A Study on Supply Chain ' Emissions Reduction Investments and Offshore Production Strategies in Consideration of Carbon Border Adjustment Mechanism

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Abstract. This paper, based on the international context of EU's Carbon Border Adjustment Mechanism, focuses on the impact of this policy on emissions reduction and production procurement strategies for cross-border supply chain enterprises. By constructing a multi-level supply chain enterprise decision-making game theory model, the paper analyzes the emissions reduction and production strategies of enterprises along the supply chain using optimization theory and methods. The aim is to provide enterprises with response decision-making recommendations under the current carbon tariff implementation scenario and, thereby, offer policy recommendations for governments to implement or address carbon tariffs. In the context of the “dual carbon” goals, this paper constructs a theoretical analysis model to study how cross-border supply chains can address the new challenges posed by carbon tariffs, holding significant theoretical and practical significance.

Keywords: Carbon Tariffs, Green Supply Chain, Production.

1. Introduction

1.1. Background and Motivation

In recent years, global attention to climate change issues has been steadily increasing, particularly the problem of excessive energy consumption leading to increased greenhouse gas emissions and ecological degradation, which has drawn the attention of countries worldwide. Existing research indicates that companies' understanding of regulations has a significant impact on emissions reduction (Ramadorai & Zeni, 2024), suggesting that carbon tax policies are an effective means of controlling carbon emissions. Emissions reduction investments and carbon emissions financing can simultaneously reduce manufacturers' carbon emissions and enhance supply chain profitability (Cheng et al., 2025), prompting companies to opt for emissions reduction investments. However, when carbon tax policies vary across countries, global carbon emissions face obstacles. Regulatory disparities in carbon emissions are the primary barrier to global emissions reduction (Zhou et al., 2024). Companies subject to stricter regulations may strategically relocate production to regions with more lenient regulations, potentially leading to carbon leakage (Hua et al., 2024).

To effectively control carbon emissions, the EU has launched the Carbon Border Adjustment Mechanism (CBAM), which establishes a new pricing method for carbon emissions from carbon-intensive products entering the EU market during production, aiming to address carbon leakage—where strict regulations in one region prompt companies to relocate production to regions with weaker regulations, resulting in increased greenhouse gas emissions in those weaker regions. A carbon tariff is a border tax adjustment applied to products imported from regions with weaker environmental regulations into regions with stricter environmental regulations, ensuring that the carbon costs of production in regulated regions and offshore production are fair. Clearly, this will impact foreign investment inflows and offshore production decisions.

Under the CBAM policy, companies also face the challenge of losing their autonomy in setting carbon prices in the carbon emissions market. Companies must pay a carbon price when their products enter the EU market, which means higher export costs for their products, reducing their competitive advantage and causing short-term shocks to exports of high-carbon-intensive products, thereby influencing corporate production and procurement decisions. From a cost perspective, low-carbon products can reduce tax costs; from a demand perspective, as environmental awareness grows, consumers are more willing to purchase green products and accept higher prices. Therefore, low-carbon products may have a greater competitive advantage when exported. Carbon tariffs can incentivize carbon reduction in cross-border supply chains, encourage supply chain companies to invest in emissions reduction, promote the development and use of low-carbon technologies and equipment, and accelerate the achievement of carbon neutrality goals.

1.2. Research Questions

Under the Carbon Border Adjustment Mechanism, how supply chain companies should make emissions reduction investments and decide on offshore production strategies is the core issue studied in this project.

To address the decision-making challenges faced by firms under inconsistent carbon regulations, we adopt an operational and supply chain perspective and built a model upon the carbon border adjustment mechanism. We incorporate the influence of consumers' low-carbon preferences to establish a game model comprising a manufacturer and a retailer operating in a country with stringent carbon emission controls. The manufacturer can choose between domestic production and offshore production. Offshore production incurs fixed costs (such as transportation and compliance costs) but benefits from lower carbon tax rates. Based on this model, the main issues we investigate are: (1) How do consumers' low-carbon preferences influence the profits and pricing decisions of supply chain participants? (2) How do manufacturers choose between domestic and offshore production? (3) How do consumer surplus and social welfare change?

1.3. Organization of the Text

The rest of this paper is organized as follows: Section 2 reviews the relevant literature; Section 3 introduces the model settings; Section 4 analyzes the model and draws relevant conclusions; Section 5 summarizes the findings and provides response decision recommendations for enterprises under the current carbon tariff collection scenario, as well as strategies for governments to implement or respond to carbon tariffs, and future research directions.

2. Literature Review

2.1. Supply chain decisions that include carbon taxes

Some studies focus on analyzing the impact of carbon taxes on corporate emissions reduction investments. Tian et al. (2024) found that as unit emissions increase, high-carbon product manufacturers subject to strict carbon policies are more likely to increase their emissions reduction investments, thereby lowering product prices and expanding market share. Cheng et al. (2025) proposed a mixed-integer linear programming (MILP) model showing that under carbon tax pressure, firms prioritize producing high-profit products with low transportation and production carbon emissions. Many studies also analyze various coordination mechanisms, such as revenue-sharing contracts, cost-sharing contracts, revenue-sharing plus cost-sharing, bargaining contracts, two-part tariff contracts, manufacturer wholesale, quantity discounts, buybacks, and so on. The effectiveness of these mechanisms often depends on their model design. For example, Shi et al. (2020) considered manufacturer wholesale contracts, two-part pricing, and revenue-sharing contracts, finding that none of these could coordinate the supply chain to achieve optimization. They then further considered bargaining, concluding that this scheme could coordinate the supply chain when considering both parties' bargaining power. Bangjun et al. (2023) examined the effects of revenue sharing, cost sharing, and revenue sharing plus cost sharing in the coal power industry under renewable energy quotas, finding that only revenue sharing plus cost sharing can maximize profits and achieve a balance between the decisions of the two firms. Wang and Su (2025) constructed a bidirectional carbon emission rights option trading, showing that income-sharing and cost-sharing contracts can coordinate a two-stage supply chain under a carbon quota trading mechanism, forming a virtuous cycle of "emission reduction - revenue".

2.2. Carbon leakage under carbon taxation

Early studies have already demonstrated that carbon taxes can lead to carbon leakage. For example, Drake (2018) constructed a partial equilibrium model showing that carbon taxes may cause firms to relocate production to regions that have not implemented carbon taxes, resulting in "carbon leakage." Huang et al. (2021) found that in the absence of anti-leakage policies, uncertainty in emission prices may have the opposite effect: when expected emission prices are low (high), higher uncertainty exacerbates (mitigates) carbon leakage. Furthermore, Hua et al. (2024) examined companies' domestic or foreign investment production strategies under different carbon tax pricing scenarios. Companies allocate cross-regional production by balancing carbon costs and technology investment costs, indicating that firms strategically relocate production to regions with less stringent regulations. Thus, inconsistencies in global emissions regulation may lead to emissions shifting.

2.3. Global supply chains considering carbon tariffs

Carbon tariffs are designed to address the issue of carbon leakage. Bellora & Fontagné (2023) explored the environmental and economic impacts of carbon leakage, gross domestic product (GDP), trade, and value added by industry through quantifying different design schemes of carbon border adjustment mechanisms, demonstrating the effectiveness of the CBAM in reducing carbon leakage. However, some studies have identified certain shortcomings. For instance, Fang et al. (2020) found that carbon tariffs may not necessarily reduce carbon emissions when suppliers have dual domestic and international sales channels, as suppliers can produce more products for the unregulated domestic market, leading to carbon leakage. Zhou et al. (2024) found that for manufacturers with low emissions reduction costs, carbon tariffs increase both production and profits, and carbon tariffs always have a negative impact on low-carbon regulated countries. They further compared two strategies to reduce emissions reduction costs: carbon quotas and subsidies in low-carbon regulated countries. They found that for both countries and social welfare, both strategies are win-win under moderate emissions reduction subsidies. When subsidies are too high, carbon quotas become the win-win strategy. For emissions reduction in remanufacturing enterprises, Li et al. (2024) studied the cross-border remanufacturing models of original equipment manufacturers in exporting countries under tariff and carbon tax conditions, including conducting remanufacturing in-house or authorizing remanufacturing operations to be carried out by retailers in importing countries. They found that when carbon tariffs are high, the optimal sales volume of remanufactured products increases. Carbon tariffs cannot effectively incentivize original equipment manufacturers to invest in emissions reduction efforts. Remanufactured products must have carbon emissions comparable to new products for manufacturers to prefer authorizing retailers to perform remanufacturing. If importing countries impose high carbon tariffs to protect domestic enterprises, profitability cannot be achieved.

Our research combines the above three aspects. Considering different levels of carbon regulation under carbon tariff conditions and consumers with low-carbon preferences, we solve how the company of countries with high levels of regulation make decision and conclude the influence on the social welfare and consumer surplus.

3. Modeling Framework

We studied the relationship between emission reduction investments and offshore production strategies of supply chain companies consisting of manufacturers (she) and retailers (he) under a carbon tax collection mechanism. Manufacturers sell products to retailers at wholesale prices per unit, and retailers sell products to consumers at retail prices per unit.

3.1. Background of Carbon Tax Policy

Under a carbon tax regime, businesses must bear the carbon tax, or carbon cost, resulting from their carbon dioxide emissions. We simplify this cost as follows: $Ks = te$, where t is the carbon tax rate, and e is the unit carbon emissions of the manufacturing company. Manufacturers face pressure to reduce emissions and must invest funds and technology in emission reduction efforts. They can choose to reduce carbon emissions through green investment costs $\beta(e_0 - e)^2$ (where $\beta > 0$ is the manufacturer's green technology investment cost coefficient) to reduce carbon emissions, with e_0 being the initial unit carbon emissions of the manufacturer and $(e_0 - e)$ representing the carbon emission reduction efforts made by the manufacturer.

Considering that carbon tariffs are border tax adjustments for products from regions with no prior environmental regulations, cross-border supply chain companies often choose to relocate production to other countries or regions with cost advantages to reduce costs and improve efficiency. We assume that under a carbon tax framework, cross-border supply chain companies face two carbon tax policies:

(1) Manufacturers choose to produce in domestically regulated regions with stricter regulations (strategy n): the carbon tax rate is t_1, and the company must pay the carbon cost $t_1 e$.

(2) Manufacturers choose to produce offshore in regions with weaker regulation (strategy o): The carbon tax rate is t_2 (usually $t_2 < t_1$), but they must bear additional fixed offshore costs K (such as transportation and compliance costs), and the total cost is $t_2 e + K$.

3.2. Consumer Utility and Demand

We assume that consumers' willingness to pay v for a product is uniformly distributed over the interval $[0, 1]$. All consumers in the market have a sense of social responsibility, and the carbon emissions of a product will reduce their utility. Consumers will be more resistant to high-carbon products, while low-carbon products can increase utility through an environmental premium. We define γ as consumers' environmental preferences, i.e., their sensitivity to carbon emissions. A higher γ indicates greater sensitivity to a product's carbon emissions, resulting in consumer utility $v - p - \gamma e$. If utility is non-negative, consumers will purchase the product. Scaling the market to 1, total consumer demand is $q = 1 - p - \gamma e$.

To avoid a syllogistic conclusion, we assume that $\underline{e_0} = \frac{4t_1+\gamma}{8\beta} < e_0 \le \overline{e_0} = \frac{4t_1+\gamma}{\gamma^2}$. This condition ensures that emission reduction technologies are feasible and profits are non-negative.

3.3. Manufacturer Strategy

The manufacturer's profit under each strategy is denoted as $\pi_m^i(w, e)$, where $i \in \{n, o\}$, and the subscript m represents the supplier. While bearing significant carbon reduction costs, manufacturers also benefit from emission reduction activities, such as increased demand and reduced carbon costs. After balancing these factors, suppliers maximize profits by determining wholesale prices and carbon reduction efforts under each strategy. The corresponding profit functions under the two strategies are as follows:

$$\pi_m^n(w, e) = w(1 - p - \gamma e) - t_1 e - \beta(e_0 - e)^2$$
$$\pi_m^o(w, e) = w(1 - p - \gamma e) - t_2 e - \beta(e_0 - e)^2 - K$$

The first term of each profit function represents the manufacturer's sales revenue. The second and third terms are the carbon reduction investment cost and carbon tax cost, respectively. Under strategy o, the manufacturer's expected cost is affected by K. Offshore production reduces the carbon tax $t_2 < t_1$, but fixed costs K must be taken into consideration.

Retailers maximize their profits. The subscript r represents retailers, and the profit function is as follows:

$$\pi_r(p) = pq - wq$$

4. Analysis

4.1. Business Objectives and Optimal Results

We employ the Steinberg game (leader-follower game) model for game analysis, with the specific process outlined below. First, the manufacturer decides which strategy to adopt. Then, she determines the level of carbon emissions reduction and the wholesale price. After observing the manufacturer's strategy, carbon emissions reduction efforts, and wholesale price, the retailer sets the corresponding retail price.

Using backward induction, we can derive the corresponding equilibrium results. Under strategy i, the manufacturer's wholesale price, retail price, final unit carbon emissions, corresponding demand, optimal profit, and the retailer's optimal profit are denoted as w^i, p^i, e^i, D^i, and π_m^i and π_r^i, respectively. Among these, we summarize the equilibrium results in the following two equations.

Proposition 1: (1) The optimal decisions and corresponding demands under different strategies are summarized in the following table.

Strategy	w^i	p^i	e^i	D^i
$i = n$	$\frac{4\beta + 2t_1\gamma - 4e_0\beta\gamma}{8\beta - \gamma^2}$	$\frac{6\beta + 3t_1\gamma - 6e_0\beta\gamma}{8\beta - \gamma^2}$	$\frac{-4t_1 + 8e_0\beta - \gamma}{8\beta - \gamma^2}$	$\frac{2\beta + t_1\gamma - 2e_0\beta\gamma}{8\beta - \gamma^2}$
$i = o$	$\frac{4\beta + 2t_2\gamma - 4e_0\beta\gamma}{8\beta - \gamma^2}$	$\frac{6\beta + 3t_2\gamma - 6e_0\beta\gamma}{8\beta - \gamma^2}$	$\frac{-4t_2 + 8e_0\beta - \gamma}{8\beta - \gamma^2}$	$\frac{2\beta + t_2\gamma - 2e_0\beta\gamma}{8\beta - \gamma^2}$

(2) The optimal profits of the manufacturer and retailer under different strategies are shown as follows.

Strategy	π_m^i	π_r^i
$i = n$	$\frac{2t_1{}^2 + t_1(-8e_0\beta + \gamma) + \beta(-1 + e_0\gamma)^2}{8\beta - \gamma^2}$	$\frac{(t_1\gamma + \beta(2 - 2e_0\gamma))^2}{(8\beta - \gamma^2)^2}$
$i = o$	$\frac{2t_2{}^2 + K\gamma^2 + t_2(-8e_0\beta + \gamma) + \beta(-8K + (-1 + e_0\gamma)^2)}{8\beta - \gamma^2}$	$\frac{(t_2\gamma + \beta(2 - 2e_0\gamma))^2}{(8\beta - \gamma^2)^2}$

Before comparing the optimal decisions and related performance under different strategies, we first conduct a sensitivity analysis of the optimal results to identify key factors and their corresponding influencing factors. The optimal decisions and related performance structures for local production and offshore production are similar, so we use local production by manufacturers as an example for analysis.

Corollary 1:

(1) The effect of γ: When e_0 is low ($\underline{e_0} < e_0 < \frac{8t_1\beta+4\beta\gamma+t_1\gamma^2}{16\beta^2+2\beta\gamma^2}$), demand D^n increases with an increase in γ, carbon emissions e^n decrease with an increase in γ, and manufacturer profits π_m^n decrease with an increase in γ. When e_0 is high ($\frac{8t_1\beta+4\beta\gamma+t_1\gamma^2}{16\beta^2+2\beta\gamma^2} < e_0 \leq \overline{e_0}$), demand D^n decreases as γ increases, e^n increases as γ increases, and manufacturer profit π_m^n decreases as γ increases.

(2) The effect of t_1: Demand D^n increases with increasing t_1, carbon emissions e^n decrease with increasing t_1, and manufacturer profit π_m^n decreases with increasing γ.

(3) The effects of the technology cost coefficient β and initial carbon emissions e_0 are as follows:

Variable	w^n	p^n	D^n	e^n	π_m^n
β	−	−	−	+	−
e_0	−	−	−	+	−

Corollary 1 reveals that initial carbon emissions are a key threshold in determining how companies respond to consumer environmental sensitivity. When initial carbon emissions e_0 are low, an increase in consumer environmental sensitivity γ reinforces “low-carbon preferences.” Companies can reduce their product carbon footprint through moderate emissions reductions (e^n decreases), aligning with consumer demand and offsetting the negative impact of price or cost increases, ultimately driving market demand growth. As consumers become more sensitive to carbon emissions, the market acceptance of high-carbon products decreases. To maintain demand, companies increase their emissions reduction efforts (e.g., by adopting cleaner technologies) to reduce actual carbon emissions and meet environmental demands. The lower e_0 is, the higher the costs companies must incur (due to increasing marginal costs), leading to increases in wholesale and retail prices and indirectly suppressing demand. Despite increased demand for emissions reduction, manufacturers must bear higher emissions reduction costs, and savings from carbon taxes may not cover emissions reduction investments. Additionally, to maintain market competitiveness, wholesale prices w may be forced downward, leading to reduced manufacturer profits. When e_0 increases, companies face reduced emissions reduction pressure and can moderately lower prices (due to reduced emissions reduction investments), stimulating demand. As consumers' environmental preferences rise, the premium for low-carbon products expands, allowing retailers to adjust retail prices p (moderately increasing them) to achieve higher unit profits. Meanwhile, the increase in demand further amplifies profits through higher sales volumes, and retailers do not directly bear emissions reduction costs, so profits rise as γ increases.

When the initial carbon emissions e_0 are high, increased consumer environmental sensitivity significantly amplifies the negative impact of carbon emissions on demand. At this point, companies face significant challenges in reducing emissions (high initial emissions, sharply rising marginal costs of emissions reduction) and struggle to offset the negative effects by reducing carbon emissions, leading to a decline in demand as γ increases. Manufacturers proactively lower wholesale prices to share the cost of emissions reduction in order to maintain market share. Retailers respond to the wholesale price reduction but keep the reduction smaller than the wholesale price to maintain profits. Under high initial emissions, the cost of emissions reduction is too high, and manufacturers may choose to reduce emissions reduction efforts (or even abandon some emissions reduction efforts), leading to an increase in actual carbon emissions e^n. This is a compromise between high emissions reduction costs and low demand. Rather than incurring massive emissions reduction expenses yet still failing to meet demand, manufacturers opt to accept higher carbon emissions to reduce costs. Despite the decline in demand, manufacturers save significant costs by reducing emissions reduction efforts and tolerating higher carbon emissions. With controlled wholesale price reductions and reduced emissions reduction efforts, manufacturers' cost savings exceed the losses from declining demand, resulting in rising profits as γ increases.

An increase in the domestic carbon tax rate t_1 will raise manufacturers' carbon tax costs, prompting them to reduce carbon tax expenditures by increasing their emissions reduction investments (lowering actual carbon emissions e^n). At this point, the carbon footprint of products will decrease, better aligning with consumers' environmental preferences and thereby driving market demand growth. Although an increase in t_1 encourages manufacturers to reduce emissions to boost demand, the costs of emission reduction efforts exhibit diminishing marginal returns, and the savings from reduced carbon tax costs may not fully offset the increased costs of emission reduction efforts. Manufacturers may raise wholesale prices to pass on part of the costs, but retailers will adjust retail prices, and the resulting growth in demand may not fully offset the cost increases, further compressing profit margins and ultimately leading to a decline in manufacturer profits. An increase in the technological cost coefficient β implies rising marginal costs of emissions reductions, weakening manufacturers' incentives to reduce emissions, leading them to raise prices to cover costs, thereby suppressing demand and reducing profits. Meanwhile, an increase in the original emissions level e_0 increases the difficulty and cost of emissions reductions, resulting in similar effects of reduced demand and profit declines, while actual carbon emissions also rise due to increased emissions reduction pressures.

For companies producing low-carbon products, emissions reductions can align with demand, so they should prioritize investments in emissions reduction technologies to alleviate profit pressures. Governments can balance environmental protection and economic benefits through subsidies or tiered carbon taxes (e.g., reducing taxes for low-emission companies). Companies producing high-carbon products must weigh the costs of emissions reduction technology investments against carbon tax costs, which may lead them to abandon deep emissions reductions. Governments can incentivize companies to reduce emissions through increased taxes or subsidies to avoid reliance on high-emission pathways.

4.2. Manufacturers' strategic choices

Next, we examine the manufacturer's production strategy selection problem. Comparing the optimal profits of suppliers under the two strategies, we have the following proposition.

Proposition 2: When $0 < K < K_0$, π_m^o is greater than π_m^n; when $K > K_0$, π_m^n is greater than π_m^o.

Proposition 2 reveals the manufacturer's production location. When K is small, the cost savings $((t_1 - t_2)e)$ from the carbon tax advantage of offshore production $(t_2 < t_1)$ exceed the fixed offshore cost K. At this point, although K must be paid, the reduced carbon tax is sufficient to offset K and generate additional profits, so offshore production is more profitable. When the fixed offshore cost K is too high, exceeding the carbon tax savings from offshore production, K becomes the primary cost burden. Even with lower carbon taxes, K cannot be offset, while domestic production does not incur K. Despite higher carbon taxes, the total cost is lower, making domestic production more profitable.

Manufacturers' strategic choices essentially involve balancing “offshore carbon tax savings” against “fixed offshore costs”: when fixed offshore costs are below the critical threshold K_0, the carbon tax advantage of offshore production dominates profits; when fixed offshore costs exceed K_0, the advantage of domestic production avoiding fixed costs becomes more significant. This principle provides clear decision-making criteria for corporate production layout under carbon tariff policies.

Offshore production reduces costs by lowering carbon taxes $(t_2 < t_1)$, but incurs fixed costs K (e.g., logistics, compliance). The critical value $K_0 = -\frac{(t_1-t_2)(2(t_1+t_2-4e_0\beta)+\gamma)}{16\beta^2+2\beta\gamma^2}$ represents the equilibrium point between the two trade-offs.

Corollary 2: (1) $K_0 = -\frac{(t_1-t_2)(2(t_1+t_2-4e_0\beta)+\gamma)}{16\beta^2+2\beta\gamma^2}$, increases as t_1 increases, decreases as t_2 increases, increases as e_0 increases, and increases as γ increases; (2) $0 < t_2 < \frac{1}{2}(-2t_1 - \gamma + e_0\gamma^2)$, K_0 decreases as β increases; $\frac{1}{2}(-2t_1 - \gamma + e_0\gamma^2) < t_2 < t_1$, K_0 increases as β increases.

Corollary 2 reveals the impact of relevant influencing factors on manufacturers' production decisions. When the domestic carbon tax rate t_1 is higher, the carbon tax cost of domestic production $(t_1 e)$ is higher. At this point, the carbon tax savings advantage of offshore production $((t_1 - t_2)e)$ becomes more significant, and the upper limit of the fixed offshore cost K acceptable to manufacturers (i.e., K_0) increases accordingly. Even if K is slightly larger, the carbon tax savings can still cover the costs, so K_0 increases as t_1 increases. t_2 is the carbon tax rate for offshore production. The higher t_2, the higher the carbon tax cost of offshore production $(t_2 e)$, and the smaller the difference in carbon tax between domestic and offshore production $(t_1 - t_2)$. The carbon tax savings advantage of offshore production weakens, and the upper limit of the fixed offshore cost K acceptable to manufacturers decreases. If t_2 approaches t_1, the carbon tax advantage of offshore production almost disappears, and even if K is small, it may not cover the costs. Therefore, K_0 decreases as t_2 increases. e_0 are the initial carbon emissions of the company's production. The larger e_0, the higher the initial carbon emissions baseline of the company, and the higher the sensitivity of carbon tax costs (whether domestic or offshore) to emissions. At this point, the cost savings from the carbon tax advantage $(t_2 < t_1)$ of offshore production $((t_1 - t_2)e)$ increase as e_0 increases (due to higher emissions, the impact of tax rate differences becomes more significant). Therefore, the upper limit of the fixed offshore cost K that manufacturers can accept increases, i.e., K_0 increases as e_0 increases.

The offshore carbon tax rate t_2 is at a relatively low level, at which point the carbon tax advantage of offshore production (compared to the domestic tax rate t_1) is significant, and companies are more sensitive to the costs of emissions reduction. An increase in the emission reduction technology cost coefficient β implies rising marginal costs of emission reduction (the marginal cost increases as $(\beta(e_0 - e)^2)$, weakening firms' incentives to reduce emissions. Instead, firms are more likely to rely on the low tax rate advantage of offshore production (rather than actively reducing emissions) to lower carbon costs. At this point, the core advantage of offshore production is the “direct savings from low tax rates,” rather than “further cost reductions through emissions reductions.” Therefore, as β increases (emissions reductions become more expensive), firms' tolerance for offshore tax rates decreases. Even if t_2 is slightly lower, excessively high emissions reduction costs weaken the offshore advantage, causing the critical threshold K_0 (the acceptable upper limit for fixed offshore costs) to decrease as β increases. When the offshore carbon tax rate t_2 is at a moderate level (still below t_1), the carbon tax advantage of offshore production weakens, and companies must re-evaluate the trade-off between “low-tax savings” and “emission reduction costs.” As β increases (emission reduction costs rise), companies realize that relying solely on low offshore tax rates cannot fully offset high emission reduction costs, and must instead reduce total carbon emissions through moderate emission reductions (thereby reducing carbon tax expenditures). At this point, a higher t_2 (compared to a lower t_2) actually incentivizes companies to increase emissions reduction investments (as the cost per unit of carbon emissions becomes more significant after the tax rate increases), indirectly reducing the combined burden of total carbon taxes and emissions reduction costs. Therefore, as β increases (emission reduction becomes more expensive), firms' tolerance for offshore tax rates rises — a higher t_2 can optimize total costs through “forced emission reduction,” and the advantages of offshore production are enhanced, causing the critical value K_0 to increase with β.

If the government increases the domestic carbon tax t_1, companies are more likely to choose offshore production (which may trigger “carbon leakage”). By subsidizing offshore costs K or emissions reduction technology costs β, companies can be guided toward green transformation.

4.3. Stakeholder perspectives

In this section, we will examine manufacturers' emissions reductions and production strategies from the perspective of stakeholders by comparing retailers' profits, consumer surplus, and social welfare.

4.3.1. Retailer

First, we examine the impact of relevant influencing factors on retailers' profits. The optimal decisions for retailers regarding local production and offshore production, as well as the optimal profit structure, are similar. Therefore, we use local production as an example.

Proposition 3: When e_0 is low ($\underline{e_0} < e_0 < \frac{2\beta+t_1\gamma}{2\beta\gamma}$), π_r^n increases with an increase in t_1, decreases with an increase in β, and decreases with an increase in e_0; When e_0 is higher ($\frac{2\beta+t_1\gamma}{2\beta\gamma} < e_0 \leq \overline{e_0}$), π_r^n decreases with increasing t_1, increases with increasing β, and increases with increasing e_0.

Proposition 3 reveals the patterns of change in retailer profits across different initial carbon emission levels.

When the initial carbon emissions e_0 are low, the difficulty of emissions reduction for enterprises is small (marginal costs are controllable), and consumers' preference for low-carbon products (γ) can be effectively converted into market demand.

(1) Increasing t_1 increases manufacturers' carbon tax costs, prompting manufacturers to reduce carbon emissions e^n through emissions reduction (to reduce carbon tax expenditures). At this point, the reduced product carbon footprint aligns with consumer environmental demands, leading to increased market demand. Although manufacturers may raise wholesale prices, retailers can leverage the premium associated with “low-carbon products” to increase retail prices. The profit increase is

driven by the rise in demand, resulting in higher sales, and ultimately, retailer profits rise as t_1 increases.

(2) An increase in β implies rising marginal costs of emissions reduction, weakening manufacturers' incentives to reduce emissions, and an increase in actual carbon emissions e^n (approaching e_0). High carbon emissions led to a decline in consumer demand, and manufacturers may raise wholesale prices due to increased carbon tax costs ($t_1 e^n$), compressing retailers' cost margins. Therefore, retailers' profits decrease as β increases.

(3) An increase in e_0 (even if it remains in a low range) increases manufacturers' pressure to reduce emissions (requiring reductions from a higher initial value), leading to higher emission reduction costs and increased wholesale prices. Simultaneously, the increase in actual carbon emissions e^n suppresses consumer demand, with both factors causing retailer profits to decrease as e_0 increases.

When the initial carbon emissions e_0 are high, the marginal cost of emissions reduction for companies' surges (the second derivative of $\beta(e_0 - e)^2$ is positive), making it difficult to reduce the carbon footprint through deep emissions reduction. Consumers' expectations for "absolute low-carbon" give way to a focus on "relative emissions reduction efforts."

(1) When t_1 increases, manufacturers with high initial emissions face prohibitively high reduction costs, making it difficult to reduce carbon taxes by lowering e^n. Instead, they must pass on costs by raising wholesale prices. At this point, product carbon emissions remain high, consumer demand declines due to high emissions, and retailers cannot compensate for sales losses through price hikes (which further suppress demand), leading to reduced profits as t_1 increases.

(2) An increase in β causes manufacturers to completely abandon deep emissions reductions (where the costs far exceed the benefits) and instead maintain high carbon emissions. However, at this point, manufacturers' emissions reduction costs significantly decrease, limiting the increase in wholesale prices. Simultaneously, the market forms a "relatively stable" demand expectation for products with "high emissions but no further deterioration." Reduced emissions reduction investments lower supply chain costs, causing profits to rise as β increases.

(3) In the high e_0 range, consumers become less sensitive to "absolute low-carbon" and instead accept products with "high emissions but where the company has made efforts to reduce emissions" (e.g., by emphasizing reduction efforts through marketing). Manufacturers, due to their high initial emission baseline, can demonstrate "environmental action" with moderate emissions reductions without incurring excessive emissions reduction costs, resulting in relatively stable wholesale prices; retailers can obtain premium prices through differentiated marketing, with improved demand stability and profits increasing as e_0 rises.

Corollary 3: When $\underline{e_0} < e_0 < \frac{8t_1\beta+4\beta\gamma+t_1\gamma^2}{16\beta^2+2\beta\gamma^2}$, π_r^n increases with increasing γ; When $\frac{8t_1\beta+4\beta\gamma+t_1\gamma^2}{16\beta^2+2\beta\gamma^2} < e_0 < \frac{2\beta+t_1\gamma}{2\beta\gamma}$, π_r^n decreases as γ increases; When $\frac{2\beta+t_1\gamma}{2\beta\gamma} < e_0 \leq \overline{e_0}$, π_r^n increases as γ increases.

Contrary 3 reveals that the impact of consumer environmental preferences on retailer profits varies across different initial carbon emission ranges.

In the low initial emission range, companies have lower emission reduction costs (e_0 is small) and can effectively reduce the carbon footprint of their products through emission reductions (e^n decreases). Consumer environmental preferences (γ increases) drive growth in low-carbon demand, enabling retailers to raise retail prices through a "green premium" while also increasing sales volume. Although manufacturers may raise wholesale prices due to increased emissions reduction costs, the growth in demand and premium space are sufficient to offset the cost increase, resulting in higher retailer profits. In the medium initial emissions range, the initial emissions e_0 are high, and the marginal cost of emissions reduction for companies increases sharply ($\beta(e_0 - e)^2$ non-linear increase), making it difficult to significantly reduce e^n through emissions reduction. Consumers resist high-carbon emission products, but companies cannot recover demand through sufficient emissions reduction. Manufacturers are forced to lower wholesale prices to maintain market share, but retail price reductions are limited (to avoid further suppressing demand), compressing retailers' profit margins. In the high initial emissions range, companies abandon deep emissions reductions due to excessive costs and instead adopt “relatively low-carbon” marketing strategies to redefine product differentiation. The market develops differentiated demand for “relatively low-carbon” products (even if their absolute emissions remain high). As long as companies demonstrate emissions reduction actions, they can gain partial consumer recognition. Although companies cannot achieve deep emissions reductions, they can convey environmental signals through symbolic emissions reductions. Meanwhile, retailers can optimize supply chains, and manufacturers may further lower wholesale prices to stimulate demand, while retailers enhance profits through supply chain optimization.

4.3.2. Consumer surplus

Next, we will examine the impact of different manufacturer strategies on consumers. Let CS represent consumer surplus, which is defined as follows:

$$CS^i = \int_{p^i+\gamma e^i}^{1} \left(v - p^i - \gamma\xi^i\right) f(v)dv$$

After substituting the optimal decision, we can obtain the consumer surplus under strategy i, $i \in \{n, o\}$.

$$CS^i = \frac{(t^i\gamma + \beta(2 - 2e_0\gamma))^2}{2(\gamma^2 - 8\beta)^2}$$

Proposition 4: When e_0 is low (i.e., $\underline{e_0} < e_0 < \frac{2\beta+t^i\gamma}{2\beta\gamma}$), CS^i increases as t^i increases; when e_0 is high (i.e., $\frac{2\beta+t_1\gamma}{2\beta\gamma} < e_0 \leq \overline{e_0}$), CS^i decreases as t^i increases.

Proposition 4 reveals the impact of the carbon tax rate t^i on consumer surplus CS^i. When initial carbon emissions are low (i.e., e_0 is low), the cost of emissions reduction for enterprises is relatively low, and an increase in the carbon tax rate t^i will prompt enterprises to further reduce carbon emissions, thereby lowering the carbon footprint of their products. Consumer preference for low-carbon products increases demand, while product prices may rise due to increased emission reduction costs. However, the utility consumers derive from environmental premiums (i.e., their willingness to pay higher prices for low-carbon products) outweighs the negative impact of price increases, resulting in an increase in consumer surplus. When initial carbon emissions are high (e_0 is high), the marginal cost of emissions reduction for businesses surges, making it difficult to significantly reduce carbon emissions through emissions reduction. An increase in the carbon tax rate will cause businesses to pass on the carbon tax cost to consumers, resulting in a significant increase in product prices. Since carbon emissions remain high, consumers' environmental preferences cannot be satisfied, leading to a decline in demand. The combined effects of price increases and declining demand result in a decrease in consumer surplus.

Corollary 4: When e_0 is low ($\underline{e_0} < e_0 < \frac{2\beta+t^i\gamma}{2\beta\gamma}$), $CS^n > CS^o$; when e_0 is high ($\frac{2\beta+t_1\gamma}{2\beta\gamma} < e_0 \leq \overline{e_0}$), $CS^n < CS^o$.

Corollary 4 reveals the comparative mechanism of consumer surplus under different manufacturers' decisions. When initial carbon emissions are low (e_0 is low), the carbon tax rate t_1 for domestic production is high, but companies can significantly reduce e^n through emission reductions to better meet consumer demand for low-carbon products. Offshore production, although it has a lower carbon tax rate t_2, may indirectly increase prices due to fixed costs K, and lacks sufficient incentive for emissions reduction (due to lower carbon tax pressure), resulting in relatively higher product carbon footprints. Therefore, domestic production is more favored by consumers. At high initial carbon emissions (e_0 is high), the high carbon tax rate t_1 for domestic production makes it difficult for companies to reduce emissions, forcing them to pass on costs through price increases. Consumers face high-priced, high-carbon-emission products, leading to a decline in demand.

Offshore production's lower tax rate reduces companies' carbon tax burdens. Despite the existence of fixed costs K, companies may attract consumers through moderate emissions reductions or lower price strategies.

4.3.3. Social Welfare

Through the above calculations, we have obtained the optimal solutions for retail prices, wholesale prices, and green investment levels under the two decision-making scenarios. Based on the above conditions and the following formula, we can calculate social welfare.

$$SW_i = \pi_r + \pi_m + CS_i + \alpha(e_0 - e)^2, \qquad i \in 1,2$$

By substituting the optimal decision, we obtain:

SW_1	$\frac{t_1{}^2(32\beta - 5\gamma^2) + 2\beta(-1 + e_0\gamma)\left(\gamma^2(2 - e_0\gamma) + 2\beta(-7 + 3e_0\gamma)\right) + t_1(20\beta\gamma - 3\gamma^2 + 4e_0\beta(-32\beta + 5\gamma^2))}{2(-8\beta + \gamma^2)^2}$
SW_2	$\frac{\left(4\beta((7 - 32K)\beta + 8t_2(t_2 - 4e_0\beta)\right) + 20\beta(t_2 - 2e_0\beta)\gamma + \left(-5t_2{}^2 + 20e_0t_2\beta + 4\beta(-1 + 8K + 3e_0\beta)\right)\gamma^2 - 3(t_2 - 2e_0\beta)\gamma^3 - 2(K + e_0{}^2\beta)\gamma^4)}{2(-8\beta + \gamma^2)^2}$

In social welfare SW_1 and SW_2, the variables $\gamma, t_i(i \in 1,2), \beta, e_0, K$ are exogenous variables. Therefore, we will next conduct sensitivity analyses on these six variables separately. We set the domestic carbon tax rate $t_1 = 0.2$, the offshore carbon tax rate $t_2 = 0.1$, the environmental benefit weight $\alpha = 0.5$, the offshore fixed cost $K = 0.033$, the emission reduction cost coefficient $\beta = 0.4$, and the consumer environmental preference $\gamma = 0.2$.

In Fig.1, we simulate low/medium/high initial carbon emissions. As e_0 increases, social welfare decreases in both scenarios. However, the decrease in social welfare is faster when fixed offshore costs are not considered compared to when they are considered. In simple terms, when initial emissions are low, companies' emission reduction costs are relatively low, and a strict domestic carbon tax mechanism can incentivize companies to increase their green investment levels. Additionally, reducing product carbon footprints helps enhance consumer satisfaction with green preferences, thereby promoting sales growth at both the retail and manufacturing ends, leading to an overall increase in social welfare. Furthermore, the environmental benefits α resulting from emissions reductions are also significant. These factors collectively make the domestic production scenario more advantageous in terms of social welfare. However, as e_0 continues to increase, the marginal emissions reduction costs of the domestic production model rise rapidly, weakening the incentive effect of the carbon tax mechanism on firms. When companies cannot effectively reduce carbon costs through emissions reductions, they can only pass on costs by increasing wholesale and retail prices, leading to rising product prices, declining market demand, compressed profits, and ultimately a decline in social welfare. In contrast, while offshore production entails fixed offshore costs K, it faces smaller carbon tax pressures and lighter emissions reduction burdens in scenarios with higher initial emissions. Therefore, as e_0 increases, the decline in social welfare from offshore production is slower, and it overtakes domestic production at a certain point, demonstrating higher system adaptability and stability.

Additionally, we considered the impact of the carbon tax rate t_1 on social welfare in domestic production (Fig.2). Under domestic production, social welfare SW_1 exhibits a “U-shaped” change with respect to t_1. We provide a straightforward explanation for this: when the tax rate is too low, businesses lack sufficient incentives to reduce emissions, resulting in lower social welfare; when the tax rate is moderate, emission reduction costs and environmental benefits achieve relative equilibrium, leading to an increase in social welfare; further increasing the tax rate may stimulate consumer demand for green products, driving an overall improvement in benefits. In contrast, social welfare SW_2 under the offshore production model is almost unaffected by changes in domestic carbon taxes, reflecting its low sensitivity to environmental policies.

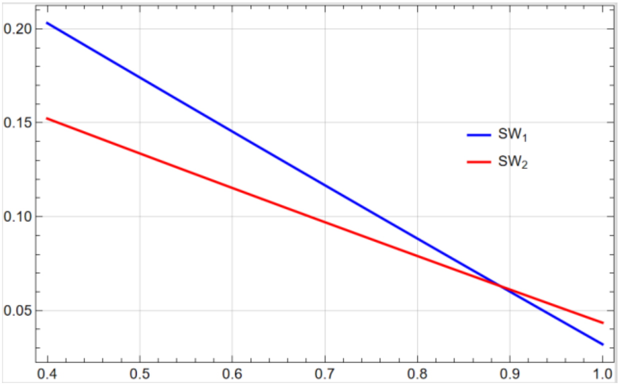

Figure 1. The impact of e_0 on social welfare

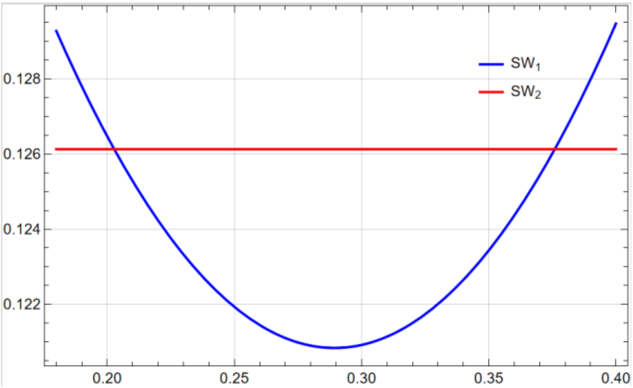

Figure 2. The impact of t_1 on social welfare

Next, we analyzed the emission reduction cost coefficient β. As shown in Fig.3, the emission reduction cost coefficient has a significant nonlinear effect on social welfare. When the emission reduction cost coefficient is low, the social welfare SW_1 under domestic production is higher than that under offshore production. However, as the emission reduction cost coefficient β increases, the social welfare under domestic production gradually decreases, while the social welfare under offshore production exhibits relatively strong stability. When the emission reduction cost coefficient exceeds a certain threshold, the social welfare under offshore production will surpass that under domestic production. This is because lower emission reduction costs mean that enterprises can achieve higher emission reduction efficiency at lower costs, thereby more effectively addressing higher carbon tax rates domestically. At this point, enterprises reduce the carbon footprint of their products through emission reduction measures, not only meeting consumers' environmental preferences but also reducing cost pressures caused by carbon taxes. Additionally, the environmental benefits of emission reductions further enhance the overall level of social welfare, making domestic production the optimal choice. Thereafter, the high emissions reduction cost coefficient significantly increases the economic burden of implementing emissions reduction measures. Under the domestic production model, companies must bear higher emissions reduction costs to comply with strict carbon tax policies, compressing their profit margins. In contrast, offshore production faces lower carbon tax rates and is less sensitive to emissions reduction costs.

Finally, we will explore the impact of the environmental benefit weight α on social welfare under different conditions. As shown in Fig.4, as the environmental benefit weight α increases, the social welfare of both production modes shows an upward trend, but with distinct differences. When the environmental benefit weight is at a lower level ($\alpha < 0.6$), the social welfare of domestic production SW_1 remains higher than that of offshore production SW_2. This is because, when the environmental benefit weight is relatively small, social welfare is more significantly influenced by corporate profits and consumer surplus. Since the domestic production model has advantages such as high supply chain efficiency and low transportation costs, it holds a certain advantage in terms of profits and consumer surplus, resulting in higher social welfare. However, as the environmental benefit weight continues to increase ($\alpha > 0.6$), the gap in social welfare between the two models gradually narrows and crosses at $\alpha \approx 0.7$. Once the environmental benefit weight exceeds this critical value, the social welfare of offshore production SW_2 begins to surpass that of domestic production SW_1.

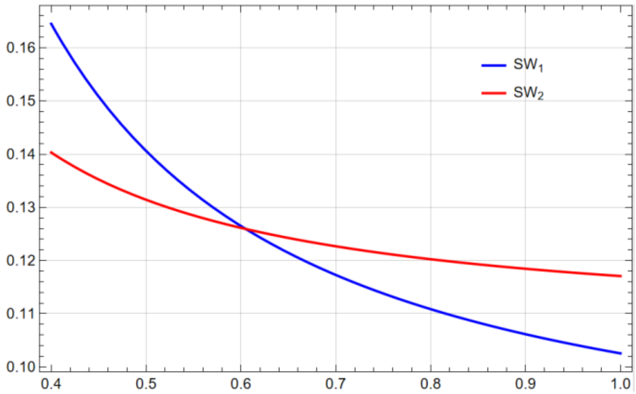

Figure 3. The impact of β on social welfare

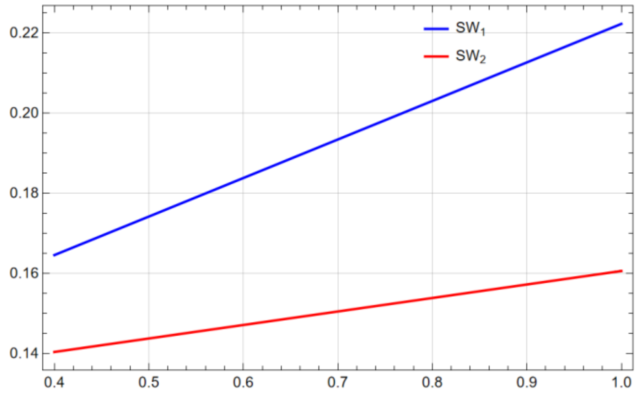

Figure 4. The impact of α on social welfare

5. Summary

Against the backdrop of the gradual implementation of the Carbon Border Adjustment Mechanism (CBAM), cross-border supply chain enterprises are facing unprecedented dual pressures: on the one hand, increasingly stringent carbon emissions regulations from domestic or export destination governments; on the other hand, market pressures driven by consumers' growing preference for green products. This paper constructs a game model involving manufacturers and retailers to systematically explore enterprises' emissions reduction investment and production location strategy choices under carbon tariff policies. The study finds that the influence of different factors on corporate behavior exhibits significant nonlinear characteristics, and optimal strategies are highly dependent on external variables such as initial carbon emissions levels, technology investment costs, tax rate differentials, and consumer preferences.

When facing production location decisions, manufacturers often weigh the trade-off between “offshore carbon tax incentives” and “fixed offshore costs,” exhibiting clear threshold characteristics. When domestic carbon tax rates are high and offshore tax rates are low, if offshore fixed costs are controllable, offshore production becomes more attractive; conversely, under high fixed costs or rising offshore carbon taxes, domestic production becomes the profit-maximizing choice. This finding provides quantitative reference for current corporate behaviors of blindly “going offshore” or conservatively “staying put.”

Second, corporate emissions reduction investment decisions are jointly influenced by initial carbon emissions levels and consumer environmental preferences. When initial emissions are low, consumer preference for low-carbon products can effectively translate into increased demand, giving companies the potential to drive profit growth through emissions reduction; however, when initial emissions are high, the marginal cost of emissions reduction rises rapidly, leading companies to abandon deep emissions reduction and instead respond to market pressure through pricing strategies or “symbolic environmentalism.” This also explains why, under the same policy, different companies exhibit markedly different levels of emissions reduction initiative.

From the perspective of retailers and consumers, consumer surplus and retailer profits also exhibit a dual effect influenced by the interaction between initial emissions and carbon tax rates. When emissions reductions are effective and green products are priced reasonably, overall market efficiency improves; however, when carbon taxes or penalty mechanisms are overly aggressive, the cost pressure on companies is passed on to consumers, and rising prices and declining demand in turn weaken social welfare.

Interestingly, social welfare does not increase monotonically with the intensity of environmental protection. Research shows that moderate carbon penalty mechanisms can effectively incentivize businesses to engage in reasonable emissions reductions, thereby achieving synergistic growth in business profits, consumer surplus, and environmental protection goals; however, once environmental protection goals are set too high, investment costs or penalties become overly stringent, not only will this suppress businesses' economic willingness to reduce emissions, but it will also lead to significant price increases and shrinking demand, ultimately harming overall social welfare. This finding suggests that policymakers must achieve a dynamic balance between "green goals" and "economic realities" in environmental regulation policies, rather than simply raising environmental standards.

In summary, the green transformation of supply chains under a carbon tariff framework is a systematic endeavor. Only through the coordinated efforts of market mechanisms, rational corporate decision-making, and government policy incentives can the dual objectives of carbon reduction and development be truly achieved.

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