refund scheme imposes a tax or disposal fee (i.e., deposit) per unit of new product produced or sold. Upon successful completion of the recycling process for the corresponding end-of-life product, the government provides a subsidy or refunds the deposit. This mechanism aims to incentivize all stakeholders-manufacturers, recyclers, retailers, and consumers-to actively fulfill their recycling responsibilities throughout the product life cycle [1]. Huang Chunxiang investigated strategy optimization and profit allocation within a closed-loop supply chain comprising one recycler and two competing manufacturers operating under DRS [2]. Empirical evidence suggests

DRS can simultaneously reduce the retail price of new products and lower the buy-back prices for end-of-life items [3]. Crucially, DRS increases consumer participation in recycling programs, promotes the reuse of end-of-life products, and advances resource circularity and sustainable development [4]. In summary, DRS implementation effectively mitigates resource waste and environmental pollution caused by discarded products. However, research examining remanufacturing in closed-loop supply chains under DRS remains limited, particularly concerning unit carbon price and the deposit/rebate coefficients set by authorities.

To ensure consumers return end-of-life products to designated collection points, manufacturers utilize deposits or advance-payment discounts. Liu Liang et al. [5] constructed a three-tier (manufacturer-retailer-consumer) incentive model, proposing an "incentive cost-sharing contract." Under this contract, the manufacturer directly refunds the deposit or provides discounts to consumers, while retailers solely handle collection. Numerical results demonstrate that this contract can increase the recycling rate by approximately 18 % even under centralized decision-making [5]. Yu Chunhai et al. [6] extended the scenario to address dual-channel conflict (online direct sales + offline retail). Their research indicates that a combined "wholesale price plus revenue-sharing" contract resolves channel competition effectively. Furthermore, when manufacturers directly pay consumer rebates, this approach increases recycling rates while avoiding double marginalization [6]. Wang Xingtang, from a green R&D perspective, compared three contracts: green R&D subsidies, cost-sharing, and revenue-sharing [7]. The study found that the cost-sharing contract yields the most significant synergistic effect on both recycling rates and green R&D investment when manufacturers implement "deposit-refund/discounts" directly with consumers [7]. Addressing consumer heterogeneity, Yi Yuyin et al. [8] segmented consumers into high/low environmental-awareness groups, designing a hybrid "deposit-refund plus tiered discounts" contract: manufacturers sign recycling agreements with consumers, refund deposits upon product return, and provide additional discount coupons [8]. When the deposit refund promised by manufacturers constitutes 8 %–12 % of the selling price, end-of-life product collection volume increases by 35 % while maintaining manufacturer profit growth [9]. Current literature has validated the effectiveness of manufacturer-consumer take-back contracts across multiple dimensions: contract type (cost-sharing, revenue-sharing, hybrid discounts), channel structure (single-channel, dual-channel), and consumer heterogeneity. Nevertheless, a significant research gap persists regarding sustainable multi-agent contract design for high-remanufacturing-ratio scenarios.

In summary, China’s DRS is anchored in the producer responsibility principle. Against this backdrop, this study investigates how manufacturers can sign take-back agreements directly with consumers to increase the remanufacturing yield from post-consumer returns and examines how they should rationally adjust production strategies to maximize profits under evolving policy conditions.

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2. Model Formulation

2.1 Problem Description

Based on the governmental policy framework allocating carbon quotas via the grandfathering allocation rule and imposing a carbon tax on each newly produced unit, this study constructs a remanufacturing closed-loop supply chain (CLSC) model comprising one manufacturer and one recycler. The manufacturer is capable of simultaneously producing both new and remanufactured products. Two operational modes are compared: Mode A (Manufacturer–Consumer Take-Back Contract): The manufacturer signs a take-back agreement with consumers, collects post-consumer returns via recyclers for remanufacturing, and continues new product production. Mode B (Third-Party Recovery): The manufacturer outsources post-consumer returns collection to third-party recyclers for remanufacturing while concurrently producing new products.

2.2 Model Assumptions

Assumption 1: A carbon trading market exists with sufficient quota liquidity and a stable market adjustment mechanism.

Assumption 2: The government calculates initial carbon quotas via the grandfathering allocation rule and allocates corresponding quotas to the manufacturer free of charge.

Assumption 3: Drawing on prior studies [6], remanufactured products exhibit lower resource intensity than new products; their unit cost is 50 % of that of a new product, energy use is 60 % lower, and material use is 70 % lower, i.e.,$C_n > C_r$and$e_n > e_r$.

Assumption 4: The quantity of post-consumer returns procured by the manufacturer from recyclers must not exceed the planned remanufacturing volume, ensuring closed-loop operation aligned with resource circulation principles.

Assumption 5: Following Reference [2], a government-mandated deposit–refund scheme is implemented. Manufacturers receive corresponding deposit refunds when using collected post-consumer returns for remanufacturing.

Table 1. Nomenclature

Symbol	Description
n, r	Subscripts denoting new products and remanufactured products, respectively
A, B	Superscripts denoting Mode A and Mode B
p_n^i, p_r^i	Selling price of the new and remanufactured products under mode i ∈ {A, B}.
q_n^i, q_r^i	Production quantity of the new and remanufactured products in mode i ∈ {A, B}
π_n^i, π_r^i	Profit generated from the new and remanufactured products in mode i ∈ {A, B}
τ_i	The recovery rate of end-of-life products is defined as the ratio of reusable returned units to the total quantity of new and remanufactured products placed on the market, i ∈ {A, B}.
E	Carbon emission allowance allocated to the manufacturer under the grandfathering allocation rule.
pe	Unit market price of carbon emission permits (positive for purchasing and negative for selling)
δ	Consumer preference for remanufactured products, defined as the valuation ratio of a unit remanufactured product to that of a new product, $0 < \delta < 1$.
c_n, c_r	Unit production costs for new and remanufactured products, respectively, with, $c_n > c_r$
e_n, e_r	Carbon emissions per unit of new and remanufactured products are denoted by, implying carbon savings from remanufacturing.
Q	Total potential market size.
g	Proportion of the total carbon allowance allocated to the production of new products.
m	Deposit coefficient per new product unit remitted to the government by the manufacturer.
R	Consumer rebate coefficient offered by the manufacturer under manufacturer–consumer take-back agreement.

2.3 Model Assumptions

Linear inverse demand functions are adopted:

$$p_n^i = Q - q_n^i - \delta q_r^i \tag{1}$$

$$p_n^i = \delta(Q - q_n^i - q_r^i), i \in \{A, B\} \tag{2}$$

Following Reference, the collection cost of end-of-life products is assumed to be quadratic in terms of the collected quantity:

$$p_n^A = (Q - q_n^A - \delta q_r^A)(1 - R), 0 \le R \le 1 \tag{3}$$

$$p_n^A = \delta(Q - q_n^A - q_r^A) \tag{4}$$

Collection Mode A (Manufacturer–Consumer Contract):

$$\pi_n^A = (p_n^A - C_n - mp_n^A)q_n^A - (e_n q_n^A - gE)pe \tag{5}$$

$$\pi_r^A = (p_r^A - C_r + mp_n^A)q_r^A - (e_n q_n^A - (1-g)E)pe - \frac{k}{2}(\tau q_n^A)^2 \tag{6}$$

Inverse demand functions for Mode B:

$$p_n^B = Q - q_n^B - \delta q_r^B \tag{7}$$

$$p_r^B = \delta(Q - q_n^B - q_r^B) \tag{8}$$

Collection Mode B:

$$\pi_n^B = (p_n^B - C_n - mp_n^B)q_n^B - (e_n q_n^B - gE)pe \tag{9}$$

$$\pi_r^B = (p_r^B - C_r + mp_n^B)q_r^B - (e_n q_r^B - (1-g)E)pe - \frac{k}{2}(\tau q_n^B)^2 \tag{10}$$

2.4 Model Assumptions

Step 1: Substitute Eqs. (5) and (6) into Eq. (8): $p_r^A = p_n^A \tau_{\mathrm{A}}$

$$\pi_r^A = \left(m\left(-\delta q_n^A \tau_{\mathrm{A}} + Q - q_n^A\right)(1-R) - c_r^A + \delta\left(-q_n^A \tau_{\mathrm{A}} + Q - q_n^A\right)\right)\tau_{\mathrm{A}} q_n^A - \left(e_n q_n^A - (1-g)E\right)p_e - k(\tau_{\mathrm{A}} q_n^A)^2 \tag{11}$$

Step 2: First-order conditions

$$\frac{d(\pi_r^A)}{d(\tau_\mathrm{A})}=(-\delta m q_n^A(1-R)-\delta q_n^A)\tau_\mathrm{A} q_n^A+(m(-\delta q_n^A\tau_\mathrm{A}+Q-q_n^A)(1-R)-c_r^A+\delta(-q_n^A\tau_\mathrm{A}+Q-q_n^A))q_n-2k\tau_\mathrm{A}(q_n^A)^2 \tag{12}$$

Step 3: Second-order conditions

$$\frac{d^2(\pi_r^A)}{d(\tau_\mathrm{A})^2}=2(-\delta m q_n^A(1-R)-\delta q_n^A)q_n^A-2k(q_n^A)^2 \tag{13}$$

for all positive parameters; hence the profit function is jointly concave and a unique maximum exists.
Step 4: Setting the first-order partial derivatives to zero yields

$$\tau_\mathrm{A}{}^*=\frac{QRm-Rmq_n^A-Q\delta-Qm+\delta q_n^A+mq_n^A+c_r^A}{2q_n^A(R\delta m-\delta m-\delta-k)} \tag{14}$$

Step 5: Substituting Eqs. (5) and (14) into Eq. (7) gives

$$\pi_n^A=\left((m+1)\left(\delta\frac{QRm-Rmq_n^A-Q\delta-Qm+\delta q_n^A+mq_n^A+c_r^A}{2(R\delta m-\delta m-\delta-k)}-Q+q_n^A\right)-c_n\right)(1-R)q_n^A+\left(Er+e_nq_n^A\right)p_e \tag{15}$$

Repeating the same steps yields

$$\begin{aligned}q_n^{A*}=&\frac{1}{2(R\delta m+\delta^2-\delta m-2\delta-2k)(R-1)(m-1)}(QR^2\delta m^2-QR^2\delta m+QR\delta^2m-2QR\delta m^2-2R\delta e_nmp_e-QR\delta^2-2QRkm\\&-Q\delta^2m+Q\delta m^2-2Rc_n^A\delta m-Rc_r^A\delta m-Rmp_e\varepsilon+2\delta e_nmp_e+2QR\delta+2QRk+Q\delta^2+Q\delta m+2Qkm+Rc_r^A\delta+2c_n^A\delta m+c_r^A\delta m\\&+2\delta e_np_e+\delta p_e\varepsilon+2e_nkp_e+mp_e\varepsilon-2Q\delta-2Qk+2c_n^A\delta+2c_nk-c_r^A\delta)\end{aligned} \tag{16}$$

Substituting the obtained key solutions into Eqs. (3), (4), (5), and (6) yields the equilibrium prices, quantities, and profits, $q_r^{A*},p_n^{A*},p_r^{A*},\pi_n^{A*},\pi_r^{A*}$.
The same derivation applies to Mode B and is therefore omitted here.

3. Numerical Analyses

3.1 Data Calibration

Based on Reference [9], parameters are set as:Q=1000, δ=0.8, C_n^i=200, C_r^A=50, C_r^B=100, k=1.1, E=100, e_n=8, e_r=4, pe ∈{0,10}, i ∈ {A, B}

3.2 Remanufacturing Yield from Post-consumer Returns

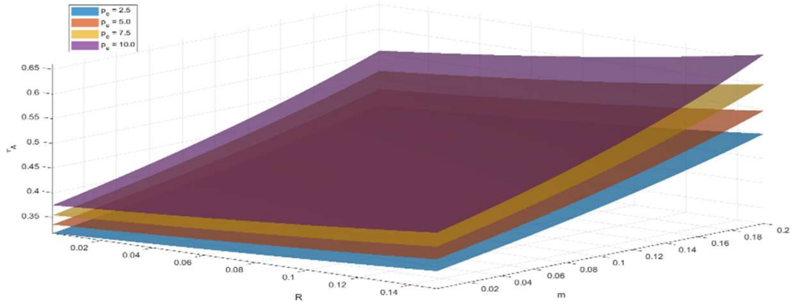

Figure 2. Remanufacturing Yield from post-consumer returns under Mode A

Following Reference [10], the consumer rebate coefficient range is set at [0, 0.15]. For Mode A, numerical simulations were conducted to analyze the remanufacturing yield from post-consumer returns into remanufactured goods.

As illustrated in Figure 2, within Mode A, the remanufacturing yield from post-consumer returns increases monotonically with the unit carbon price. Faced with higher carbon costs, the manufacturer expands remanufactured output to curb compliance expenditure, thereby enhancing total profit. Both the government-imposed deposit coefficient m and consumer rebate R reinforce this upward trend, albeit through distinct mechanisms.

The deposit, grounded in extended producer responsibility, mechanically boosts the remanufacturing yield by increasing the financial penalty for non-collection. However, its escalation simultaneously tightens the manufacturer's cash-flow constraints. Conversely, consumer rebates are discretionary levers: by lowering the effective retail price of new products and reducing the input cost of remanufactured goods, rebates stimulate consumer participation and enlarge the remanufacturing scale. The key difference lies in governance: the deposit is exogenously enforced and liquidity-sensitive, whereas the rebate is an endogenous, demand-responsive decision that the manufacturer can fine-tune to the market conditions.

The simulated remanufacturing yield trajectory for Mode B follows the same pattern observed earlier and is therefore omitted for brevity.

3.3 Total-profit Comparison

The consumer rebate coefficient R was discretized over the interval [0, 0.15]. Two carbon-pricing scenarios were simulated: an intermediate price pe = 5 and an upper-bound price pe = 10. For each (pe, m, R) triplet, the total profit of Mode A (Manufacturer–Consumer Take-Back Contract) and Mode B (Third-Party Recovery) is computed and compared through numerical integration of the closed-form solutions derived.

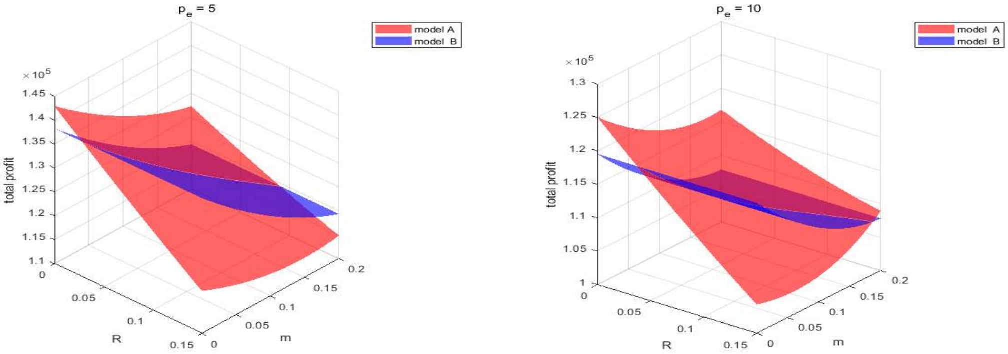

Figure 3. Comparison of total profit between Mode A and Mode B

Figure 3 reveals that aggregate profits in both Mode A and Mode B decline monotonically as unit carbon prices increase. At pe= 5, when the consumer rebate coefficient (R) and the deposit coefficient (m) are low, Mode A outperforms Mode B. Raising m erodes profits in both modes, yet Mode A retains its advantage. However, beyond a threshold level of R, the profit of Mode A drops below that of Mode B. When pe = 10, the qualitative pattern persists, yet in a narrow interval around m ≈ 0.2, Mode A consistently yields higher profit than Mode B. Overall, higher carbon prices and deposit rates tighten the manufacturer's margin, whereas an increase in R exclusively depresses Mode A's profit. This negative effect is attenuated as the carbon price and deposit level rise.

The underlying mechanism is two-fold. First, elevated carbon prices and deposit rates directly compress profit margins. Second, in Mode A, the rebate itself reduces the per-unit profit. Nevertheless, when pe = 5 and R < 0.02, or pe = 10 and R < 0.03, the lower effective price of new products and reduced input cost of remanufactured goods expand demand. The resulting scale economies outweigh the margin loss, enabling Mode A to deliver higher profits than Mode B.

3.4 Profit-intersection Analysis between Mode A and Mode B

To further investigate how the government deposit coefficient (m) and unit carbon price (pe) jointly affect the critical consumer rebate coefficient (R) at which Mode A and Mode B yield identical total profits, pe is treated as the independent variable and varied continuously over the interval [0, 10].

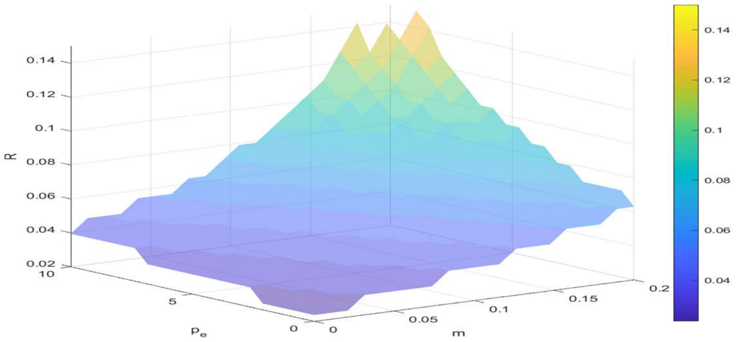

Figure 4. Analysis of the profit-intersection point between Mode A and Mode B

Figure 4 reveals that the critical rebate level *R*-the consumer rebate coefficient at which Mode A and Mode B generate identical profits -exhibits a step-wise response to increases in the government deposit coefficient *m*. However, as the unit carbon price p_e increases, this stepped pattern gradually transitions to a quasi-linear ascent. Conversely, when *pe* is incremented while *m* remains fixed, *R* also displays a pronounced step-like trajectory; however, once *m* surpasses a high threshold, the curve fragments into a sawtooth profile.

These phenomena arise because, at elevated deposit levels, the DRS already exerts strong leverage on *R*, while the marginal impact of further carbon-price increases on the return rate diminishes. Consequently, manufacturers operating under Mode A must dynamically calibrate the rebate coefficient: first, in response to changes in *m* and, second, in light of evolving p_e. The firm can justify an expanded remanufacturing scale only by maintaining *R* within the identified feasible band.

4. Conclusion

Targeting the persistently low remanufacturing yield of post-consumer returns into remanufactured goods, this study develops a two-echelon closed-loop supply chain model that incorporates a government-run deposit-refund system. A manufacturer coexists with a recycler, and two collection modes are compared: Mode A (Manufacturer–Consumer Take-Back Contract) and Mode B (Third-Party Recovery). The numerical experiments calibrated with real battery data yielded the following findings.

(1) Under the deposit-refund system, a take-back agreement between the manufacturer and consumers raises the remanufacturing yield from post-consumer returns by 18–35 %. By expanding remanufacturing output, the manufacturer accelerates deposit refund cycles and simultaneously improves environmental performance and total profit.

(2) The critical consumer rebate coefficient *R* -the threshold at which Mode A and Mode B deliver identical profit-follows a mixed “step-linear” pattern. When the unit carbon price *pe* and deposit coefficient *m* are low, *R* exhibits discrete jumps and offers a narrow feasible band. As *pe* and *m* increased, the curve evolves into an approximately linear ascent, widening the adjustable range. Under the joint pressure of high *m* and high *pe*, the trajectory turns sawtooth; manufacturers must then stabilize *R* at approximately 14 % to secure profit maximization.

Managerial insights

Governments should set deposit bands differentiated by historical emission levels, granting manufacturers finer levers for production planning.

Manufacturers can reduce collection costs via take-back agreement while offering consumers price discounts. By dynamically aligning the rebate level with evolving carbon prices and deposit coefficients, profitability can be further enhanced.

Limitations and future research

The current model abstracts quality heterogeneity among returned products. Future work should integrate stochastic quality inspection and yield loss into the analytical framework to enrich policy designs and operational practices.

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