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COMPARISON OF RECYCLING MODES OF CLOSED-LOOP SUPPLY CHAIN UNDER CARBON TRADING MECHANISM

Abstract: Under a cap-and-trade mechanism, this paper investigates the optimal recycling channel selection within a closed-loop supply chain (CLSC). We construct three distinct Stackelberg game models - manufacturer recycling (M mode), retailer recycling (R mode), and third-party recycling (T mode) - by incorporating decisions on forward carbon abatement technology investment and reverse logistics efforts into a unified framework. Analytical and numerical results demonstrate that government-allocated free carbon quotas enter the manufacturer's profit function as an additive constant, shifting the absolute financial baseline without altering optimal decisions or mode rankings. Comparative static analyses show that while the direct manufacturer recycling (M mode) consistently yields overwhelming economic dominance across the feasible parameter space due to the elimination of reverse double-marginalisation, its environmental efficiency is conditional. Specifically, when the carbon intensity of remanufactured products exceeds the threshold or the consumer recycling price falls below the critical value, the retailer recycling (R mode) demonstrates stronger environmental resilience, generating higher per-unit carbon reductions. These findings indicate a critical trade-off between economic and environmental objectives in decentralised supply chains, suggesting that environmental regulations, transfer-pricing mechanisms, and channel structures must be coordinated through an integrated governance framework.

Keywords: carbon trading mechanism, recycling and manufacturing, investment in carbon emission reduction technology, Stackelberg game

Introduction

In the context of global warming, China faces an urgent need for low-carbon transformation [1]. Besides carbon trading, recycling and remanufacturing are also critical components of this transition. Manufacturers should not only focus on forward supply chain operations but also emphasise reverse supply chain activities such as recycling and remanufacturing [2, 3]. Companies like Xiaomi, IBM, and Apple have initiated efforts towards remanufacturing and low-carbon production [4], striving to establish their own green closed-loop supply chain modes [5]. From an environmental perspective, remanufactured products significantly reduce costs, material usage [6], energy

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consumption, waste emissions, and pollution [7]. Currently, major enterprises have developed several economically efficient recycling channels, such as BMW's waste recycling facility in Munich and third-party recyclers like Love Recycling, which have achieved notable recycling efficiencies [8]. At the regional and industrial level, government-led carbon reduction initiatives are also being implemented, with carbon footprint assessment serving as a key tool for evaluating industrial emission reduction performance [9].

Based on policies issued by various countries [10] and research by domestic and international scholars, low-carbon policies can be categorised into four types: carbon cap-and-trade [11], carbon tax, carbon subsidy, and carbon penalty. Among these, carbon trading policy [12] is one of the most emphasised, encouraged, and widely applied low-carbon policies. Studies have shown that carbon trading policies play a crucial role in achieving carbon reduction goals [13]. In the new era of green development, how enterprises make decisions regarding recycling, remanufacturing, and carbon emission reduction under carbon trading policies to achieve sustainable supply chain management is a significant practical issue. Therefore, studying more efficient and greener closed-loop supply chain recycling modes [14] holds great significance. As a major carbon emitter, China's transition to a low-carbon economy has been guided by an evolving policy framework, which has progressively shaped the institutional context for enterprise-level carbon decisions [15].

Recycling and remanufacturing of used products [16] are integral parts of the supply chain. Savaskan et al. [17] examined three recycling modes - manufacturer recycling, retailer recycling, and third-party recycling - and found that when the manufacturer leads, retailer recycling is optimal [18]. Zhang et al. [19] explored end-of-life power battery echelon utilisation and material recycling within a closed-loop supply chain framework, deriving an optimal mode for carbon reduction. Long et al. [20] concluded that manufacturers can maximise profits by participating in remanufacturing in either single-period or multi-period settings. Narang et al. [21] highlighted the importance of developing an efficient closed-loop recycling system and managing retired electric vehicle (EV) batteries effectively. They proposed a closed-loop supply chain for EV batteries with four mixed-channel recycling modes. Some studies have also considered the impact of carbon trading policies on closed-loop supply chains. Barragán-Beaud et al. [22] found that the carbon trading mechanism is effective in the long term under current global economic and environmental conditions [23]. Yenipazarli [24] studied the impact of carbon emission taxes on remanufacturing production and pricing strategies, concluding that remanufacturing can maximise profits, minimise emissions, and enhance overall social and environmental benefits. In addition to carbon trading, other carbon regulations such as carbon taxation and carbon labelling systems have also been shown to significantly influence inventory and coordination decisions in reverse supply chains [25].

In summary, although some existing studies have considered subsets of these factors [26], there remains a lack of comprehensive analysis that simultaneously incorporates carbon emission reduction technology input, carbon trading policies, and the three classic recycling modes within a unified Stackelberg game framework [3, 18]. This paper differs from prior work by incorporating both carbon abatement technology investment decisions and carbon trading costs into each of the three recycling mode structures, thereby examining the interaction between emission reduction incentives and recycling channel choices. We aim to address this gap by integrating carbon emission reduction technology

input and carbon trading policies. It categorises methods for manufacturers to obtain carbon emission reduction rights into three: free carbon allowances from the government, carbon emissions after investing in carbon reduction technologies, and carbon emission rights obtained through carbon trading markets. The manufacturer recycling [27], retailer recycling, and third-party recycling modes proposed by Savaskan et al. [17] are introduced. Using a Stackelberg game model [28-30], this study considers carbon trading costs, carbon emission reduction technology input costs, and waste product recycling and remanufacturing costs, comparing differences across various recycling modes and conducting numerical simulation analysis. Compared with studies that focus on a single recycling channel or a specific product context, this paper highlights how the optimal mode changes with carbon price, remanufacturing emission intensity, recycling price, transfer price, and unit remanufacturing cost savings. The analysis provides a conditional decision reference for enterprises choosing recycling channels under carbon regulation, providing a theoretical basis for improving carbon trading policies and a reference model for enterprises to build green closed-loop supply chains.

Problem description and modelling

Description of the problem

This paper constructs the following three different closed-loop supply chain recycling modes respectively, as shown in Figures 1-3, with the solid line as the forward supply chain, the same as the manufacturer to the retailer to the consumer, and the dotted line as the reverse supply chain, and the recycling main body and the channel under different recycling modes, in which the manufacturer needs to take into consideration the carbon trading market mechanism, the free carbon quota given by the government, and the financial investment of the manufacturer to carry out carbon emission reduction on its own. The study is conducted with the manufacturer as the leader and retailers and third-party recyclers as the followers [17]. To avoid ambiguity in the game structure and facilitate understanding, the decision sequence of each mode is stated before the corresponding mode is solved.

M Mode: The reverse supply chain consists of manufacturers directly recovering used products from consumers for remanufacturing at the price of b (Fig. 1).

R Mode: The reverse supply chain consists of retailers recovering used products from consumers at the price of b and then reselling them to manufacturers for remanufacturing at the price of f (Fig. 2).

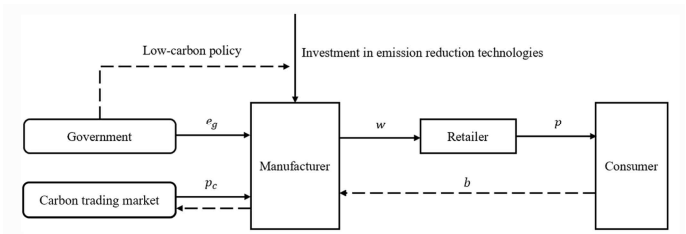


Fig. 1. Manufacturer recycling mode (M mode)

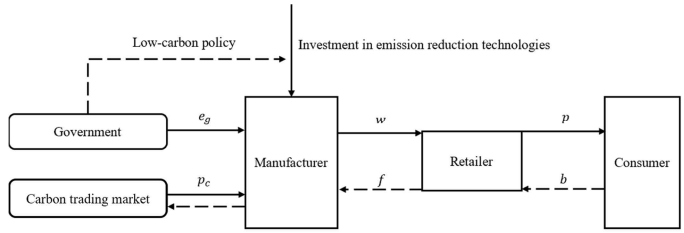


Fig. 2. Retailer recycling mode (R mode)

T Mode: The reverse supply chain consists of a third-party recycler who recovers waste products from consumers at a price of b and then resells them to manufacturers for remanufacturing at a price of f (Fig. 3).

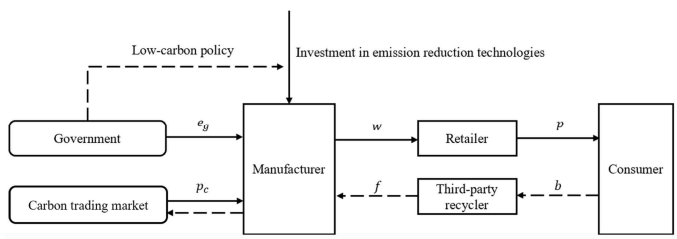


Fig. 3. Recycling mode of third-party recyclers (T mode)

Parameter symbols

α indicates maximum market demand;
β indicates the price sensitivity factor;
C_n is the unit production cost of the new product;
C_r is the unit production cost of the remanufactured product;
Δ is the unit production cost savings for remanufacturing;
w is the wholesale price for new and remanufactured products;
p is the retail price for new and remanufactured products;
b indicates the unit recycling price for recovering used products from consumers;
f indicates the unit recovery price of a used product recovered by a manufacturer through indirect recycling;
C_L is the cost factor for recycling activities;
λ indicates the abatement cost factor;
τ indicates the carbon reduction per unit of product;
θ_j is the recycling rate of used products of the participating entities j in each recycling mode of the closed-loop supply chain ($0 \leq \theta_j \leq 1$);
e is carbon emissions per unit of new product before carbon reduction ($0 < \tau < e$);
γ is the carbon emission intensity per unit of remanufactured product before carbon reduction ($0 < \gamma < 1$);
e_g is the total amount of free carbon allowances;
p_c is the market trading price of carbon credits;

D for product demand in the marketplace;
π_j^i is the profit of the participant j in the recycling mode i, where $i \in (\mathrm{M}, \mathrm{R}, \mathrm{T})$ denotes the M, R, and T recycling modes respectively; and $j \in (1, 2, 3)$ denotes the three supply chain participants: manufacturers, retailers, and third-party recyclers, respectively.

Underlying assumptions

Hypothesis 1: It is assumed that new and remanufactured products are assumed to have the same observable quality, performance, and selling price, so consumers do not distinguish between them in the basic demand function. In this paper, the method of dealing with used products is to dismantle and recycle every internal and external part, and reuse these functional components in the manufacturing of new products, and the remanufacturing process is carried out in full accordance with the original design and international standards, and the remanufactured products are not "second-hand goods" but brand-new products. The market demand is a linear function of price: $D = \alpha - \beta p$, $\alpha, \beta > 0$, and we assume $\alpha > \beta p$ holds under optimal solutions.

Hypothesis 2: Assume that there is only a single manufacturer, a single retailer, and a single third-party recycler in the study environment, that there are no competitors for each subject of interest, and that each subject of interest is in a state of perfect rationality.

Hypothesis 3: Assuming that all recovered used products have value and can be used for remanufacturing, the cost and carbon footprint of producing a remanufactured product is lower than that of a new product, i.e., $\Delta = C_n - C_r > 0$, and the price of recycling from consumers is lower than the transfer price paid by manufacturers to intermediaries, i.e., $f > b$.

Hypothesis 4: Assuming that all recycling entities invest costs in the recycling of used products, which includes channeling and advertising costs in the recycling process, etc., it is assumed that the benchmark model uses $C_{(L)} = C_L {\theta_j}^2$ as a reduced-form effort cost that depends on recycling rate rather than total output. This specification captures fixed channel-effort intensity; an alternative demand-dependent cost, such as $C_L(D\theta_j)^2$ or $C_L {\theta_j}^2 D$, can be examined in future research.

Hypothesis 5: Assuming that only the carbon emissions from the manufacturer's production process are considered in the study, and the carbon emissions from the recycling process are not taken into account, the carbon emissions from the manufacturer's production of a unit of a new product after the implementation of the carbon emission reduction policy will be $e - \tau$; and the carbon emissions from the production of a remanufactured product will be $\gamma e - \tau$. To ensure non-negative net emissions for remanufactured products, we impose the strict physical feasibility condition $\tau \leq \gamma e$. Consequently, when conducting comparative static and numerical analyses, the lower bound of the carbon emission intensity of remanufactured products is strictly restricted to $\gamma \geq \tau / e$ to prevent the mathematical anomaly of negative physical emissions.

Hypothesis 6: When a manufacturer's carbon emissions are less than the carbon emission allowances e_g, the excess can be sold to increase revenue; when the carbon emission allowances e_g are not enough to meet the manufacturer's carbon emissions, the excess has to be bought from the carbon market, and the free carbon credits are only for use in a single cycle, and cannot be carried over to the next cycle. In the present static model, e_g enters the profit function as an additive term. It affects absolute profit but does

not affect the first-order conditions, optimal decision variables, or mode ranking unless the quota rule is made endogenous or linked to output.

Hypothesis 7: Referring to other studies, it can be concluded that the input cost of a manufacturer's carbon abatement technology is an increasing convex function with respect to the amount of emission reduction per unit of product, and so this paper assumes that the cost function of carbon abatement is $C_{(\tau)} = \frac{1}{2}\lambda\tau^2$, it is interpreted as a fixed research and development (R&D) or technology-investment cost for achieving a per-unit emission-reduction level, rather than a purely variable production-scale cost, the cost of carbon abatement will be very large when the amount of emission reduction τ tends to be e.

Model construction and solution based on Stackelberg game

M recycling mode

In the M mode, a two-stage dynamic game is solved using backward induction, where the manufacturer first sets the wholesale price of new and remanufactured products at w, the recycling rate of used products at θ_1, and the carbon emission reduction per unit of product at τ. Then the retailer sets the retail price of the product at p, knowing the optimal wholesale price and emission reduction level. The profit function for the manufacturer and retailer in this model is:

$$max\pi_1^{\mathrm{M}} = (w - C_n)D + (\Delta - b)D\theta_1 - C_L{\theta_1}^2 - \frac{1}{2}\lambda\tau^2 + e_g p_c - D(1-\theta_1)(e-\tau)p_c - D\theta_1(\gamma e - \tau)p_c \quad (1)$$

$$max\pi_2^{\mathrm{M}} = (p - w)D \quad (2)$$

In the second stage of the game, first find the second-order partial derivative of π_2^{M} with respect to p, $\frac{\partial^2\pi_2^M}{\partial p^2} = -2\beta < 0$, and substitute $D = \alpha - \beta p$ into Eq. (2) to find the first-order partial derivative of π_2^{M} with respect to p and make it equal to zero, i.e., $\frac{\partial\pi_2^{\mathrm{M}}}{\partial p} = 0$, which yields the optimal retail price of the product p:

$$p = \frac{\alpha + \beta w}{2\beta} \quad (3)$$

Entering the first stage of the game, substituting p into Eq. (1) yields the Hessian matrix (Eq. (4)) of π_2^{M} with respect to the wholesale price of the product w and the carbon emission reduction per unit of product τ as:

$$H(\pi_1^{\mathrm{M}}) = \begin{bmatrix} \frac{\partial^2\pi_1^{\mathrm{M}}}{\partial w^2} & \frac{\partial^2\pi_1^{\mathrm{M}}}{\partial w\partial\tau} & \frac{\partial^2\pi_1^{\mathrm{M}}}{\partial w\partial\theta_1} \\ \frac{\partial^2\pi_1^{\mathrm{M}}}{\partial w\partial\tau} & \frac{\partial^2\pi_1^{\mathrm{M}}}{\partial w\partial\tau} & \frac{\partial^2\pi_1^{\mathrm{M}}}{\partial\tau\partial\theta_1} \\ \frac{\partial^2\pi_1^{\mathrm{M}}}{\partial\theta_1\partial w} & \frac{\partial^2\pi_1^{\mathrm{M}}}{\partial\theta_1\partial\tau} & \frac{\partial^2\pi_1^{\mathrm{M}}}{\partial{\theta_1}^2} \end{bmatrix} = \begin{bmatrix} -\beta & -p_c\beta & \frac{1}{2}\beta[\Delta - b + p_c e(1-\gamma)] \\ -p_c\beta & -\lambda & p_c\beta \\ \frac{1}{2}\beta[\Delta - b + p_c e(1-\gamma)] & p_c\beta & -2C_L \end{bmatrix} \quad (4)$$

To ensure that the manufacturer's profit function π_1^{M} is strictly concave with respect to the joint decision variables (w, τ, θ_1), the corresponding Hessian matrix $H(\pi_1^{\mathrm{M}})$ presented in Eq. (4) must be negative definite. According to Sylvester's criterion, a symmetric matrix is negative definite if and only if its leading principal minors alternate in sign. By substituting

the parameter condition $\beta > 0$ and $C_L > 0$, the first-order leading principal minor is $-\beta < 0$, the second-order leading principal minor yields $\beta\lambda - p_c^2\beta^2 > 0$ under sufficient investment efficiency. Finally, the third-order leading principal minor is strictly negative under the joint threshold condition $8C_L\lambda - \beta\lambda[\Delta - b + p_c e(1-\gamma)]^2 - 2C_L {p_c}^2\beta^2 > 0$, which is assumed throughout this study. Since the first, second, and third-order sequential principal minors simultaneously fulfill the negative definiteness requirements, the full joint concavity is rigorously established. Consequently, π_1^{M} is a strictly concave function globally, ensuring that a unique global optimal solution $(w^*, \tau^*, {\theta_1}^*)$ exists and can be derived by setting the first-order partial derivatives to zero simultaneously. The conjunction can be obtained the optimal wholesale price of the product w, the carbon emission reduction per unit of the product τ, and the recycling rate θ_1 are respectively (Eqs. (5)-(7)):

$$w = \frac{\alpha}{\beta} + \frac{4C_L\lambda(\beta C_n + p_c\beta e - \alpha)}{8C_L\beta\lambda - \beta^2\lambda[\Delta - b + p_c e(1-\gamma)]^2 - 2C_L {p_c}^2\beta^2} \tag{5}$$

$$\tau = \frac{2C_L p_c(\alpha - \beta C_n - p_c\beta e)}{8C_L\lambda - \beta\lambda[\Delta - b + p_c e(1-\gamma)]^2 - 2C_L {p_c}^2\beta} \tag{6}$$

$$\theta_1 = \frac{\lambda(\alpha - \beta C_n - p_c\beta e)[\Delta - b + p_c e(1-\gamma)]}{8C_L\lambda - \beta\lambda[\Delta - b + p_c e(1-\gamma)]^2 - 2C_L {p_c}^2\beta} \tag{7}$$

To ensure that the optimal recycling rate θ_1 derived in Eq. (7) is mathematically valid and resides within the interior boundaries, we formally impose a Karush-Kuhn-Tucker (KKT) analytical constrain. For an interior optimal solution characterised by $0 \le \theta_1 \le 1$, the structural parameters must strictly satisfy the following full joint condition: $0 \le \frac{\lambda(\alpha - \beta C_n - p_c\beta e)[\Delta - b + p_c e(1-\gamma)]}{8C_L\lambda - \beta\lambda[\Delta - b + p_c e(1-\gamma)]^2 - 2C_L {p_c}^2\beta} \le 1$.Within the defined feasible parameter domain, if the recycling efficiency or cost savings increase excessively such that this upper boundary is violated, the constraint binds, and the system seamlessly converges to the boundary solution $\theta_1 = 1$. All comparative statics are restricted to this non-empty interior domain.

Substituting the above optimal solution into Eq. (3) yields the retailer's optimal retail price p as Eq. (8):

$$p = \frac{\alpha}{\beta} + \frac{2C_L\lambda(\beta C_n + p_c\beta e - \alpha)}{8C_L\beta\lambda - \beta^2\lambda[\Delta - b + p_c e(1-\gamma)]^2 - 2C_L {p_c}^2\beta^2} \tag{8}$$

Finally, substituting the above optimal solutions into the profit function of each supply chain subject respectively, the expressions of π_1^{M} (Eq. (9)) and π_2^{M} (Eq. (10)) can be obtained:

$$\pi_1^{\mathrm{M}} = \frac{C_L\lambda(\alpha - \beta C_n - p_c\beta e)^2}{8C_L\beta\lambda - \beta^2\lambda[\Delta - b + p_c e(1-\gamma)]^2 - 2C_L {p_c}^2\beta^2} + e_g p_c \tag{9}$$

$$\pi_2^{\mathrm{M}} = \frac{4{C_L}^2\lambda^2(\alpha - \beta C_n - p_c\beta e)^2}{\beta\{8C_L\lambda - \beta\lambda[\Delta - b + p_c e(1-\gamma)]^2 - 2C_L {p_c}^2\beta\}^2} \tag{10}$$

Lemma 1*:* There are in the manufacturer's recycling mode:

1) $\frac{\partial p}{\partial\lambda} > 0, \frac{\partial w}{\partial\lambda} > 0, \frac{\partial\tau}{\partial\lambda} < 0, \frac{\partial\theta_1}{\partial\lambda} < 0, \frac{\partial\pi_j^{\mathrm{M}}}{\partial\lambda} < 0;$

As the carbon emission reduction cost factor rises, manufacturers' used - product recycling rate and per - unit product carbon reduction both drop. A higher factor implies

more capital for carbon-reduction policies, leading to higher wholesale and retail prices, lower demand, and thus reduced profits for manufacturers and retailers.

2) $\frac{\partial p}{\partial C_L} > 0, \frac{\partial w}{\partial C_L} > 0, \frac{\partial \tau}{\partial C_L} < 0, \frac{\partial \theta_1}{\partial C_L} < 0, \frac{\partial \pi_j^{\mathrm{M}}}{\partial C_L} < 0;$

Manufacturers' recycling rates for used products and carbon emission reductions per unit of product both decrease with an increase in the recycling cost factor, and an increase in recycling costs will result in lower profits.

3) $\frac{\partial p}{\partial \Delta} < 0, \frac{\partial w}{\partial \Delta} < 0, \frac{\partial \tau}{\partial \Delta} > 0, \frac{\partial \theta_1}{\partial \Delta} > 0, \frac{\partial \pi_j^{\mathrm{M}}}{\partial \Delta} > 0;$

The higher the unit production cost savings of remanufactured products over new products, the more manufacturers and retailers will tend to recycle and remanufacture, while more remanufactured products can increase carbon emission reduction, and if manufacturers continue to improve their remanufacturing capacity and technology, then they can get more profits and carbon emission reduction.

4) $\frac{\partial p}{\partial \gamma} > 0, \frac{\partial w}{\partial \gamma} > 0, \frac{\partial \tau}{\partial \gamma} < 0, \frac{\partial \theta_1}{\partial \gamma} < 0, \frac{\partial \pi_j^{\mathrm{M}}}{\partial \gamma} < 0;$

The lower the emission intensity of remanufactured products relative to new products, the more favorable the recycling of used products and the increase in carbon emission reduction, and the lower the carbon emission is conducive to environmental development.

5) $\frac{\partial p}{\partial b} > 0, \frac{\partial w}{\partial b} > 0, \frac{\partial \tau}{\partial b} < 0, \frac{\partial \theta_1}{\partial b} < 0, \frac{\partial \pi_j^{\mathrm{M}}}{\partial b} < 0.$

The higher the per unit recovery price at which a manufacturer recovers used products from consumers, the lower the rate of recycling of used products, making it more costly for the manufacturer.

R recycling mode

In the R mode, the manufacturer first sets wholesale price w, emission reduction τ, and the transfer price f. The retailer then chooses the retail price p and recycling rate θ_2 after observing the manufacturer's decisions, and the transfer price f is an endogenous decision variable of the manufacturer, with $f > b$. Accordingly, the manufacturer's remanufacturing benefit is based on the transfer price paid to the retailer, whereas the retailer earns the recycling margin and bears the recycling effort cost, this distinguishes the R mode profit structure from the direct manufacturer recycling mode. Its Stackelberg game model can be described as Eqs. (11)-(21) similarly:

$$max\pi_1^{\mathrm{R}} = (w - C_n)D + (\Delta - f)D\theta_2 - \frac{1}{2}\lambda\tau^2 + e_g p_c - D(1-\theta_2)(e-\tau)p_c - D\theta_2(\gamma e - \tau)p_c \tag{11}$$

$$max\pi_2^{\mathrm{R}} = (p - w)D + (f - b)D\theta_2 - CL{\theta_2}^2 \tag{12}$$

$$H(\pi_2^{\mathrm{R}}) = \begin{bmatrix} \frac{\partial^2 \pi_2^{\mathrm{R}}}{\partial p^2} & \frac{\partial^2 \pi_2^{\mathrm{R}}}{\partial p \theta_2} \\ \frac{\partial^2 \pi_2^{\mathrm{R}}}{\partial \theta_2 p} & \frac{\partial^2 \pi_2^{\mathrm{R}}}{\partial {\theta_2}^2} \end{bmatrix} = \begin{bmatrix} -2\beta & (f-b)\beta \\ (f-b)\beta & -2C_L \end{bmatrix} \tag{13}$$

For the retailer's problem to be concave, the second-order condition must hold and the resulting solution must satisfy $0 < \theta_2 < 1$ and $D > 0$. After substituting the retailer's

reaction functions into the manufacturer's problem, the manufacturer's second-order and denominator-positivity conditions are also imposed before the closed-form solution is used, we require $4C_L - (f-b)^2\beta > 0$. The space of exogenous parameters of the system is analytically restricted to the KKT tight constraint region: $\lambda[4C_L - (f-b)^2\beta] > \beta\lambda\left[(f-b)\left(\Delta - f + p_c e(1-\gamma)\right)\right]^2 + C_L {p_c}^2\beta$, if this boundary is exceeded, the system will automatically converge to the boundary solution θ =1. Solving the first-order conditions yields:

$$p = \frac{\alpha(2C_L - (f-b)^2\beta) + 2\beta C_L w}{\beta(4C_L - (f-b)^2\beta)} \tag{14}$$

$$\theta_2 = \frac{(f-b)(\alpha - \beta w)}{4C_L - (f-b)^2\beta} \tag{15}$$

Substituting into the manufacturer's problem and solving simultaneously with the first-order condition for τ yields:

$$w = \frac{\alpha}{\beta} + \frac{\lambda[4C_L - (f-b)^2\beta](\beta C_n + p_c\beta e - \alpha)}{8\lambda\beta C_L - 2\beta^2\lambda(f-b)[\Delta - f + p_c e(1-\gamma)] - 2C_L {p_c}^2\beta^2} \tag{16}$$

$$\tau = \frac{C_L p_c(\alpha - \beta C_n - p_c\beta e)}{4C_L\lambda - \lambda\beta(f-b)[\Delta - f + p_c e(1-\gamma)] - C_L {p_c}^2\beta} \tag{17}$$

$$p = \frac{\alpha}{\beta} + \frac{\lambda C_L(\beta C_n + p_c\beta e - \alpha)}{4C_L\lambda\beta - \beta^2\lambda(f-b)[\Delta - f + p_c e(1-\gamma)] - C_L {p_c}^2\beta^2} \tag{18}$$

$$\theta_2 = \frac{\lambda(f-b)(\alpha - \beta C_n - p_c\beta e)}{8C_L\lambda - 2\beta\lambda(f-b)[\Delta - f + p_c e(1-\gamma)] - 2C_L {p_c}^2\beta} \tag{19}$$

$$\pi_1^{\mathrm{R}} = \frac{\lambda C_L(\alpha - \beta C_n - p_c\beta e)^2}{8\lambda\beta C_L - 2\beta^2\lambda(f-b)[\Delta - f + p_c e(1-\gamma)] - 2C_L {p_c}^2\beta^2} + e_g p_c \tag{20}$$

$$\pi_2^{\mathrm{R}} = \frac{\lambda^2 C_L[4C_L - (f-b)^2\beta](\alpha - \beta C_n - p_c\beta e)^2}{\beta\{8C_L\lambda - 2\beta\lambda(f-b)[\Delta - f + p_c e(1-\gamma)] - 2C_L {p_c}^2\beta\}^2} \tag{21}$$

As demonstrated in the corrected equilibrium results from Eq. (16) to Eq. (21), the economic performance and optimisation structures of the R mode are strictly bound to the penalised margin $\Delta - f$ instead of the raw cost savings $\Delta - b$. This accurately reflects the institutional setting where the manufacturer must transfer a positive channel markup to the retailer follower, dynamically scaling both the optimal emission reduction and reverse collection rates.

Lemma 2: There are in the retailer recycling mode:

1) $\frac{\partial p}{\partial \lambda} > 0, \frac{\partial w}{\partial \lambda} > 0, \frac{\partial \tau}{\partial \lambda} < 0, \frac{\partial \theta_2}{\partial \lambda} < 0, \frac{\partial \pi_j^{\mathrm{R}}}{\partial \lambda} < 0$;

Both the recycling rate of used products and the carbon emission reduction per unit of product are inversely proportional to the carbon emission reduction cost coefficient. Manufacturers will reduce the amount of carbon emission reduction and the recycling rate due to the higher carbon emission reduction cost coefficient, and increase the wholesale and retail prices of their products, thus resulting in a lower demand for their products and a lower profit for manufacturers and retailers.

2) $\frac{\partial p}{\partial C_L} > 0,\ \frac{\partial w}{\partial C_L} > 0,\ \frac{\partial \tau}{\partial C_L} < 0,\ \frac{\partial \theta_2}{\partial C_L} < 0,\ \frac{\partial \pi_j^{\mathrm{R}}}{\partial C_L} < 0;$

Both the recycling rate of used products and the carbon emission reduction per unit of product decrease with the increase of the recycling cost coefficient, while the increase of the recycling cost will increase the wholesale price and the retail price, which will result in the decrease of demand and the decrease of the profit of the manufacturer and the retailer.

3) $\frac{\partial p}{\partial \Delta} < 0, \frac{\partial w}{\partial \Delta} < 0, \frac{\partial \tau}{\partial \Delta} > 0, \frac{\partial \theta_2}{\partial \Delta} > 0, \frac{\partial \pi_j^{\mathrm{R}}}{\partial \Delta} > 0;$

The higher the unit production cost savings of a remanufactured product over a new product, the more obvious the advantages of remanufacturing become, and remanufacturing also contributes to higher carbon emissions reductions, with profits from increased demand fully offsetting losses from lower prices, and therefore increased profits for manufacturers and retailers.

4) $\frac{\partial p}{\partial \gamma} > 0, \frac{\partial w}{\partial \gamma} > 0, \frac{\partial \tau}{\partial \gamma} < 0, \frac{\partial \theta_2}{\partial \gamma} < 0, \frac{\partial \pi_j^{\mathrm{R}}}{\partial \gamma} < 0;$

The lower the emissions intensity of a remanufactured product relative to a new product, the more favorable it is to recycle the used product and increase carbon reductions, which in turn increases the cost savings.

5) $\frac{\partial p}{\partial b} > 0, \frac{\partial w}{\partial b} > 0, \frac{\partial \tau}{\partial b} < 0, \frac{\partial \theta_2}{\partial b} < 0, \frac{\partial \pi_j^{\mathrm{R}}}{\partial b} < 0.$

The higher the recycling price paid by retailers to recycle used products, the less willing they will be to recycle them, and the lower recycling rate will make it more expensive for manufacturers.

T recycling mode

In the T mode, the manufacturer first sets w, τ, and the transfer price f paid to the third party. The retailer then sets p. The third-party recycler, observing w and given f and b, chooses θ_3 to maximise its own profit. The third party acts after the manufacturer but simultaneously with or after the retailer; we assume the third party chooses θ_3 after observing w. The Stackelberg game model can be described as Eqs. (22)-(32) similarly:

$$max\pi_1^{\mathrm{T}} = (w - C_n)D + (\Delta - f)D\theta_3 - \frac{1}{2}\lambda\tau^2 + e_g p_c - D(1-\theta_3)(e-\tau)p_c - D\theta_3(\gamma e - \tau)p_c \tag{22}$$

$$max\pi_2^{\mathrm{T}} = (p - w)D \tag{23}$$

$$max\pi_3^{\mathrm{T}} = (f - b)D\theta_3 - C_L{\theta_3}^2 \tag{24}$$

From the third party's first-order condition:

$$\theta_3 = \frac{(f-b)(\alpha - \beta w)}{4C_L} \tag{25}$$

Substituting into the manufacturer's problem and solving yields:

$$w = \frac{\alpha}{\beta} + \frac{2\lambda C_L(\beta C_n + p_c\beta e - \alpha)}{4C_L\lambda\beta - \beta^2\lambda(f-b)[\Delta - f + p_c e(1-\gamma)] - C_L{p_c}^2\beta^2} \tag{26}$$

$$\tau = \frac{C_L p_c(\alpha - \beta C_n - p_c\beta e)}{4C_L\lambda - \beta\lambda(f-b)[\Delta - f + p_c e(1-\gamma)] - C_L{p_c}^2\beta} \tag{27}$$

$$p = \frac{\alpha}{\beta} + \frac{\lambda C_L(\beta C_n + p_c\beta e - \alpha)}{4C_L\lambda\beta - \beta^2\lambda(f-b)[\Delta - f + p_c e(1-\gamma)] - C_L {p_c}^2\beta^2} \tag{28}$$

$$\theta_3 = \frac{\lambda(f-b)(\alpha - \beta C_n - p_c\beta e)}{8C_L\lambda - 2\beta\lambda(f-b)[\Delta - f + p_c e(1-\gamma)] - 2C_L {p_c}^2\beta} \tag{29}$$

$$\pi_1^{\mathrm{T}} = \frac{\lambda C_L(\alpha - \beta C_n - p_c\beta e)^2}{8\lambda\beta C_L - 2\beta^2\lambda(f-b)[\Delta - f + p_c e(1-\gamma)] - 2C_L {p_c}^2\beta^2} + e_g p_c \tag{30}$$

$$\pi_2^{\mathrm{T}} = \frac{{C_L}^2\lambda^2(\alpha - \beta C_n - p_c\beta e)^2}{\beta\{4C_L\lambda - \beta\lambda(f-b)[\Delta - f + p_c e(1-\gamma)]^2 - C_L {p_c}^2\beta\}^2} \tag{31}$$

$$\pi_3^{T} = \frac{C_L\lambda^2(f-b)^2(\alpha - \beta C_n - p_c\beta e)^2}{4\{4C_L\lambda - \beta\lambda(f-b)[\Delta - f + p_c e(1-\gamma)]^2 - C_L {p_c}^2\beta\}^2} \tag{32}$$

Lemma 3: In the third-party recycling mode, the following comparative-static relationships hold within the feasible parameter range:

1) $\frac{\partial p}{\partial\lambda} > 0, \frac{\partial w}{\partial\lambda} > 0, \frac{\partial\tau}{\partial\lambda} < 0, \frac{\partial\theta_3}{\partial\lambda} < 0, \frac{\partial\pi_j^{\mathrm{T}}}{\partial\lambda} < 0;$

Similar to Lemma 1 and Lemma 2, both the recycling rate of used products and the carbon reduction per unit of product for third-party recyclers decrease as the carbon reduction cost factor increases.

2) $\frac{\partial p}{\partial C_L} > 0, \frac{\partial w}{\partial C_L} > 0, \frac{\partial\tau}{\partial C_L} < 0, \frac{\partial\theta_3}{\partial C_L} < 0, \frac{\partial\pi_j^{\mathrm{T}}}{\partial C_L} < 0;$

Both the recycling rate of used products and the carbon emission reduction per unit of product decrease with the increase of the recycling cost coefficient, and the increase of recycling cost will increase the wholesale price and the retail price, which will make the profit of the manufacturers and retailers lower.

3) $\frac{\partial p}{\partial\Delta} < 0, \frac{\partial w}{\partial\Delta} < 0, \frac{\partial\tau}{\partial\Delta} > 0, \frac{\partial\theta_3}{\partial\Delta} > 0, \frac{\partial\pi_j^{\mathrm{T}}}{\partial\Delta} > 0;$

The higher the unit production cost savings of a remanufactured product over a new product, the more willing manufacturers and third-party recyclers will be to recover used products for remanufacturing, while remanufacturing can increase carbon emissions reductions, and the profits generated by increased demand can fully offset the losses generated by lower prices, thus increasing the profitability of the supply chain.

4) $\frac{\partial p}{\partial\gamma} > 0, \frac{\partial w}{\partial\gamma} > 0, \frac{\partial\tau}{\partial\gamma} < 0, \frac{\partial\theta_3}{\partial\gamma} < 0, \frac{\partial\pi_j^{\mathrm{T}}}{\partial\gamma} < 0;$

The lower the emissions intensity of a remanufactured product relative to a new product, the more beneficial it is to recycle used products and increase carbon emissions reductions, resulting in increased cost savings and thus higher profits for manufacturers and retailers.

5) $\frac{\partial p}{\partial b} > 0, \frac{\partial w}{\partial b} > 0, \frac{\partial\tau}{\partial b} < 0, \frac{\partial\theta_3}{\partial b} < 0, \frac{\partial\pi_j^{\mathrm{T}}}{\partial b} < 0.$

The higher the recycling price to be paid by third-party recyclers for recovering used products, the more unfavorable it is to the expansion of the scale of recycling and remanufacturing in the closed-loop supply chain.

Comparative analysis of three closed-loop supply chain recycling modes

Comparison 1: The optimal retail price relationship is $p^T > p^R > p^M$, and this paper assumes that product demand conforms to the functional relationship: $D = \alpha - \beta p$, hence $D^T < D^R < D^M$.

Proof:

$$p^M - p^R = \frac{2C_L\lambda(\beta C_n + p_c\beta e - \alpha)}{8C_L\beta\lambda - \beta^2\lambda[\Delta - b + p_c e(1-\gamma)]^2 - 2C_L{p_c}^2\beta^2} - \frac{2\lambda C_L(\beta C_n + p_c\beta e - \alpha)}{8C_L\lambda\beta - 2\beta^2\lambda(f-b)[\Delta - f + p_c e(1-\gamma)] - 2C_L{p_c}^2\beta^2}$$

When the numerators are the same, the denominator of the Manufacturer Recycling mode, $8C_L\beta\lambda - \beta^2\lambda[\Delta - b + p_c e(1-\gamma)]^2 - 2C_L{p_c}^2\beta^2$, is smaller. Therefore, the retail price under the Manufacturer Recycling mode is smaller, yielding $p^M - p^R < 0$, and the following inequality compares in the same way as the above inequality, yielding $p^R - p^T < 0$. From the above inequality, we know that the retail price under the third-party recycler recycling mode is the highest.

Comparison 2: The wholesale price relationship for the optimal manufacturer is $w^T > w^R > w^M$, and the following inequality comparisons in the same way as the above inequality.

Proof:

$$w^M - w^R = \frac{4C_L\lambda(\beta C_n + p_c\beta e - \alpha)}{8C_L\beta\lambda - \beta^2\lambda[\Delta - b + p_c e(1-\gamma)]^2 - 2C_L{p_c}^2\beta^2} - \frac{\lambda[4C_L - (f-b)^2\beta](\beta C_n + p_c\beta e - \alpha)}{8\lambda\beta C_L - 2\beta^2\lambda(f-b)[\Delta - f + p_c e(1-\gamma)] - 2C_L{p_c}^2\beta^2}$$

The numerator of w^M is smaller than that of w^R, while the denominator of w^M is larger than that of w^R. Therefore, w^M must be less than the value of w^R, yielding $w^M - w^R < 0$, and the following inequality compares in the same way as the above inequality, yielding $w^R - w^T < 0$.

Comparison 3: The optimal manufacturer's carbon reduction per unit of product relationship is: $\tau^T < \tau^R < \tau^M$, provided that Δ is sufficiently large. The proof uses the fact that denominators are positive and the numerators are identical across models; under the benchmark feasible parameter set, manufacturer recycling generally provides a higher per-unit emission reduction, but the ranking can change when the remanufacturing cost-saving parameter, transfer price or carbon price moves outside the benchmark interval, the ordering follows from the relative magnitudes of the terms involving $(f-b)$ and $[\Delta - b + p_c e(1-\gamma)]$ versus $[\Delta - f + p_c e(1-\gamma)]$.

Comparison 4: The optimal waste product recovery rate relationship for a reverse closed-loop supply chain is: $\theta_3^T < \theta_2^R \leq \theta_1^M$. The recycling-rate ranking is also conditional on the recycling-cost coefficient, transfer price, and consumer recycling price. Direct manufacturer recycling avoids the double-margin effect in the reverse channel, but indirect recycling can improve collection incentives when the transfer price is sufficiently attractive to the retailer or third-party recycler.

Comparison 5: The optimal case manufacturer profit relationship is: $\pi_1^T < \pi_1^R < \pi_1^M$ under the baseline parameter set. The optimal recycling mode is identified according to a specified criterion, here the manufacturer's profit and per-unit emission reduction, rather than total social welfare or every participant's profit. Unlike direct

manufacturer recycling which captures the unmitigated cost-saving margin $(\Delta - b)$, the manufacturer in the R mode must operate under the penalised margin $(\Delta - f)$. Because $f > b$ is established by contract, the manufacturer must surrender a positive vertical channel markup to the retailer follower. In a manufacturer-led Stackelberg game, this reverse double-marginalisation cannot be fully offset by the retailer's proxim R&D stands for research and development ity to consumers. Thus, the algebraic deduction yields $\pi_1^M - \pi_1^R > 0$ universally.

Numerical analysis

From the above analysis of the main model and solution results, this paper applies Matlab2021b software to analyse the changes of carbon emission reduction and manufacturer's profit under the three recycling modes. Based on the parameter design of the existing literature [31-33], we set the corresponding initial parameters as $\alpha = 100,\ \beta = 4,\ C_n = 10,\ f = 2.5,\ C_L = 60,\ \lambda = 100,\ e = 2, e_g = 100,\ p_c = 1, \gamma = 0.5, b = 1, \Delta = 3$. Sensitivity analyses are conducted for key parameters λ, C_L. The following is an analysis of all sensitivity analysis parameters $(p_c, \gamma, b, \Delta, f)$ on carbon emission reductions and profits, with λ and C_L listed separately as a robustness check.

To establish the institutional implementability of the decentralised reverse channels, the followers' Individual Rationality (IR) or participation constraints must be strictly satisfied, ensuring that both the retailer and the third-party recycler yield non-negative returns ($\pi_2^R \geq 0$ and $\pi_3^T \geq 0$) under the contractual transfer price f. Analytically, as derived in Eq. (32), the third-party profit π_3^T comprises a square over a squared denominator, guaranteeing $\pi_3^T > 0$ universally within the feasible domain. For the retailer, Eq. (21) dictates that $\pi_2^R \geq 0$ requires $4C_L - (f - b)^2\beta \geq 0$, which is completely identical to the secondary optimisation concavity condition already imposed on the forward market. Under our baseline calibrated parameter set, we verify that $\pi_2^R = 64.12 > 0$ and $\pi_3^T = 16.03 > 0$, confirming that both followers satisfy basic financial non-negativity within the decentralised closed-loop supply chain. A comprehensive numerical synthesis of these baseline equilibrium configurations, operational boundary controls, and basic feasibility checks across all three competitive recycling modes is summarised and explicitly verified in Table 1.

Table 1

Baseline equilibrium configurations and follower participation viability under distinct recycling modes

Parameter	M Mode	R Mode	T Mode	IR Check
Baseline participant profit	$\pi_2^M = 245.54$ (Forward choice)	$\pi_2^R = 64.12$	$\pi_3^T = 16.03$	$\pi_j^i \geq 0$
Recycling rate	$\theta_1 = 0.355$	$\theta_2 = 0.355$	$\theta_3 = 0.178$	$0 \leq \theta_j \leq 1$
Net remanufactured emission	$\gamma e - \tau = 0.858$	$\gamma e - \tau = 0.858$	$\gamma e - \tau = 0.864$	$\gamma e - \tau > 0$

To explicitly address the institutional implementability of the decentralised reverse channels and resolve the conceptual boundary of followers' reservation utilities, Figure 4 evaluates the dynamic configurations of follower profits against their respective true outside options as λ sweeps from 50 to 200. As visually captured in Figure 4, while the third-party recycler eagerly participates in the closed-loop system since its absolute baseline

remains universally strictly positive ($\pi_3^T > 0$), a prominent Individual Rationality (IR) friction is revealed for the retailer recycling mode. Crucially, across the entire feasible domain of λ, the retailer's simulated profit under the R mode consistently falls below its forward-channel external choice under the M mode ($\pi_2^R < \pi_2^M$). This graphical contrast rigorously validates that although the basic non-negativity constraint ($\pi_2^R > 0$) is technically satisfied due to concavity specifications, a purely decentralised R mode inherently lacks spontaneous voluntary participation incentives for the retailer follower. Therefore, to ensure supply chain resilience in practice, the leading manufacturer must strategically coordinate the channel via advanced transfer-pricing extensions or secondary profit-sharing agreements, shielding the follower from reverse logistics markup strains.

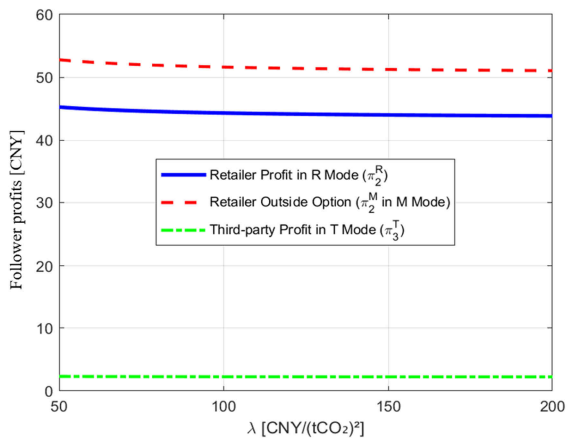


Fig. 4. Follower participation viability and Individual rationality (IR) check across different carbon abatement cost factors (λ)

Impact of p_c on carbon emission reductions and profits

In this subsection, we will study the impact of carbon trading price p_c on carbon emission reduction per unit of product and manufacturer's profit, assuming that the carbon emission intensity meets the requirements of $\gamma = 0.5, \Delta = 3, b = 1$. Since real carbon prices are determined by market supply and demand and may fluctuate, p_c is treated here as an exogenous long-run equilibrium or scenario parameter rather than a short-term stochastic price, we will study the change of unit product emission reduction and manufacturer's profit when p_c varies from 0 to 2.4.

In Figure 5a, as p_c gradually rises from 0 to 2.4, the carbon emission reductions under all three recycling modes increase monotonically from 0, and the three curves almost completely overlap. This indicates that the incentive effect of carbon pricing on emission reductions is highly consistent across different recycling channels, which is closely aligned with the core logic of the current national carbon market construction that price signals reshape corporate behaviour. Specifically, under $p_c = 2.4$, the emission reductions for the M, R, and T modes reach 0.31, 0.29, and 0.28 respectively, with the M mode slightly superior.

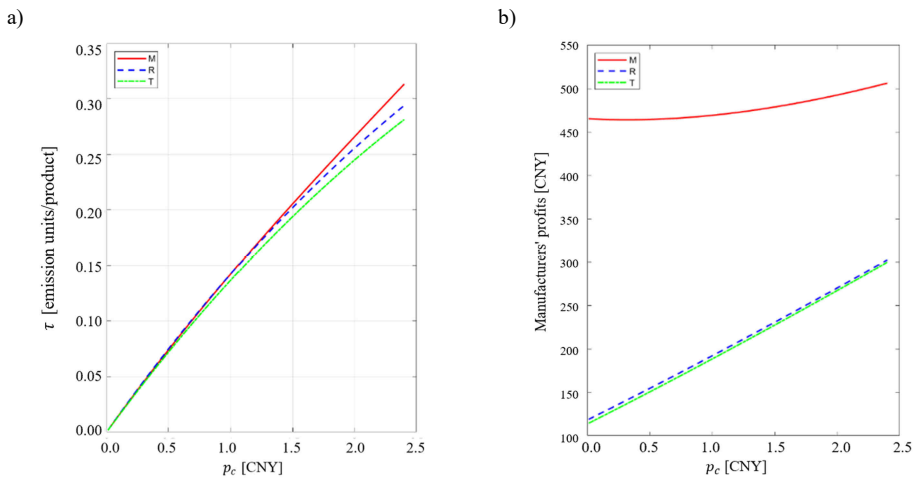


Fig. 5. Impact of carbon trading prices ($0 < p_c \leq 2.4$): a) carbon emission reductions, b) manufacturers' profits

In Figure 5b, the profits of all three modes increase linearly with rising carbon prices, with the M mode consistently the highest profit about 500, the R mode second, and the T mode the lowest. Since, given the free allowance $e_g = 100$, manufacturers are net sellers of carbon allowances, so higher carbon prices directly increase revenue from selling allowances. From a practical perspective, the average transaction price of allowances in the first compliance period of the national carbon market was 42.85 yuan/t (t = tonne = 10^6 g = Mg). As the carbon market expands to high energy-consuming industries such as steel, cement, and electrolytic aluminium, the carbon price has already exceeded 100 yuan/t, and the introduction of a future paid allocation proportion will further reshape the carbon cost landscape. This validates the model's conclusion: appropriately raising the carbon trading price can not only effectively incentivise enterprise emission reductions but also simultaneously increase manufacturers' profit levels, forming a 'win-win' for the environment and the economy. Therefore, the government should gradually raise the unit price of the carbon market and ensure that allowance allocation is not too generous to strengthen the price signal.

To examine whether the positive relationship between manufacturer profit and carbon price p_c is sensitive to the level of free allowance e_g, we recompute the equilibrium profit under the manufacturer recycling (M) mode for five representative allowance levels: $e_g = 0, 50, 100, 150, 200$, the results are reported in Figure 6.

When $e_g = 0$, the manufacturer's profit decreases monotonically from 465 to 260 as p_c rises from 0 to 2.4, because every unit of emission must be purchased at an increasing cost. For $e_g = 50$, the profit also declines, but the slope is slightly less steep, indicating that a small free quota partially offsets the carbon cost, yet the manufacturer remains a net buyer.

In contrast, when $e_g = 100$, the profit increases from 465 to 500 as p_c rises, confirming that the manufacturer is a net seller of allowances. The upward trend becomes stronger for $e_g = 150$ and $e_g = 200$, where profits rise from 465 to 625 and from 465 to

700, respectively, over the same p_c range. This exercise reveals a critical threshold: the sign of $\frac{\partial \pi_1^M}{\partial p_c}$ switches from negative to positive when e_g is approximately between 50 and 100. Under our baseline $e_g = 100$, the positive profit-price relationship is robust. However, if the government significantly reduces free allocations (e.g., to 50 or below), higher carbon prices would harm manufacturer profitability. This result underscores the importance of considering quota allocation rules in carbon market design and suggests that the positive synergy between carbon price and profit is contingent upon sufficient free allowances, confirming that the policy allocation rules act as a critical boundary condition shaping green corporate performance.

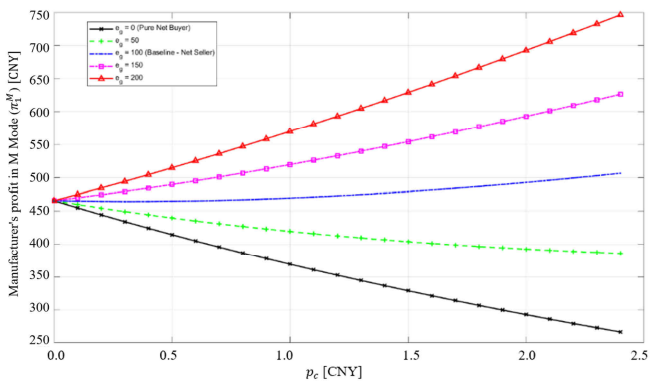


Fig. 6. Impact of p_c on profit under different e_g

Impact of γ on carbon emission reductions and profits

This subsection is devoted to the study of how the carbon emission intensity γ affects the carbon emission reduction per unit product and the manufacturer's profit. At this time, $p_c = 1, \Delta = 3, b = 1$ is set, $0.2 \leq \gamma \leq 0.9$ is known from the parameter assumptions in the previous section.

Figure 7a illustrates the variation of unit product carbon reduction τ under different carbon emission intensities γ for three recycling modes. The lower bound γ = 0.2 is chosen to ensure the feasibility condition $0 < \tau < \gamma e$ holds for all plotted points. At γ = 0.2, τ values for M, R, and T modes are 0.147, 0.144, and 0.139, respectively; at γ = 0.9, they drop to 0.137, 0.139, and 0.134. With an increase in γ triggers a continuous, monotonic reduction in the optimal carbon abatement level τ under all three recycling channels. This downward trajectory is driven by economic law: a higher γ implies that remanufactured products are carbon-intensive, which significantly erodes the carbon-saving premium or compliance cost-relief achievable through reverse-loop operations, thereby directly suppressing the manufacturer's motivation to invest in forward low-carbon R&D. From a channel-comparison perspective, a prominent crossover phenomenon is captured between the direct and indirect systems. When the remanufacturing process is highly clean ($\gamma < 0.5$), the manufacturer recycling mode (M mode) establishes clear superiority, yielding the maximum emission reduction (τ = 0.147 at $\gamma = 0.2$). This occurs because direct integration maximises operational control and eliminates intermediate friction.

However, because the M mode is highly sensitive to carbon penalties, its abatement performance degrades at a faster rate than the indirect channels as γ expands. Once γ exceeds the critical intersection threshold, the retailer recycling mode (R mode) surpasses the M mode, demonstrating stronger environmental performance resilience under higher baseline remanufacturing carbon intensities. Throughout the entire range, the third-party recycling mode (T mode) consistently lags behind as the least environmentally efficient option.

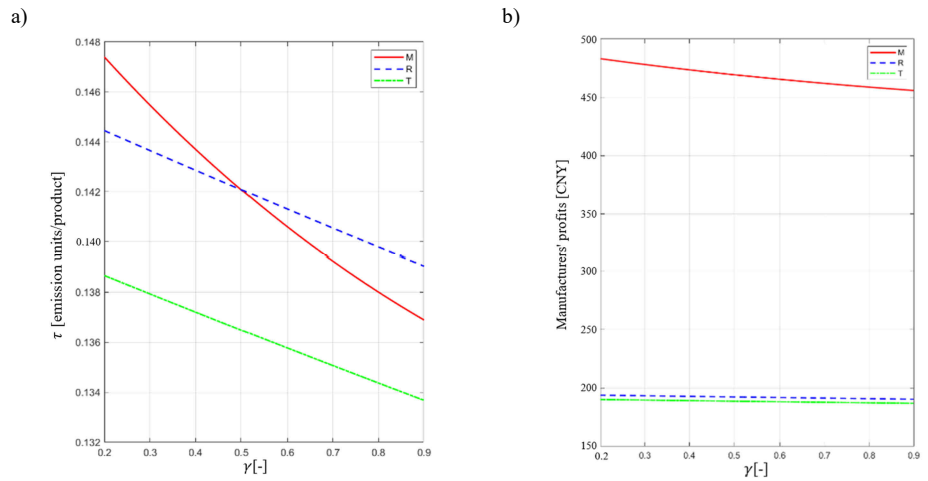


Fig. 7. Impact of carbon emission intensity ($0.2 \leq \gamma \leq 0.9$): a) carbon emission reductions, b) manufacturers' profits

Figure 7b shows that when $\gamma = 0.2$, the profits of the M, R, and T modes are 495, 195, and 190, respectively, with the M mode significantly higher than the other two modes. In contrast to the environmental performance, Figure 7b reveals a highly stratified and stable economic landscape for the manufacturer's profit. Across the valid spectrum of γ, the manufacturer's profit drops monotonically across all modes as carbon intensities climb, reflecting the escalating financial burden of compliance. Crucially, the absolute profit ranking remains entirely invariant, strictly obeying the order of $\pi_1^T < \pi_1^R < \pi_1^M$ with no intersection points. Even when γ surpasses 0.5 (where the R mode yields slightly superior carbon reductions), the direct M mode stubbornly maintains its overwhelming economic dominance, which far outstrips the R mode and the T mode. This clear divergence between environmental superiority and economic dominance indicates that while indirect retailer integration can buffer carbon reduction efforts under dirtier remanufacturing processes, it severely penalises the manufacturer's total profitability due to localised double-marginalisation and reverse channel markup extraction.

Impact of b on carbon emission reductions and profits

This subsection is dedicated to the study of how the recycling price b to be paid for recycling used products from consumers affects the carbon emission reduction per unit of product and the manufacturer's profit, and thus the choice of recycling mode. At this

point, $p_c = 1, \gamma = 0.5, \Delta = 3$ is set, and since the parameter $f = 2.5$ was previously set in this paper, along with the previous assumption $b < f$.

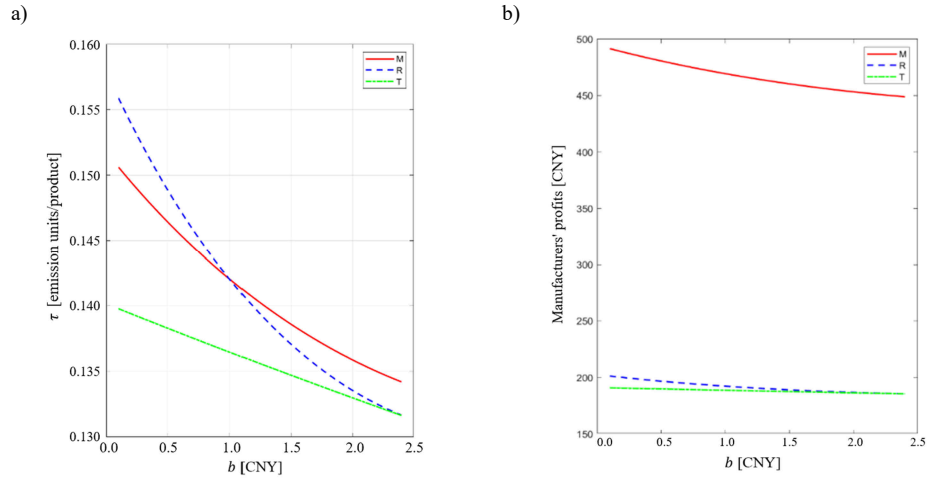


Fig. 8. Impact of recycling prices $(0 < b < 2.5)$: a) carbon emission reductions, b) manufacturers' profits

In Figure 8a, as the recycling price b increases from 0 to 2.5, the carbon reduction per unit product τ under the three recycling modes all show a downward trend. This indicates that an increase in recycling price weakens the firm's incentive to reduce emissions because higher recycling costs compress the profit margin brought by remanufacturing. In the range $0 < b < 1$, τ under the R mode is always slightly higher than that under the M mode, while the T mode is the lowest. The R mode is slightly more sensitive to changes in recycling price b than the M mode. The reason the R mode maintains a slightly higher carbon reduction is that the retailer's recycling channels are closer to consumers, resulting in a higher recycling rate. However, as b increases, the retailer's recycling costs rise, and the growth rate of their recycling rate slows down. In contrast, the M mode, which directly controls recycling, has more direct cost transfer, so the decline in carbon reduction is relatively gradual.

Figure 8b shows that the manufacturer's profit varies significantly with the recycling price b. The M mode's profit is most sensitive to b because the manufacturer directly bears the recycling costs; the R mode's profit also decreases as b rises, but to a smaller extent; the T mode's profit is almost unaffected by b because the third party bears the recycling costs, while the manufacturer only pays a fixed transfer price f. At all values of b, the M mode's profit is far higher than that of the R and T modes, indicating that direct recycling has an absolute economic advantage. So from a profit-maximisation perspective, manufacturers should prioritise self-operated recycling and keep the recycling price b as low as possible, for example, through an efficient reverse logistics system.

To sum up, the consumer recycling price b acts as a pivotal fiscal parameter linking consumer behaviour with corporate operations. According to Lemma 1-3, an increase in b elevates supply chain operational costs, which subsequently compresses profit margins, raises retail prices, and curtails both market demand and carbon mitigation incentives.

Therefore, government intervention should not blindly subsidise the nominal recycling price b itself, as maintaining an excessively high b induces financial friction that harms the entire closed-loop supply chain. Instead, fiscal policies such as R&D subsidies, tax abatements, or public infrastructure investments should be strategically channeled into reinforcing the industry's reverse logistics infrastructure, effectively minimising the recycling cost coefficient C_L. Lowering C_L expands the collection scale while shielding manufacturers from cost shocks, thereby successfully reconciling profit maximisation with environmental sustainability. For regional markets burdened with high initial collection barriers, policymakers should utilise accumulated carbon trading revenues to offset corporate reverse logistics investments rather than directly inflating consumer payouts. This structural approach effectively prevents the crowding-out effect of soaring recycling costs on emission-reduction efforts, driving the sustainable development of the green supply chain.

Impact of Δ on carbon emission reductions and profits

This subsection investigates how the unit production cost saved by remanufactured products relative to new products Δ affects the carbon emission reduction per unit of product and the profit of the manufacturer, which in turn affects the choice of recycling mode. At this time, $p_c = 1, \gamma = 0.5, b = 1$ is set, because of the previous assumption of the parameter $C_n = 10$, and $C_n > \Delta$ is known, the remanufactured product has a certain production cost, so Δ obtains a roughly reasonable range of 0 to 7. We study the change of carbon emission reduction per unit of product and the manufacturer's profit when the unit production cost saved varies between 0 and 7.

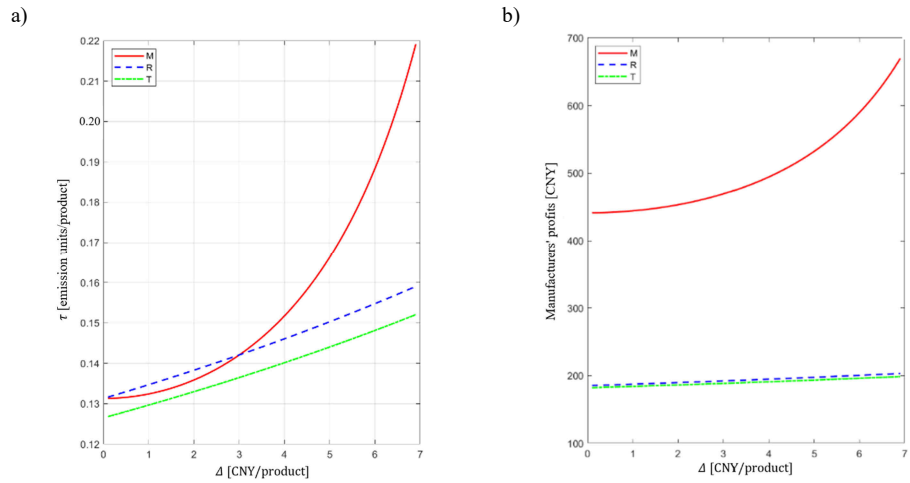


Fig. 9. Impact of unit production costs saved $(0 < \Delta < 7)$: a) carbon emission reductions, b) manufacturers' profits

Figure 9a shows that as the unit cost savings Δ increase from 0 to 7, the carbon reduction τ of all three recycling modes exhibits an upward trend, but there are obvious differences in growth rate and ranking. In the range $\Delta < 3$, the τ of R mode is always

slightly higher than that of M mode, with only a small difference, while the T mode is the lowest. Once Δ exceeds approximately 3, τ of the M mode experiences a leap growth, whereas R and T modes only increase gradually, causing the M mode to surpass and significantly lead in emission reductions. This intersection point ($\Delta = 3$) is evaluated through systemic numerical experiments based on localised industrial profiles. While the exact crossing threshold may fluctuate depending on real-world empirical data, the primary objective of this graphical analysis is to reveal the dynamic operational trends across different regimes, thereby providing a strategic decision-making reference for both corporate managers and policymakers. To further facilitate comprehensive verification, the quantitative performance metrics and mode rankings across three representative regime configurations ($\Delta = 1.0$, $\Delta = 3.0$, and $\Delta = 5.0$) are presented explicitly in Table 2.

Table 2

Environmental and economic regime shift metrics under varied cost savings (Δ)

Cost savings (Δ)	**τ Numerical value and ranking**	**π_1 Numerical value and ranking**
$\Delta = 1.0$	$\tau^R(0.135) > \tau^M(0.132) > \tau^T(0.129)$	$\pi_1^M(444.088) > \pi_1^R(187.671) > \pi_1^T(184.388)$
$\Delta = 3.0$	$\tau^R(0.142) = \tau^M(0.142) > \tau^T(0.136)$	$\pi_1^M(469.939) > \pi_1^R(192.417) > \pi_1^T(188.776)$
$\Delta = 5.0$	$\tau^M(0.165) > \tau^R(0.150) > \tau^T(0.144)$	$\pi_1^M(532.702) > \pi_1^R(197.706) > \pi_1^T(193.645)$

Figure 9b shows that manufacturer profits increase overall as Δ increases, but the profit growth rate of the M mode is much faster than that of the R and T modes. Throughout the entire range of Δ, the M mode always has the highest profit, followed by the R mode, with the T mode being the lowest, and no crossing of profit rankings occurs. This indicates that from an economic efficiency perspective, direct manufacturer recycling has an overwhelming advantage that continues to strengthen as Δ expands. Combining the analysis of both emission reductions and profits, the following conclusions can be drawn: when the remanufacturing cost savings are low ($\Delta < 3$), retailer recycling can achieve slightly better emission reductions without sacrificing much profit, making it suitable as a transitional mode when technological maturity is not high; once Δ exceeds 3, direct manufacturer recycling achieves both the highest profit and the best emission reduction performance. Therefore, the government should use policies such as R&D subsidies and tax reductions to help manufacturers increase the Δ value, and set industry benchmark thresholds to guide enterprises to proactively switch to self-operated recycling channels after meeting the Δ standard, maximising the overall benefits of low-carbon remanufacturing.

Impact of f on carbon emission reductions and recycling rates

In order to investigate the impact of the intermediate recycling price f paid by the manufacturer to the retailer (R mode) or third-party recycler (T mode) on system performance, we vary f from 1.5 to 4.0 while keeping other benchmark parameters unchanged. Since the M mode involves direct recycling by the manufacturer and is not affected by f, we use it as a comparison benchmark.

In Figure 10a, we can observe the response characteristics of carbon emission reduction amount τ to f. When the intermediate recycling price f gradually increases from 1.5 to 4.0, the carbon emission reduction per unit product τ in M mode remains constant at 0.142 and is unaffected by f; in R mode, τ rises continuously from 0.135 to 0.155, showing

a monotonically increasing promoting effect, indicating that a higher f can indirectly encourage manufacturers to increase emission reduction investment by enhancing retailers' recycling incentives; whereas in T mode, τ first slightly increases to 0.137 (f = 2.5) and then slowly decreases to 0.132, showing an inverted U-shaped relationship, which means that a too high transfer price compresses the manufacturer's remanufacturing profit margin and instead inhibits emission reduction efforts. Overall, the emission reduction performance is most stable and optimal under the M mode; the R mode can approach M mode performance at higher f; and the T mode has an optimal f range, approximately 2.0 - 3.0.

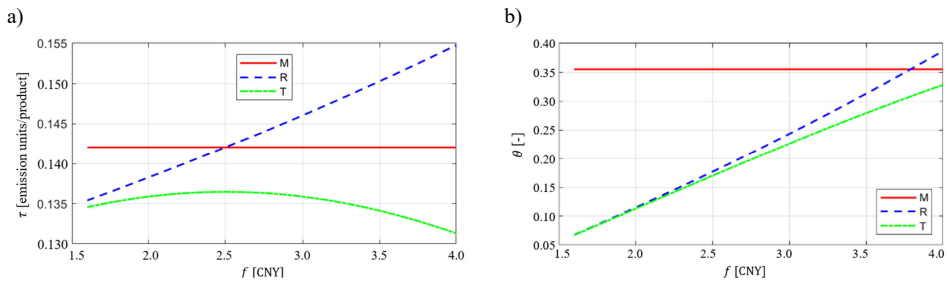


Fig. 10. Impact of intermediate recycling price ($1.5 < f < 4.0$): a) impact of f on τ, b) impact of f on θ

In Figure 10b, we can see the response characteristics of the recovery rate θ to f and the overall implications. Under the three modes, θ in M mode is consistently 0.355, regardless of f; the θ in R mode and T mode both increase almost linearly with f, with the recycling rate in R mode slightly higher than in T mode. This indicates that increasing f can effectively motivate retailers and third parties to increase recycling efforts, but the incentive effect on emission reduction shows diminishing returns or even negative effects under the T mode. Combining the two tables, it can be seen that the M mode not only has the best emission reduction effect but also the highest recycling rate, completely avoiding f pricing risk; if indirect recycling must be used due to objective conditions, the f in T mode should not be set too high, whereas in R mode, f can be appropriately increased to balance recycling rate and emission reduction.

Robustness checks for λ and C_L

To further verify the accuracy of the conclusion, we conducted a robustness test on the parameters λ and C_L. Under the condition that other parameters remained unchanged, we set $\gamma = 0.5$, $b = 1$, $\Delta = 5$, $f = 2.5$, $p_c = 1$ and illustrated the dynamic responses of manufacturers' profits, carbon emission reductions, and waste product recycling rates.

Figure 11a-c systematically illustrate the dynamic responses of manufacturers' profits π_1^{i}, carbon emission reductions τ, and waste product recycling rates θ across all three modes as the abatement cost factor λ sweeps from 50 to 200. Figure 11a shows that as λ increases, the manufacturer's profit declines slightly and smoothly across all modes. This trend is consistent with the marginal cost inflation of R&D investments. Crucially, the absolute profit ranking remains firmly locked in the order of $\pi_1^T < \pi_1^R < \pi_1^M$ without any intersecting crossings. Figure 11b captures a non-linear, convex decay in per-unit carbon reductions τ for all channels as technology costs multiply. Notably, τ in the R mode falls from approximately 0.58 to 0.14, displaying higher cost sensitivity, yet it consistently

maintains an absolute lead over the overlapping curves of the M and T modes across the entire domain. Figure 11c presents the variations in recycling rates θ. Under the direct impact of λ, the recycling rates under the R and M modes remain highly stable, hovering around 0.35, while the T mode is bounded significantly lower, around 0.17.

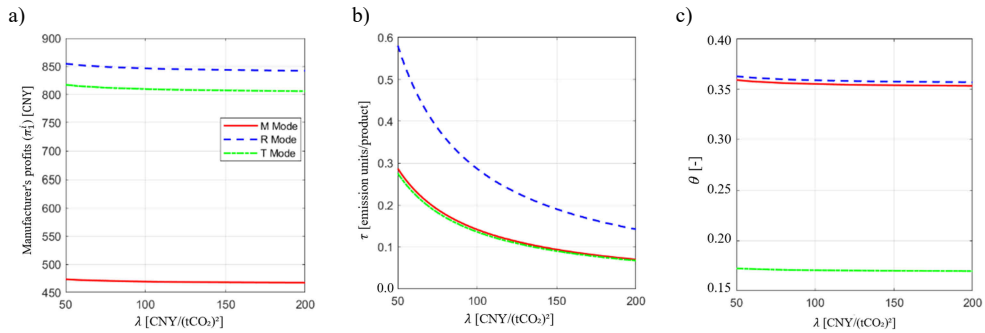


Fig. 11. Comprehensive robustness check for λ: a) manufacturers' profits, b) carbon emission reductions, c) waste product recycling rates

Across the entire parameter space of $\lambda \in [50; 200]$, all decision variables strictly satisfy the physical boundary conditions ($0 < \theta < 1$ and $0 < \tau < \gamma e$), and the structural hierarchy remains entirely invariant, proving the comprehensive robustness of the equilibrium configurations.

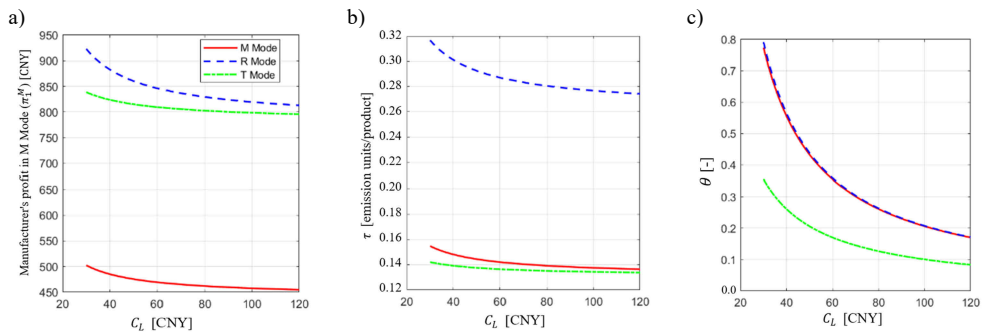


Fig. 12. Comprehensive robustness check for C_L: a) manufacturers' profits, b) carbon emission reductions, c) waste product recycling rates

Figure 12a-c delineate the parametric resilience of the closed-loop system against reverse logistics friction as the recycling cost factor C_L expands from 30 to 120. Figure 12a demonstrates that escalating reverse operations costs severely penalise the financial viability of the system, forcing a continuous downward trajectory in manufacturers' profits across all three modes. Despite these downward sloped curves, the absolute profit ranking rigidly preserves the hierarchical echelon of $\pi_1^T < \pi_1^R < \pi_1^M$ with no crossovers, demonstrating that the economic superiority of decentralised collection systems remains parameter-independent under cost shocks. Figure 12b reveals that as C_L climbs, the carbon

reduction performance under the R mode decreases slightly from 0.32 to 0.27, whereas τ for the M and T modes remains highly insulated and flat around 0.14. This subtle response mathematically confirms that forward carbon mitigation strategies are robustly buffered against reverse cost expansions. Figure 12c exhibits a steep, monotonic decay in the recycling rates θ for all recycling channels as collection efficiency degrades. The overlapping curves of the R and M modes plunge from 0.78 to 0.17, while the T mode contracts from 0.35 to 0.08.

The synchronicity of this steep decline in recycling efforts versus the stabilised flat lines in carbon reductions indicates that while reverse logistics costs directly dictate collection volumes, the core low-carbon design properties are robustly anchored by forward market policy mechanisms.

Conclusion

Theoretical contribution **-** Against the backdrop of carbon trading mechanisms and investments in emission reduction technologies, this study constructs a Stackelberg game model incorporating three distinct recycling modes. By introducing carbon emission reduction cost coefficients and recycling cost coefficients, the study systematically analyses the corporate decisions under variations of carbon trading prices, carbon emission intensity, consumer recycling prices, and unit cost savings from remanufacturing. Theoretical Findings: Government-provided free carbon allowances enter the system purely as an additive constant, changing the absolute profit level but exerting no operational influence on manufacturers' per-unit carbon emission reductions, optimal operational decisions, or the strategic selection of the optimal recycling mode. Reasonable external regulation can effectively incentivise manufacturers to simultaneously reduce emissions and engage in recycling. Integrating carbon trading, investment in emission reduction, and recycling and reuse can achieve substantial emission reductions. Crucially, our findings reveal a delicate trade-off between economic and environmental objectives: while the manufacturer-direct recovery (M mode) consistently yields the highest corporate profitability due to the elimination of reverse double-marginalisation, the retailer recovery (R mode) demonstrates higher environmental efficiency under specific technological and cost frictions. Therefore, the strategic alignment of the optimal recovery channel heavily depends on key regulatory and operational parameters such as unit cost savings and baseline carbon intensity.

Managerial implications **-** The government need not focus excessively on the allocation of free carbon allowances but should instead concentrate on reasonably setting carbon trading prices, effectively regulating carbon emission intensity, guiding the market for the recycling of end-of-life products, establishing a dynamic price adjustment mechanism, and setting appropriate emission constraints to incentivise manufacturers to increase investment in emission reduction and optimise recycling channels. In particular, when setting the intermediate recycling prices that manufacturers pay to retailers or third-party recyclers, policymakers or enterprises need to recognise that: under the third-party recycling mode, excessively high transfer prices will suppress forward emission reductions; whereas under the retailer recycling mode, moderately increasing the price can simultaneously promote reverse recycling rates and forward emission reductions. For corporate operations, manufacturers should fully utilise the carbon trading mechanism to advance emission reduction and recycling simultaneously. When the remanufacturing

process yields minor cost savings or faces clean-technology bottlenecks, cooperating with retailers (R mode) can serve as an effective strategy to secure higher environmental returns. However, once remanufacturing delivers significant unit production cost savings, priority should be firmly given to the manufacturer-direct recycling mode (M mode) to maximise both economic dominance and structural emission reductions simultaneously. The government should also actively foster the carbon trading market, lower the cost barriers for enterprises to participate in green R&D, and promote the coordinated development of low-carbon manufacturing and circular supply chains.

Limitations - Although this study provides comprehensive insights into channel selection under carbon regulations, several limitations remain. First, the model assumes that the core operational parameters - such as the carbon abatement cost factor λ, recycling effort cost factor C_L, and carbon trading price p_c - are completely exogenous, thereby ignoring the multi-period dynamic evolution, market volatility, and corporate learning-curve effects over time. Second, while the model incorporates the primary constraints on physical feasibility and joint concavity, it assumes perfect consumer rationality and full homogeneity. It overlooks critical market frictions, such as consumers' heterogeneous willingness-to-pay (WTP) for remanufactured versus brand-new products, which could reshape forward market demand.

Future work - To extend the scope and applicability of our findings, future research can pursue several directions. First, multi-period dynamic game structures should be developed to capture the endogenous fluctuations of carbon permit prices and the long-term compounding effects of green R&D investments. Second, consumer heterogeneous preferences and brand discrimination against remanufactured goods should be integrated into the market demand function to test the robustness of current channel rankings.

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References

[1] Zhu HY, Bao WP, Yu GJ. How can intelligent manufacturing lead enterprise low-carbon transformation? Based on China's intelligent manufacturing demonstration projects. Energy. 2024;313:134032. DOI: 10.1016/j.energy.2024.134032.

[2] Han XY, Yao S, Zhou YY. Transforming the reverse supply chain: Leveraging a platform for enhanced recycling and remanufacturing. Comput Ind Eng. 2026;212:111687. DOI: 10.1016/J.CIE.2025.111687.

[3] Hong XP, Wang ZJ, Wang DZ, Zhang HG. Decision models of closed-loop supply chain with remanufacturing under reverse dual competition. J Syst Eng. 2013;28(1):45-55. DOI: 10.1007/s00170-013-4982-1.

[4] Zhou MX, Li X. Low-carbon production control and resource allocation optimization. Int J Simul Model. 2022;21(2):352-63. DOI: 10.2507/IJSIMM21-2-CO9.

[5] Chen C, Ulya MA. Analyses of the reward-penalty mechanism in green closed-loop supply chains with product remanufacturing. Int J Prod Econ. 2019;210(4):211-23. DOI: 10.1016/j.ijpe.2019.01.006.

[6] Ionescu AM, Cazan AM, Truța C. Assessing the use of electric scooters and its association with personality traits to adopt pro-environmental behaviors. Environ Eng Manage J. 2020;19(12):2205-15. DOI: 10.30638/eemj.2020.208.

[7] Verma B, Balomajumder C. Reduction of obnoxious cr(vi) from electroplating effluents by hydrazine: kinetic optimization and mechanistic modeling for wastewater treatment. Environ Eng Manage J. 2021;20(1):37-42. DOI: 10.30638/eemj.2021.004.
[8] Raz G, Souza GC. Recycling as a strategic supply source. Prod Oper Manage. 2018;27(5):902-16. DOI: 10.1111/poms.12851.
[9] Ma G, Wang Z, Qin J, Cao J. Carbon reduction assessment of Shanghai industry under the constraint of "carbon park": Analysis based on carbon footprint accounting. Environ Eng Manage J. 2025;24(12):2711-20. DOI: 10.30638/eemj.2025.210.
[10] Xian BT, Wang YN, Xu YL, Wang J, Li XY. Assessment of the co-benefits of China's carbon trading policy on carbon emissions reduction and air pollution control in multiple sectors. Econ Anal Policy. 2024;81:1322-35. DOI: 10.1016/j.eap.2024.01.011.
[11] Chen HT, Li JC, Dong ZH. Equilibrium analysis of power battery sourcing strategies for competitive electric vehicle manufacturers under cap-and-trade. J Clean Prod. 2026;553:147972. DOI: 10.1016/J.JCLEPRO.2026.147972.
[12] Li G, Hu JM, Xue J. Impact of the carbon trading policy on green technological innovation in heavily polluting enterprises: A circular operations perspective. Technovation. 2025;148:103326. DOI: 10.1016/J.TECHNOVATION.2025.103326.
[13] Benjaafar S, Li Y, Daskin M. Carbon footprint and the management of supply chains: Insights from simple models. IEEE Trans Autom Sci Eng. 2013;10(1):99-116. DOI: 10.1109/TASE.2012.2203304.
[14] Fang IW, Lin WT. A multi-objective optimal decision model for a green closed-loop supply chain under uncertainty: A real industrial case study. Adv Prod Eng Manage. 2021;16(2):161-72. DOI: 10.14743/apem2021.2.391.
[15] He Y, Sun J, Tang M, He Y, Zhu Y. Evolution of China's "dual-carbon" policy: A content topic mining analysis of central government documents (2007-2024). Ecol Chem Eng S. 2025;32(1):7-25. DOI: 10.2478/eces-2025-0001.
[16] Cao J, Wu SS, Kumar S. Recovering and remanufacturing to fulfill EPR regulation in the presence of secondary market. Int J Prod Econ. 2023;263:108933. DOI: 10.1016/j.ijpe.2023.108933.
[17] Savaskan RC, Bhattacharya S, Wassenhove LNV. Closed-loop supply chain models with product remanufacturing. Manage Sci. 2004;50(2):239-52. DOI: 10.1287/mnsc.1030.0186.
[18] Huang M, Song M., Lee LH, Ching WK. Analysis for strategy of closed-loop supply chain with dual recycling channel. Int J Prod Econ. 2013;144(2):510-20. DOI: 10.1016/j.ijpe.2013.04.002.
[19] Zhang C, Chen YX, Tian YX. Collection and recycling decisions for electric vehicle end-of-life power batteries in the context of carbon emissions reduction. Comput Ind Eng. 2023;175:108869. DOI: 10.1016/j.cie.2022.108869.
[20] Long XF, Ge JL, Shu T, Liu Y. Analysis for recycling and remanufacturing strategies in a supply chain considering consumers' heterogeneous WTP. Resour Conserv Recycl. 2019;148:80-90. DOI: 10.1016/j.resconrec.2019.05.001.
[21] Narang P, De PK, Lim CP, Kumari M. Optimal recycling mode selection in a closed-loop supply chain for electric vehicle batteries under carbon cap-trade and reward-penalty policies using the Stackelberg game. Comput Ind Eng. 2024;196:110512. DOI: 10.1016/j.cie.2024.110512.
[22] Barragán-Beaud C, Pizarro-Alonso A, Xylia M, Syri S, Silveira S. Carbon tax or emissions trading? An analysis of economic and political feasibility of policy mechanisms for greenhouse gas emissions reduction in the Mexican power sector. Energy Policy. 2018;122:287-99. DOI: 10.1016/j.enpol.2018.07.010.
[23] Dou GW, Cao KY. A joint analysis of environmental and economic performances of closed-loop supply chains under carbon tax regulation. Comput Ind Eng. 2020;146:106624. DOI: 10.1016/j.cie.2020.106624.
[24] Yenipazarli A. Managing new and remanufactured productions to mitigate environmental damage under emissions regulation. Eur J Oper Res. 2016;249(1):117-30. DOI: 10.1016/j.ejor.2015.08.020.
[25] Gao H, Tang JK, Gong D, Zhao X, Yan X. Optimising low carbon inventory decisions and coordination for used clothing under carbon tax and carbon labelling system. Ecol Chem Eng S. 2024;31(4):507-25. DOI: 10.2478/eces-2024-0033.
[26] Yang Y. Green development synergies and regional disparities in the Yangtze River delta urban agglomeration. Ecol Chem Eng S. 2025;32(2):189-212. DOI: 10.2478/ECES-2025-0010.
[27] Yang L, Hu Y, Huang L. Collecting mode selection in a remanufacturing supply chain under cap-and-trade regulation. Eur J Oper Res. 2020;287(2):480-96. DOI: 10.1016/j.ejor.2020.04.006.
[28] Ren X, Wang J, Yang S, Zhao Q, Jia Y. A novel multi-objective Stackelberg game model for multi-energy dynamic pricing and flexible scheduling in distributed multi-energy system. Energy. 2025;325:136206. DOI: 10.1016/J.ENERGY.2025.136206.

[29] Wang YL, Yang L, Chen JH, Li P. Supply chain game analysis based on mean-variance and price risk aversion under different power structures. Adv Prod Eng Manage. 2023;18(1):104-15. DOI: 10.14743/apem2023.1.460.
[30] Zhu HJ, Ju LW, Wang WY, Qi X, Nie B, Li XM. Multi-agent-based dual-Stackelberg game model and improved benefit allocation strategy for virtual power plant cluster joining in energy and frequency regulation markets. Appl Energy. 2026;413:127682. DOI: 10.1016/J.APENERGY.2026.127682.
[31] Fan DX, Li CL, Wang XL. Research on selection and optimization of closed-loop supply chain recycling mode based on Stackelberg game. Oper Res Manage Sci. 2021;30(4):135-41. DOI: 10.12005/orms.2021.0121.
[32] Zou QM, Liu C, Cao Y. Carbon emission reduction and financing policy of low-carbon supply chain with yield uncertainty and fairness concerns under carbon cap-and-trade mechanism. Chin J Manage Sci. 2024;32(9):248-59. DOI: 10.16381/j.cnki.issn1003-207x.2021.0934.
[33] Wang CX, Li H. The closed-loop supply chain decision with carbon emission limits based on dual channel sales and recycling under government subsidies. J Fudan Univ (Nat Sci). 2018;57(2):131-42. DOI: 10.15943/j.cnki.fdxb-jns.2018.02.001.